

# Facies analysis of an ancient, dismembered, large caldera complex and implications for intra-arc subsidence: Middle Jurassic strata of Cobre Ridge, southern Arizona, USA

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## ABSTRACT

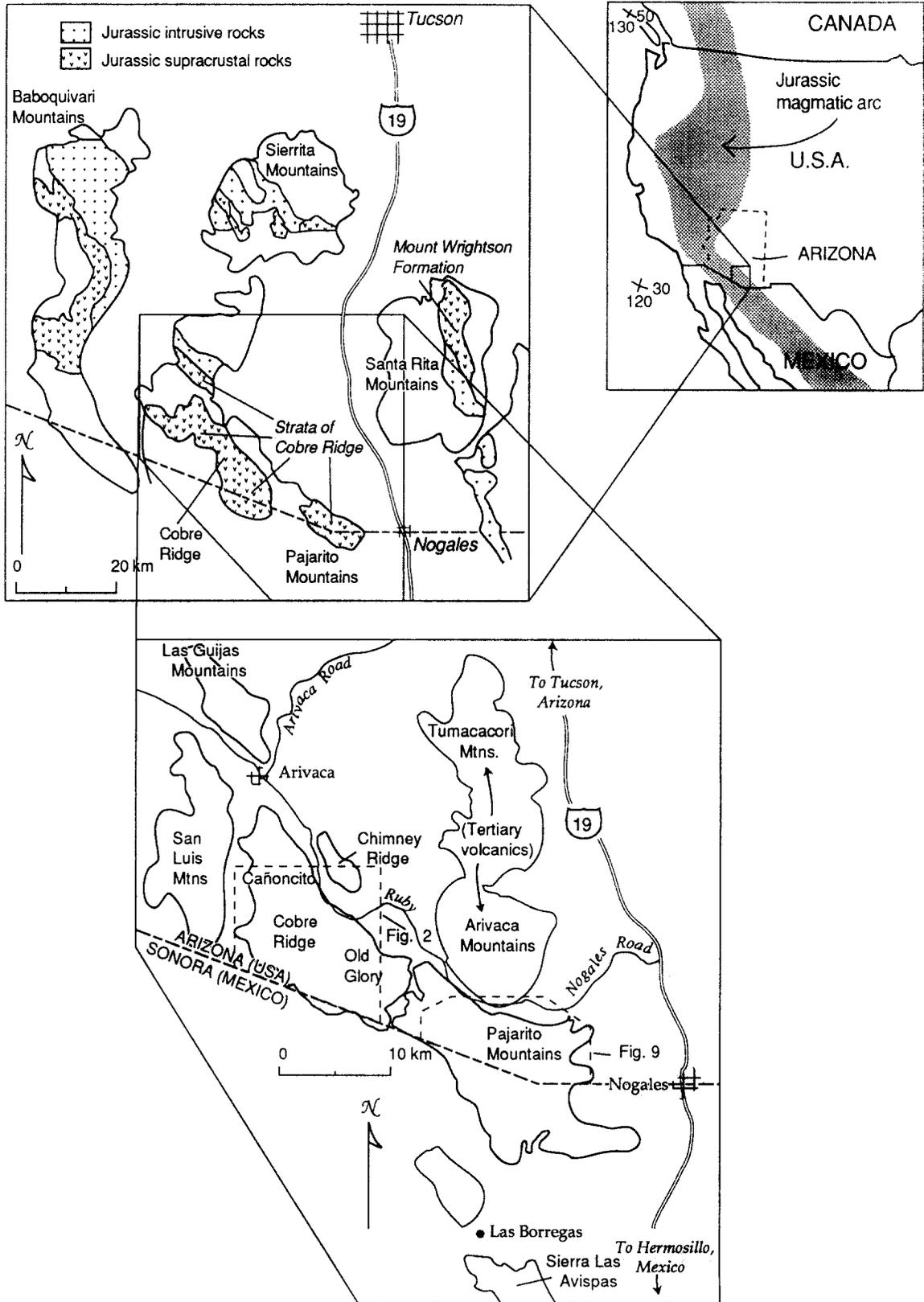
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The Middle Jurassic (~170 Ma) Cobre Ridge caldera is an elongate caldera complex that formed during the eruption of the tuff of Pajarito, a crystal-rich rhyodacite ignimbrite with an estimated volume  $\gg 1000 \text{ km}^3$ . The caldera subsided in two subequal blocks: to the southeast, caldera-forming ignimbrite is as much as 3000 m thick, whereas the northwest half of the caldera subsided to lesser depths during the initial eruption, but was the locus of subsidence during subsequent eruptions, providing a depocenter for a  $> 1.5 \text{ km}$ -thick section of secondary- and post-collapse volcanic and sedimentary strata. These strata record moat formation and filling and waning volcanism, including: (1) areally restricted ignimbrites up to several tens of meters thick that may have been ponded between caldera margins and/or fault scarps; (2) a  $\geq 600 \text{ m}$ -thick ignimbrite whose eruption probably caused further collapse of the caldera or enlargement of the caldera margins; (3) a localized debris apron deposit up to 500 m thick that represents material reworked from intra-caldera pyroclastic deposits and possibly caldera walls; and (4) eolian and fluvial sandstones and water-lain tuffs. Megabreccia blocks as large as 0.5 km along strike probably demarcate approximate caldera margins, suggesting that the composite caldera was approximately 50 km long by 25 km wide. The preserved thickness of the strata of Cobre Ridge ( $> 4500 \text{ m}$ ) is greater than many ancient continental volcanic sequences, suggesting external (i.e. tectonic) controls on subsidence, but preservation of this great thickness of strata is apparently due entirely to volcanic subsidence.

## Introduction

The interpretation of the depositional environment and tectonic setting of ancient volcanic arc sequences is commonly hampered by the lack of complete sections, due to the tendency for volcanoes to be constructional and therefore rapidly weathered and eroded. This is especially true of volcanoes in high-standing "Andean"-type arcs, considered typical of convergent continental margins. The record of these arcs, especially ancient ones, is preserved primarily in the volcaniclastic sediments deposited in basins near to the original volcanoes, or more commonly in more distant

forearc or retroarc basins. In the Cordilleran Mesozoic magmatic arc of North America, however, increasing evidence suggests that many parts of the arc, including those in south-central Arizona, were not only topographically low-standing, but neutral or extensional in tectonic character, and were characterized by deposition in grabens or basins (Busby-Spera, 1988; Busby-Spera et al., 1990). Facies analysis and interpretation of preserved remnants of the Mesozoic magmatic arc in south-central Arizona indicate that primary volcanic and volcaniclastic strata are preserved in far greater abundance than the derivative sedimentary sequences. This suggests either that these



derivative sediments were transported to basins outside of the magmatic arc, or that epiclastic strata were not produced in large volumes.

It is important to distinguish between the effects of regional tectonic activity on depositional environment and the more localized effects caused by volcanism when interpreting modes of preservation of ancient primary volcanic sequences. We have previously described the development of an Early Jurassic multi-vent volcanic complex, the Mount Wrightson Formation, that formed in an intra-arc graben depression in southern Arizona (Riggs and Busby-Spera, 1990). The graben depression probably formed in response to a regional extension, which caused continued subsidence of the depositional basin during volcanism. The present paper describes the Middle Jurassic strata of Cobre Ridge, exposed in the Arivaca area southwest of Tucson, Arizona and in northernmost Sonora, Mexico (Figs. 1 and 2). The strata of Cobre Ridge record a short-lived episode of caldera formation and filling. Although caldera-bounding structures have not been identified, we conclude that great thicknesses of homogeneous ignimbrite (tuff of Pajarito) define the areal extent of a composite caldera that was as much as 50 km × 25 km in size. Deposition of the strata of Cobre Ridge was controlled by volcano-induced subsidence, which, although local in expression, was as important in providing a locus of deposition with high preservation potential as regional tectonic subsidence documented elsewhere in southern Arizona (Riggs and Busby-Spera, 1990).

The strata of Cobre Ridge provide an opportunity to study the collapse history of a large caldera. Tertiary faults provide exposures of various structural levels of the caldera, from post-collapse sedimentary strata, down through intra-caldera ignimbrite, to subvolcanic intrusions. Collapse of this large, elongate caldera may have occurred in

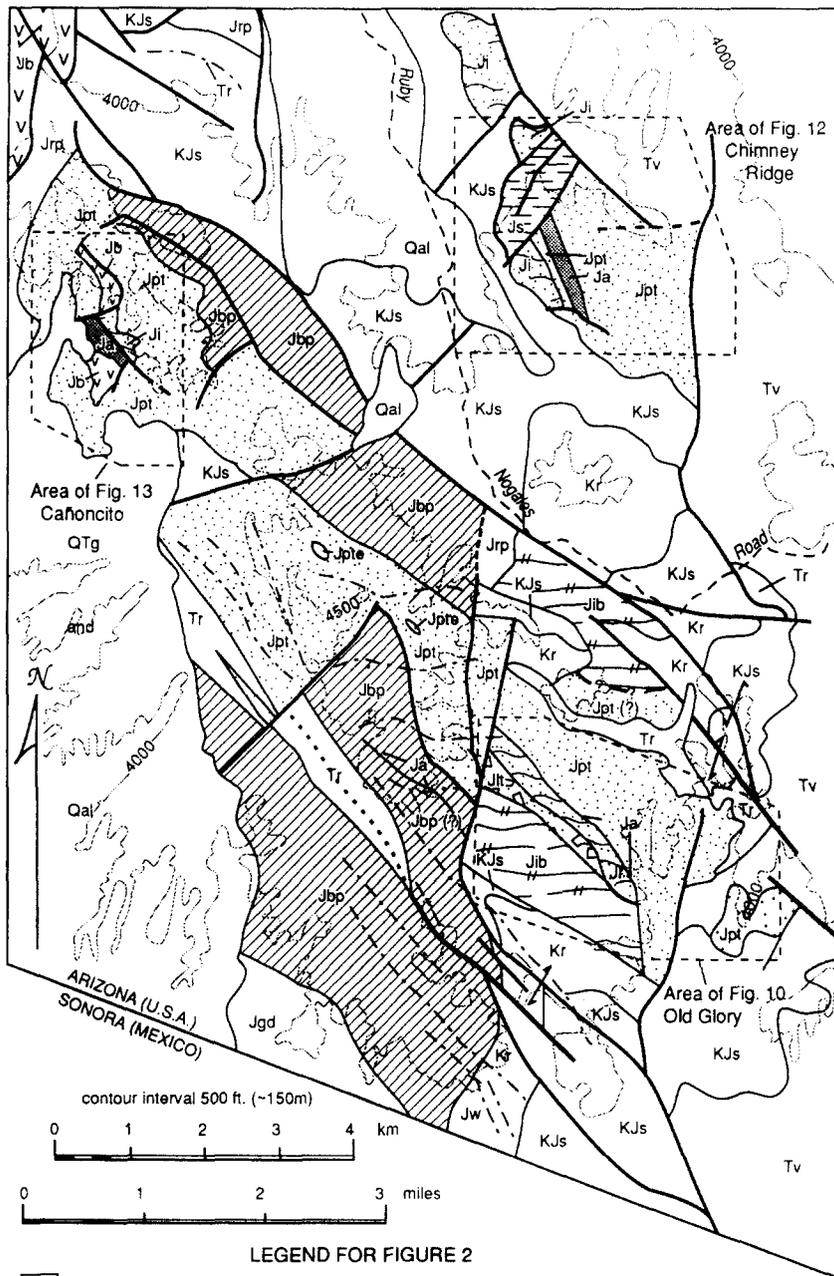
two major blocks, and possibly numerous smaller ones, and we suspect that many large elongate calderas, frequently referred to as volcano-tectonic subsidence structures, collapse as more than one block.

### Geologic background and setting

A brief review of the geologic history of southern Arizona provides the context for discussion of the strata of Cobre Ridge. Basement rocks comprise 1.8–1.4 Ga plutonic rocks and supracrustal strata (Anderson and Silver, 1978; Silver, 1978). Overlying Paleozoic strata represent stable-margin sedimentation and are ~1–2 km thick in southern Arizona (Peirce, 1976). Mesozoic Cordilleran magmatism, related to subduction along the western North American margin, began in Late Triassic and Early Jurassic time across eastern California and into southern Arizona (Dickinson, 1981; Walker, 1987; Tosdal et al., 1989) and northern Sonora, Mexico (Anderson and Silver, 1978, 1979). U–Pb zircon geochronology suggests that magmatic activity in southern Arizona began 190–200 m.y. ago (Wright et al., 1981; Asmerom et al., 1990; Riggs et al., 1991) and continued until approximately 150 m.y. (Tosdal et al., 1989). Busby-Spera (1988) has proposed that the Mesozoic magmatic arc was extensional during much of its history and over much of its extent, and regional studies in the Sierra Nevada, California (Busby-Spera, 1984a), southern Arizona (Haxel et al., 1985; Riggs and Busby-Spera, 1990), and southeastern California (Schermer and Busby-Spera, 1990) confirm that in many parts of the arc, volcanic materials were deposited largely in structural grabens, and that in general the arc was a topographically low-relief feature.

In Late Jurassic to Early Cretaceous time, the dominant tectonic style was transtensional to ex-

Fig. 1. Location diagram showing the position of Arizona within present-day exposures of the Jurassic magmatic arc (modified from Tosdal et al., 1989), arc-related strata in southern Arizona (modified from Reynolds, 1988), and mountain ranges in the Arivaca area, USA and northern Sonora, Mexico. Names in italics refer to areas within Cobre Ridge described in detail in the text. All ranges shown are underlain in part or wholly by the Cobre Ridge group except the Atascosa and Tumacacori Mountains, which contain only Tertiary volcanic rocks.



LEGEND FOR FIGURE 2

- |  |  |
|--|--|
| <b>Tv</b> Tertiary volcanic and hypabyssal rocks             | <b>Kr</b> Cretaceous(?) diorite        |
| <b>KJs</b> Jurassic-Cretaceous sedimentary rocks             | <b>Jw</b> Jurassic(?) quartz monzonite |
| <b>Jrp</b> hypabyssal rhyolitic porphyry (probably Jurassic) | <b>Jgd</b> Jurassic(?) granodiorite    |

STRATA OF COBRE RIDGE (Middle Jurassic)

- |   |  |
|---|--|
| <b>Jbs</b> breccia, conglomerate and sandstone                              | <b>Jvb</b> volcanic breccia, commonly clast-supported  |
| <b>Jba</b> arenite, locally contains structures indicative of eolian origin | <b>Jie</b> rhyolitic ignimbrite, locally with uncertain stratigraphic relation to tuff of Pajarito |
| <b>Jib</b> tuff of Brick Mine   | <b>Jpt</b> tuff of Pajarito; 'e' indicates megabreccia block                                       |
| <b>Jjt</b> lithic lapilli tuff and/or tuff breccia                          |  |
| <b>Jpb</b> tuff of Black Peak   |  |

— fault                      — depositional contact

Fig. 2. Generalized geologic map of the Cobre Ridge area. Geology modified from Knight (1970), Keith and Theodore (1975), and Riggs and Haxel (1990).

tensional. Major strike-slip faults inferred in northern Mexico (Anderson and Silver, 1979; Anderson and Schmidt, 1983; Silver and Anderson, 1983) and large basins that covered much of southern Arizona (Dickinson et al., 1989) were associated with the opening of the Gulf of Mexico. Late Cretaceous and early Cenozoic magmatism and deformation associated with the Laramide orogeny produced calc-alkaline volcanism, local synorogenic basins, and contractional deformation, and only slightly later, peraluminous magmatism (Dickinson, 1989). Mid-Tertiary

magmatism was associated with widespread extensional deformation in southern Arizona, as well as voluminous ignimbrite volcanism. Late Cenozoic Basin and Range faulting has controlled the present physiographic setting of southern Arizona, characterized by deep nonmarine basins between mountain ranges (Eberly and Stanley, 1978).

The Arivaca area as described herein encompasses exposures of the strata of Cobre Ridge in southernmost Arizona and northernmost Sonora (Figs. 1 and 2). The Arivaca area lies within the

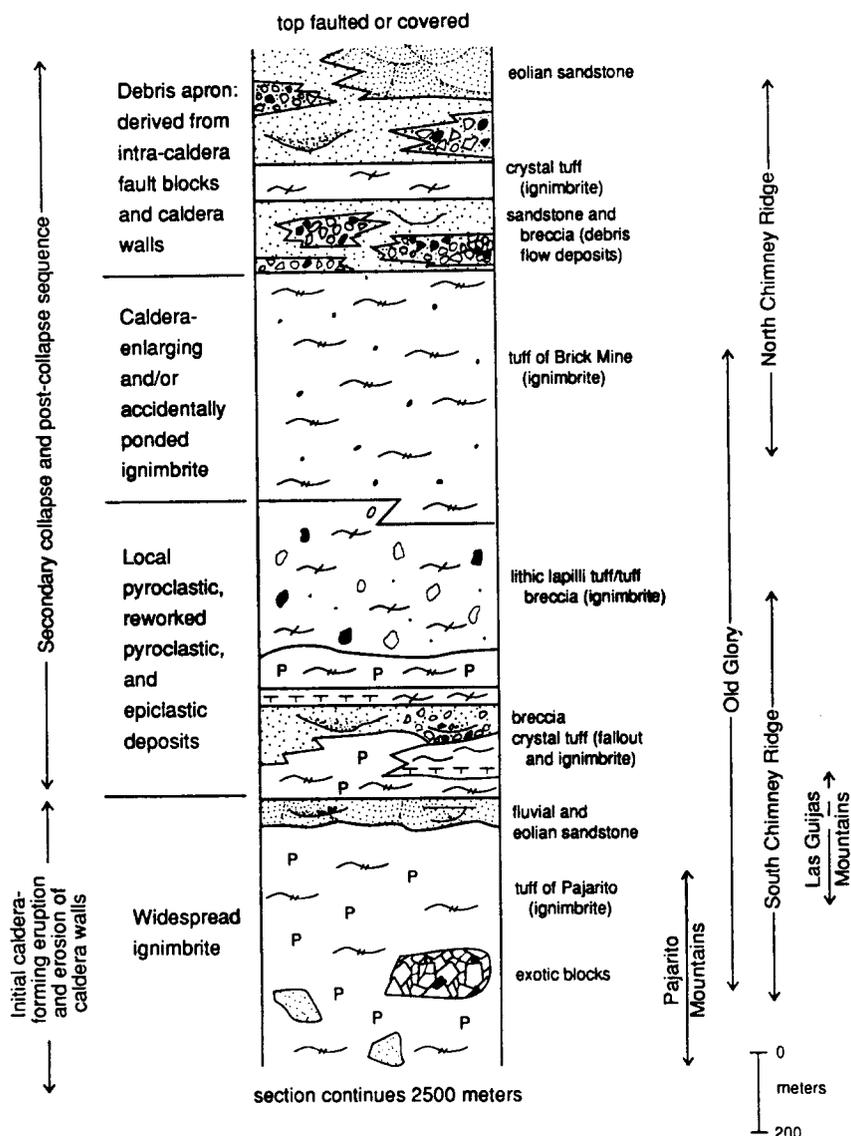


Fig. 3. Composite stratigraphic column summarizing lithofacies characteristics of the strata of Cobre Ridge. Also shown are mountain ranges and fault blocks in which different parts of the strata of Cobre Ridge are exposed.

Papago terrane, a part of south-central Arizona that differs in geology and geologic evolution from the rest of southern Arizona (Haxel et al., 1988; Riggs and Haxel, 1990). The Papago terrane is characterized by the absence or allochthonous nature of rocks older than Early or Middle Jurassic age, a far greater abundance of Jurassic magmatic arc-related rocks, and a relative paucity of Late Cretaceous arc-related rocks relative to areas outside of the terrane (Riggs and Haxel, 1990).

The strata of Cobre Ridge at Cobre Ridge (Figs. 1 and 2) were studied in detail by Knight (1970), whose work concerned the gross lithology, structural geology, and economic geology of the mining district that encompasses most of Cobre Ridge. Drewes (1981) mapped welded tuff in the Pajarito Mountains as part of his tectonic synthesis of southern Arizona, and suggested that possible hypabyssal rocks in the eastern part of the range could be associated with a caldera (Drewes, 1980, 1981). Riggs (1987) proposed that the thick ignimbrite in the Pajarito Mountains represents an intra-caldera accumulation. Our mapping of the strata of Cobre Ridge has concentrated on delineation and analysis of individual pyroclastic and epiclastic units and interpretation of the overall volcanic setting. A composite stratigraphic column of the strata of Cobre Ridge is presented in Fig. 3, together with reference to those ranges and fault blocks in the Arivaca area in which the strata of Cobre Ridge are exposed (see also Figs. 1 and 2).

The strata of Cobre Ridge have been affected by post-depositional metamorphism, alteration, and tectonism as follows.

(1) Alkali–element exchange has been noted in chemical studies of Mesozoic magmatic arc rocks throughout southern Arizona, including the strata of Cobre Ridge in the Pajarito Mountains (Drewes, 1971; Riggs, 1987; Krebs and Ruiz, 1987), and has been inferred to be Late Jurassic in age (Krebs and Ruiz, 1987).

(2) Incipient to strong metamorphism of the strata of Cobre Ridge in the San Luis Mountains (Fig. 1) has obliterated most primary structures and textures, making lithologic correlations virtually impossible. Haxel (Riggs and Haxel, 1990)

has assigned a Late Cretaceous to Early Tertiary age to this metamorphism based on correlation with metamorphism in the Baboquivari Mountains (Haxel et al., 1984; Goodwin and Haxel 1990; Fig. 1).

(3) Mid-Tertiary(?) faulting has displaced all Mesozoic units along high-angle, dominantly north-, northwest- and northeast-trending faults (Fig. 2), which in large part control the present structural and geomorphic framework of the Arivaca area, probably including steep dips throughout the area. Jurassic caldera-related rocks described herein are correlated with structural blocks formed by these faults. Some mid-Tertiary extension is suggested by a ~ 5 km-wide graben of mid-Tertiary volcanic rocks between the Pajarito Mountains and the Cobre Ridge area (Fig. 1), but this has little effect on the overall dimensions of the Cobre Ridge caldera.

#### *Age of the strata of Cobre Ridge*

Understanding of the age of the strata of Cobre Ridge is constrained by U–Pb data on the tuff of Pajarito, the most widespread unit in the strata of Cobre Ridge. We have analyzed twelve fractions from three samples, using stepwise dissolution (Mattinson, 1984) to remove radiation-damaged domains in the zircons, and these fractions have yielded data which plot in a cluster between 165 and 180 Ma (Riggs, 1991). Because the data do not give satisfactory intercepts on either Wetherill (1956) or Tera-Wasserburg (1972) concordia diagrams, we model the age of the unit as  $170 \pm 5$  Ma, or Middle Jurassic. Although the strata of Cobre Ridge and precursor ignimbrites have no older substrate in most exposures in the Papago terrane, in Sonora the strata of Cobre Ridge (including precursor ignimbrites) overlie strata identical in outcrop and in thin-section to ignimbrites of the Early Jurassic Mount Wrightson Formation exposed 50 km to the northeast of the Arivaca area (Riggs and Busby-Spera, 1990; Fig. 1). The strata of Cobre Ridge in much of the Arivaca area are unconformably overlain by a sequence of clastic rocks correlated with the Late Jurassic and/or Early Cretaceous Bisbee Group

of southeastern Arizona (Bilodeau et al., 1987; Riggs and Haxel, 1990).

### *Terminology*

The variable use of volcanic terminology necessitates a brief definition of terms used herein. "Ignimbrite" is used sensu Sparks et al (1973) as "composed predominantly of vesiculated juvenile material (pumice and shards)... whether welded or not", the result of pyroclastic flow. Rocks that contain > 75% pyroclastic fragments < 2 mm in size, are called tuffs. Those with 25–75% fragments of 2–64 mm in size are called "lapilli tuff" (Fisher and Schmincke, 1984); the term is preceded by "pumice" or "lithic", depending on the primary fragment type. "Tuff breccia" contains 25–75% fragments of pyroclastic origin larger than 64 mm; "breccia" contains > 75% fragments larger than 64 mm. Epiclastic deposits contain clasts or grains derived from pre-existing rocks and are deposited by debris flow, eolian, and fluvial processes, whereas reworked pyroclastic strata, while deposited by many of the same processes, contain a predominance of pyroclastic debris such as shards and pyrogenic crystals.

### **Lithofacies of the strata of Cobre Ridge and related strata**

The strata of Cobre Ridge are divided into two major lithofacies: widespread and localized pyroclastic and minor reworked pyroclastic deposits, and epiclastic facies; additionally we recognize two minor lithofacies: volcanic breccia and hypabyssal intrusions. These deposits were formed by pyroclastic eruptions, eolian sand migration and lesser fluvial processes, accumulation of debris shed from caldera walls and possibly intracaldera fault blocks, eruption of lava domes, and resurgent or post-eruptive magmatism.

### *Pyroclastic facies*

#### *Widespread ignimbrites*

*Tuff of Pajarito.* The Cobre Ridge caldera is delineated in part by the outcrop pattern of the tuff of the Pajarito Mountains (Fig. 1), referred to

informally herein as the tuff of Pajarito. We have recognized the tuff of Pajarito in ranges from northernmost Sonora, Mexico to the Las Guijas Mountains (Fig. 1), and it is commonly the stratigraphically lowest unit. The tuff of Pajarito is a homogeneous, massive, crystal-rich tuff, rarely containing lithic fragments. It varies in thickness from a minimum of 3000 m in the Pajarito Mountains to 350 m in the Las Guijas Mountains (Fig. 1), and locally occurs as three flow units. The tuff is rhyodacitic in composition (Riggs, 1985, 1987), but varies modally from andesite to rhyolite. It contains 30–50% crystals, primarily subequal quartz, plagioclase, and potassium feldspar (Figs. 4A, 4B); crystals are very commonly broken. Zircon is a common accessory phase, as are clots containing monazite(?) and opaque crystals. Opacite replaces hornblende in a few samples. Relict compacted pumice lapilli and blocks are locally common in the tuff and are rarely apparent in thin-section, but microscopic evidence of welding has been obliterated by post-emplacement devitrification and alteration. The groundmass contains local spherulitic and snowflake devitrification, indicating alteration of original glass. Lithic fragments range in size from a few mm to 20 cm, and are angular to rounded. The volume of the tuff of Pajarito is estimated as  $\geq 1000$  km<sup>3</sup>, based on present-day outcrop exposures. The nearly ubiquitous occurrence of broken crystals, together with relict pumice in outcrop and devitrified glassy groundmass, lead us to interpret the tuff of Pajarito as an ignimbrite.

Locally, the tuff of Pajarito appears to be stratigraphically divisible into two members based on the presence or absence of pumice. The two "members" are identical in chemistry (Riggs, 1985, 1987), modal mineralogy, and outcrop appearance, with the exception of a lack of recognizable pumice lapilli and blocks everywhere within the stratigraphically lower member. Over much of the area, however, the stratigraphic division of pumiceous and non-pumiceous tuff does not hold, and we expect that deep burial within the caldera and concomitant extremely dense welding, together with local intense hydrothermal alteration, are responsible for the stratigraphic irregularity of the apparent lack of pumice within

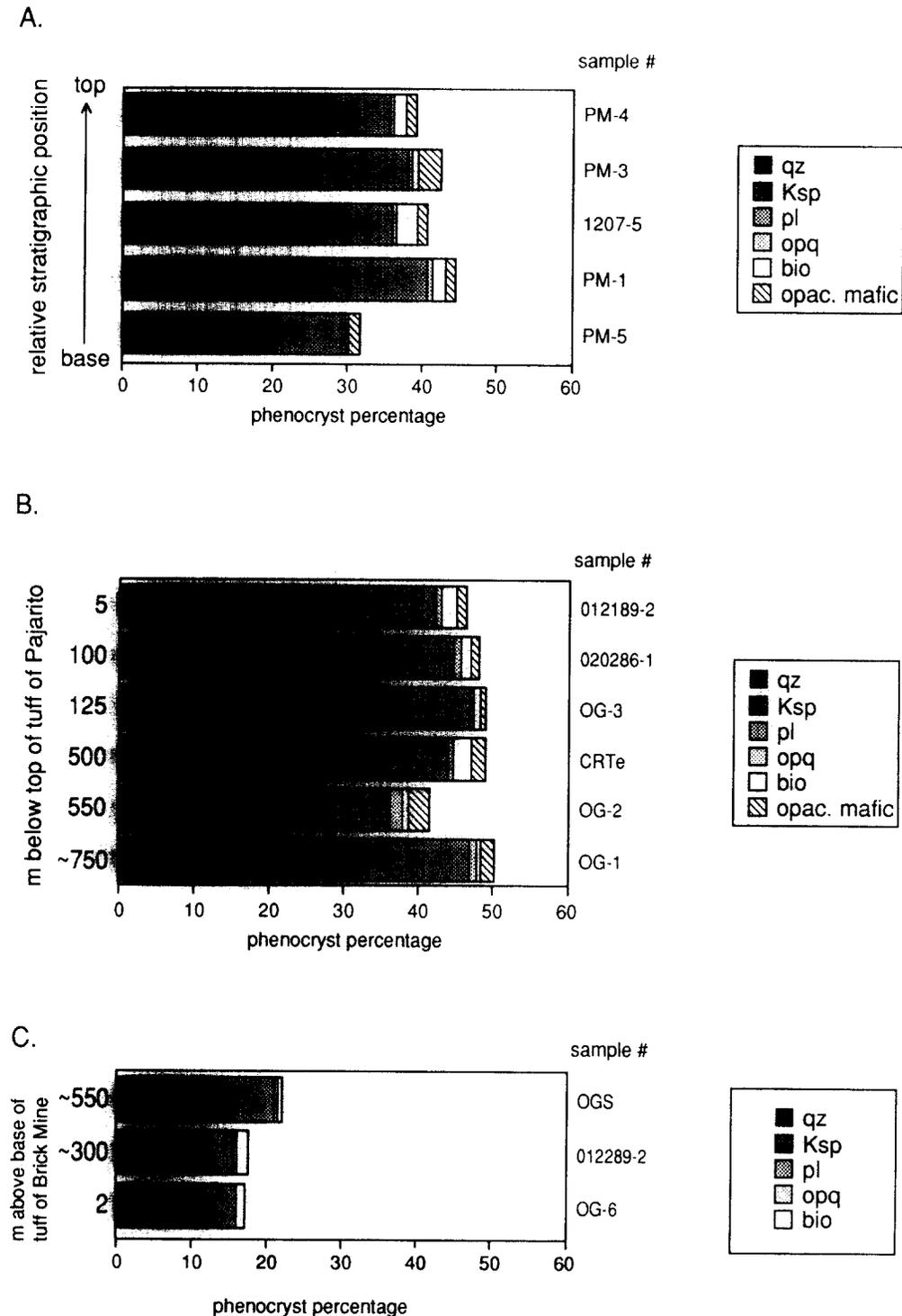


Fig. 4. Crystal percentages. A. Tuff of Pajarito in the Pajarito Mountains. Because of the faulted nature of most contacts between the Middle Jurassic tuff of Pajarito and Jurassic and/or Cretaceous conglomerate, no datum is available for reference. B. Tuff of Pajarito in the Cobre Ridge area. C. Tuff of Brick Mine. Note that there is no apparent correlation between stratigraphic position and mineral percentage in either the tuff of Pajarito or the tuff of Brick Mine.

parts of the tuff. P.W. Lipman (pers. commun., 1990) reports that obliteration of pumice textures by alteration is common in mid-Tertiary calderas. The ubiquitous occurrence of broken crystals, however, indicates that the non-pumiceous rocks are pyroclastic in origin.

Stratigraphic mineralogical zonation is not apparent in the tuff of Pajarito (Figs. 4A, 4B). Although recognition of stratigraphic position within the tuff is made difficult by its homogeneity and by faulting, composite sections from the Pajarito Mountains (3000 m thick; Fig. 4A) and Cobre Ridge and Las Guijas Mountains (approximately 1500 m thick; Fig. 4B) show no apparent systematic variation in composition, crystal content, or relative percentages of quartz versus feldspars. The size of crystals is similarly variable but unsystematic.

*Tuff of Brick Mine.* The tuff of Brick Mine (Fig. 3) is informally named for exposures at the Brick Mine in the Cobre Ridge area. It is exposed in several of the fault blocks at Cobre Ridge where it varies from ~ 600 to ~ 700 m in thickness (Figs. 2, 10 and 13). The tuff of Brick Mine is volumetrically the second largest ignimbrite in the Cobre Ridge area ( $\geq 4 \text{ km}^3$ ). It is crystal-poor relative to the tuff of Pajarito, with 15–25% crystals of quartz, plagioclase, and potassium feldspar (Fig. 4C). Zircon is a rare accessory mineral. The tuff is characteristically red or gray, flaggy in outcrop, but otherwise massive, and contains relict pumice and shards that in thin-section indicate partial to dense welding of the ignimbrite. Like the tuff of Pajarito, the tuff of Brick Mine apparently does not vary systematically in modal composition or mineral assemblage with stratigraphic position (Fig. 4C). Neither flow nor cooling unit breaks were observed in the tuff.

The source of the tuff of Brick Mine is not certain. The great thickness of the unit strongly suggests a local source for the tuff, either within or on the edges of the Cobre Ridge caldera, or close by. In the former case, eruption of the tuff of Brick Mine may have resulted in formation of a caldera nested within the boundaries of the Cobre Ridge caldera, thus contributing to the far greater subsidence of the northwestern part of the caldera than the southeastern part (Pajarito

Mountains). The primary argument against this hypothesis is the apparent lack of an outflow sheet, although no tuff of Pajarito outflow has yet been positively identified either, possibly owing to lower preservation potential of the extra-caldera facies. Boden (1986) has suggested that dominantly intra-caldera accumulation of much of the tuff of Mount Jefferson in southern Nevada resulted from a low eruption column and early collapse of the caldera. Likewise, a topographic obstruction such as a caldera wall in or just beyond the deflation zone of an eruption may cause a caldera to fill entirely before outflow begins (Valentine and Wohletz, 1990). In a similar scenario, eruption of the tuff of Brick Mine within the pre-existing Cobre Ridge caldera may have caused the tuff of Brick Mine to be emplaced primarily within the older caldera. Alternatively, the tuff of Brick Mine may have erupted outside of the Cobre Ridge caldera, and accidentally ponded in the Cobre Ridge caldera. In either case, it is clear that eruption of the tuff of Brick Mine occurred during development of the Cobre Ridge caldera complex.

#### *Local pyroclastic deposits*

Many tuff and ignimbrite units are recognized in the strata of Cobre Ridge only on the scale of a single fault block or mountain range. Some of these were probably originally local deposits, although lateral discontinuity of some may be due to poor preservation. These pyroclastic deposits include crystal-poor vitric tuff, lithic or pumice lapilli tuff, and tuff breccia, and are interpreted as being deposited by flow or fallout, based on structural characteristics such as crude bedding, and presence or absence of sorting. They overlie the tuff of Pajarito and are mineralogically similar to it, but differ from it in crystal percentage, pumice and lithic content, color, and weathering characteristics. Because these units are mineralogically similar to the tuff of Pajarito and occur in structural and stratigraphic coherence with the tuff, we infer that they are an integral part of the Cobre Ridge caldera explosive volcanism. The presence of clasts of the tuff of Pajarito within many of these units suggests that localized deposits may have been ponded between such topo-

graphic features as walls of the caldera or fault blocks within the caldera. Some of these deposits are described in more detail below in the context of their distribution.

### *Epiclastic units*

#### *Eolian and fluvial volcanoclastic sandstones*

A distinctive characteristic of the Early to Middle Jurassic arc of the southwest Cordillera lies in the unusual association of volcanic rocks with eolian quartzarenite or sandstones with a large component of eolian detritus (Hewett, 1956; Grose, 1959; Knight, 1970; Cooper, 1971; Drewes, 1971; Miller and Carr, 1978; Marzolf, 1980, 1982; Bilodeau and Keith, 1986; Tosdal et al., 1989; Riggs and Busby-Spera, 1990). Many of the sandstones in the strata of Cobre Ridge were probably deposited in eolian sand sheets and possibly on dunes, and they are rich in rounded grains probably derived from the cratonal backarc region in the area of the Colorado Plateau in northern Arizona and adjacent areas (Fig. 1). Eolian deposits in the strata of Cobre Ridge are characterized by wind-ripple laminae (Fig. 5), discontinu-

ous coarse-grained lenticles, and laterally continuous fine-grained laminae. Lesser fluvial deposits are characterized by low-angle cross-stratification, imbrication of pebbles and cobbles, and small stacked channels.

Components of eolian and fluvial sandstones in the strata of Cobre Ridge are in some samples recognizable as derived from local volcanic sources or as far-travelled. Far-travelled quartz grains were probably derived from age-equivalent eolian deposits in the area of the Colorado Plateau. These eolian deposits, in turn, derived originally from erosion of Precambrian plutonic and metamorphic sources in northern Montana and southern Canada (Stanley et al., 1965). Far-travelled grains in sandstone in the strata of Cobre Ridge are commonly well-sorted, fine-grained, ellipsoidal to rounded, and usually strained, and compose up to 20% of the rock. Locally derived volcanic quartz grains are variable in size and rounding, but characteristically are angular or partially bipyramidal in shape, and are ubiquitously unstrained. These grains make up as much as 20% of the sandstones.

Many quartz grains are not distinguishable as



Fig. 5. Eolian sandstone from Cerro Colorado Mountains (Fig. 2). Horizontal "pin-striping" is characteristic of inverse grading in wind-ripple laminations.

locally derived or far-travelled, due to recrystallization. Cobre Ridge volcanic rocks, which in their unconsolidated state probably provided the source of locally derived detritus, contain feldspar and quartz in a ratio of  $\sim 2:1$  (Fig. 4), and thus locally derived quartz grains are unlikely to be present in sandstones in excess of volcanic feldspars. We infer that the majority of quartz grains are far-travelled, and it is apparent that both fluvial and eolian depositional systems were flooded by far-travelled detritus.

Feldspar in the sandstones also includes far-travelled grains as well as locally derived volcanic components. Far-travelled grains are well-rounded microcline with distinctive chessboard twinning; these grains rarely constitute as much as 1% of the sample. Rounded microcline grains occur in Jurassic eolian quartzarenites on the Colorado Plateau, although orthoclase is more common (High and Picard, 1975; Otto and Picard, 1977; Picard, 1977; Uygur and Picard, 1980). Locally derived, volcanic potassium feldspars are commonly euhedral to slightly rounded, and always untwinned and replaced by a partially opaque mat; these make up 5–12% of the sandstones. Rounded plagioclases are very rare in eolian sandstones in the strata of Cobre Ridge; volcanic plagioclase in some cases constitutes up to 25% of the sandstones.

Volcanic lithic fragments in the sandstones are present rarely up to 7%, and average approximately 4%. Most fragments are fine- to medium-

grained silicic volcanics, and rarely fine- to medium-grained andesite. Rounded zircon or monazite grains are present in a few samples. Sandstones in the strata of Cobre Ridge are dominantly arkose and lithic arkose, with lesser subarkose (Folk, 1968; Fig. 6).

Poorly exposed small-scale sedimentary structures in sandstones in the strata of Cobre Ridge suggest deposition primarily on sand sheets. Bundles of laminae several cm thick and lenticular over a few cm to a few tens of cm are uniform, inversely graded, well-sorted, and medium-grained. Thin, uniform, inversely graded laminae are unique to eolian deposition (Kocurek and Dott, 1981) and these strata are interpreted as wind-ripple laminae. The lenses are commonly intercalated with small channelled fluvial deposits. Wind-ripple laminae preserved in sandstones of the strata of Cobre Ridge probably accumulated on sand sheets (K. Havholm, U. Texas, pers. commun., 1990), which commonly form on edges of dune fields when dune formation is inhibited by coarse grain size, vegetation, or frequent availability of water through periodic flooding or high water table (Kocurek and Nielson, 1986). The combination of medium grain size (up to 0.6 mm) and intercalated fluvial deposits in the sandstones in the strata of Cobre Ridge suggests that dominant available grain size and periodic flooding promoted the formation of sand sheets over dunes. Intercalated fluvial sandstones commonly contain intervals extremely rich in coarse (i.e.  $\leq 3$

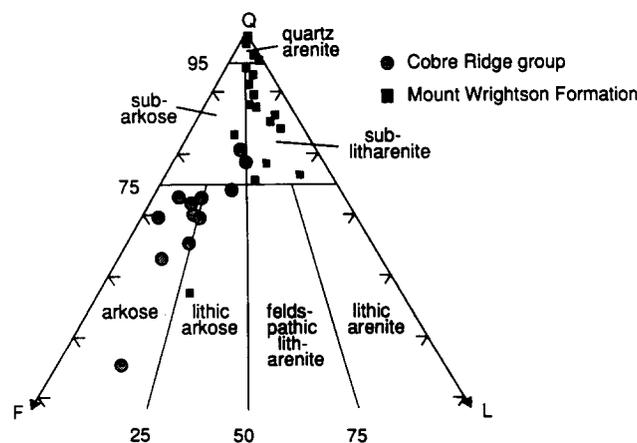


Fig. 6. Modal analyses of sandstone of the strata of Cobre Ridge, plotted on the ternary quartz–feldspar–lithic diagram of Folk, 1968. Analyses from Early Jurassic Mount Wrightson Formation (Fig. 1; Riggs and Busby-Spera, 1990) shown for comparison.

mm) angular grains of quartz, plagioclase, and K-feldspar, suggesting winnowing of unconsolidated pyroclastic debris.

Other sandstone horizons in the strata of Cobre Ridge are bedded in 1–2 cm-thick bundles of laminae that are laterally persistent over tens of meters. This parallel, continuous lamination, together with grain sizes generally finer than those seen in the sand sheet deposits, suggests grain-flow or grainfall deposition on a dune that was at least as wide as the strike length of the laminae (K. Havholm, pers. commun., 1990). Diagnostic structures characteristic of slip-face dunes, such as large-scale high-angle cross-sets and tapering basal portions of grainflow cross-strata (e.g. Hunter, 1977; Kocurek and Dott, 1981; Rubin and Hunter, 1987), are missing, probably due in large part to poor exposure, but the laterally continuous nature of fine lamination precludes fluvial deposition.

In comparison, eolian sandstones from the dominantly volcanic Early Jurassic Mount Wrightson Formation are notably poor in volcanic quartz, but are far richer in quartz than sandstones in the strata of Cobre Ridge, and in general contain less volcanic feldspar than Cobre Ridge sandstones (Fig. 6). The Mount Wrightson Formation is located approximately 50 km to the northeast of the Arivaca area, and evidently lay on the northeast or cratonward edge of the Cordilleran magmatic arc. The paucity of volcanic lithic detritus in the Mount Wrightson sandstones indicates that the volcanic arc was not being actively uplifted and eroded (Riggs and Busby-Spera, 1990). In the strata of Cobre Ridge, the high percentage of volcanic crystals compared to volcanic rock fragments indicates that abundant pyroclasts were recycled by winds into eolian and fluvial deposits, and that the contribution of consolidated volcanic rocks was negligible. In contrast to the regional implications of Mount Wrightson Formation sandstones, the composition of the Cobre Ridge sandstones apparently reflects influence of local volcanic processes.

#### *Debris-flow deposits*

Breccia and conglomerate horizons are common at north Chimney Ridge (Fig. 2), and their

facies characteristics are more fully described in that section. These deposits are predominantly matrix-supported mono- and poly lithologic volcanic-clast breccia and lesser conglomerate, and commonly contain up to 35% fine-grained, well-rounded quartz grains in the matrix. The clast population comprises tuffs that are clearly part of the strata of Cobre Ridge, tuffs that are permissively but not confidently correlated with the strata of Cobre Ridge, and fewer types such as andesite that are not present within the caldera complex. Breccias and conglomerates are interpreted dominantly as debris-flow deposits, although some hyperconcentrated flood flows may be present (see section on north Chimney Ridge, below). The mixture of clast types and matrix composition suggests that debris flows originated from domes and structural blocks within the caldera, as well as from caldera walls, and that far-travelled quartz grains were incorporated into these flows during their mobilization and transport.

#### *Intrusive rocks*

The tuff of Pajarito in the Las Guijas Mountains (Fig. 1) is intruded by granite porphyry that is mineralogically identical to the tuff of Pajarito, containing subequal parts of quartz, plagioclase, and K-feldspar, and by lesser alaskitic perthite granite (Riggs and Haxel, 1990). In contrast to the devitrified glassy matrix of the tuff of Pajarito, the granite porphyry has an allotriomorphic-granular groundmass. Riggs and Haxel interpreted the granite porphyry and granite as components of a Middle Jurassic epizonal plutonic complex, and we infer that the complex represents resurgent or post-eruptive magma within or close to the margins of the caldera.

#### *Volcanic breccia*

Volcanic breccia is confined primarily to the Cañoncito area (Fig. 2), described further below. Volcanic breccia is monolithologic with angular clasts that are commonly very closely packed (Fig. 7). Angular fragments similar to those in this



Fig. 7. Volcanic breccia from Cañoncito area (see Fig. 2 for location). Note dense close-packing of angular lava clasts; this exposure represents distal exposures of a lava dome.

deposit are also present in some localized ignimbrites.

#### **Distribution of lithofacies in the Cobre Ridge area**

We have recognized the lithofacies described above in three mountain ranges over approximately 1500 km<sup>2</sup> (Fig. 1). The strata of Cobre Ridge have a composite thickness of approximately 4.5 km (Figs. 3 and 8), including up to 3000 m of the tuff of Pajarito. The following discussion of the distribution of lithofacies is presented by mountain range or fault block (Figs. 1 and 2).

##### *Pajarito Mountains*

The tuff of Pajarito is named for exposures in the Pajarito Mountains north of the international border (Figs. 1 and 9), where it is as much as 3000 m thick (Riggs, 1987). This thickness estimate is only approximate, however, as the homogeneity of the tuff of Pajarito may well mask faults that repeat or extend sections, and the base of the tuff

is nowhere exposed where mapped north of the international border. The tuff of Pajarito is positionally overlain in rare small outcrops by Jurassic and/or Cretaceous sedimentary rocks.

Quartzarenite and xenolithic ignimbrite blocks, 10 to 100 m long, occur within the tuff of Pajarito in the eastern Pajarito Mountains (Drewes, 1981; Riggs, 1987; Fig. 9). One tabular sandstone body is 20 m thick and about 0.5 km long, and has a bedding parallel to compacted pumice foliation in the surrounding tuff. This sandstone may represent either a stratigraphic horizon or a slide block, although poor exposures preclude precise determination of the mode of emplacement.

##### *Las Borregas, Sonora*

Strata in the Las Borregas area 10 km south of the Pajarito Mountains (Fig. 1) were named the Las Avispas Formation by Segerstrom (1987). Material identical to the tuff of Pajarito was recognized at Las Borregas in reconnaissance traverses, but due to limitations of access, we do not know its thickness in that area.

The tuff of Pajarito in the Las Borregas area is underlain by several hundred meters of silicic ignimbrites and tuffs and eolian and fluvial sandstones. The ignimbrite and tuff units contain up to 35% quartz and feldspar, and may represent precursor eruptions of the tuff of Pajarito. Underlying these deposits is a section > 1 km thick of ignimbrite, lithic lapilli tuff, and lesser eolian sandstone. Ignimbrite units in this section are extremely crystal-poor, only rarely quartz-phyric, and do not appear to be part of the strata of Cobre Ridge. At the outcrop and in thin-section, the uppermost ignimbrite in this section is identical to ignimbrite in the Lower Jurassic Mount Wrightson Formation in the Santa Rita Mountains (Fig. 1; Riggs and Busby-Spera, 1990). Many other ignimbrites in the section are very similar to units in the Mount Wrightson Formation. We suggest that the Mount Wrightson Formation un-

derlies the strata of Cobre Ridge in the Las Borregas area.

*Cobre Ridge*

The most complete section through the strata of Cobre Ridge occurs in the Cobre Ridge area (Figs. 1, 2 and 3). A composite stratigraphic section through fault blocks and ranges in the Cobre Ridge area (Fig. 3) shows that a section up to 1.5 km thick overlies the tuff of Pajarito. The maximum thickness of tuff of Pajarito is approximately 1500 m, compared to 3000 m in the Pajarito Mountains.

The strata of Cobre Ridge in the Arivaca area overlie a sequence of ignimbrite, lithic lapilli tuff, and minor reworked tuff informally named the tuff of Black Peak. The tuff of Black Peak is exposed over > 100 km<sup>2</sup>, and is mineralogically

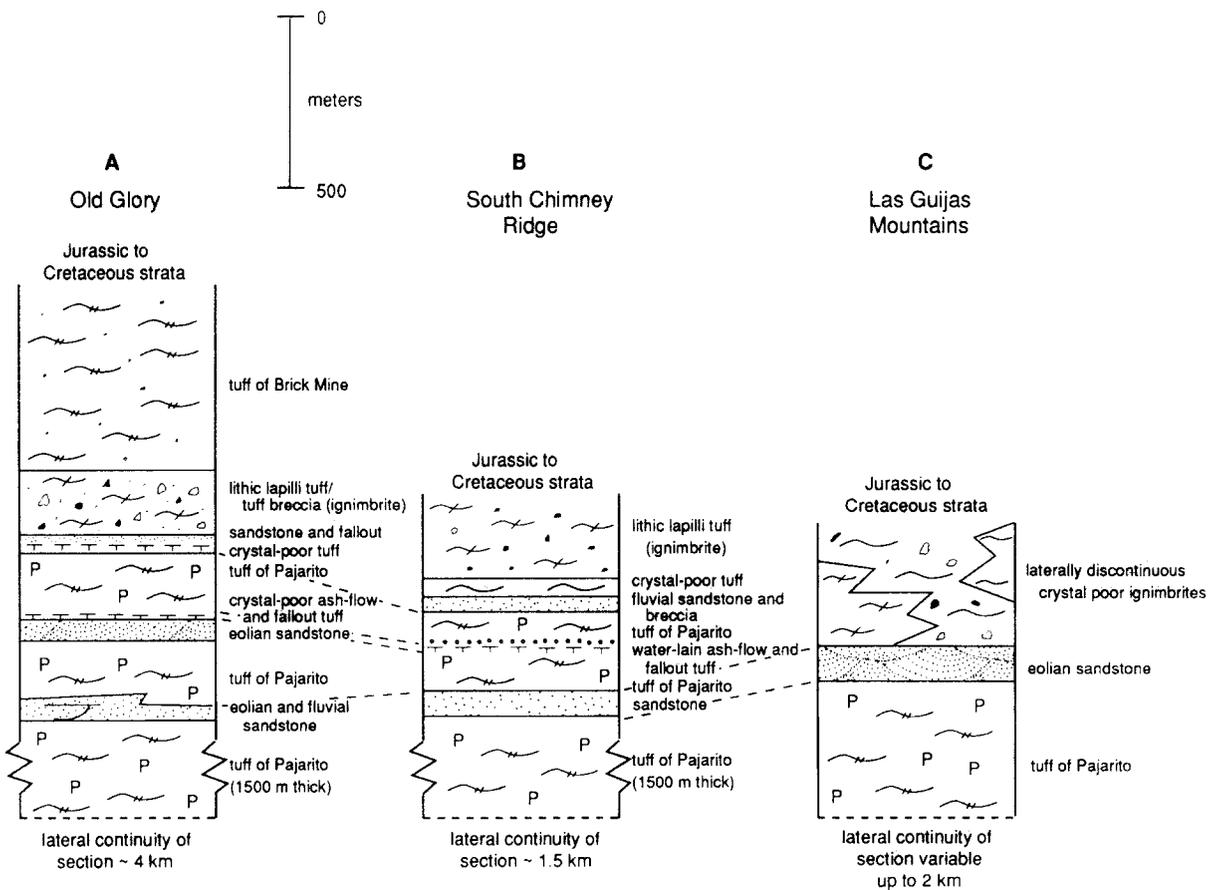


Fig. 8. Comparative stratigraphic columns of fault blocks at Cobre Ridge (see Figs. 2 and 3 for locations of sections). Datum is base of Pajarito tuff. In A and B, the tuff of Pajarito is faulted at its base; in C, the tuff of Pajarito is intruded at its base by granite porphyry.

similar to the tuff of Pajarito, containing subequal parts of quartz, plagioclase, and potassium feldspar up to ~30%. Opacitized biotite and opacitized hornblende are common mafic minerals, and zircon is a trace accessory mineral. Although not studied in detail, the tuff of Black Peak is characterized by a blue-green to grey color, small wispy pumice lapilli, and the nearly ubiquitous presence of ignimbrite and aphanitic felsic volcanic lapilli.

The following discussion is keyed into both Fig. 3 and comparative stratigraphic columns of individual areas (Fig. 8).

*Old Glory fault block*

The stratigraphic section preserved in the Old Glory fault block is the most complete in the Cobre Ridge area and is approximately 2000 m

thick (Figs. 3, 8A and 10). Strata in the Old Glory fault block face and dip to the southwest in a generally steeply dipping homocline. The base of the section is everywhere faulted, and the top is unconformably overlain by Jurassic and/or Cretaceous conglomerate. The cumulative thickness of the three flows of the tuff of Pajarito in the Old Glory fault block is ~1500 m (Fig. 10); in the California Gulch area to the east of the Old Glory fault block (Fig. 10) the one remnant flow unit of tuff of Pajarito is 600 m thick. The three horizons of tuff of Pajarito are megascopically identical, and modally very similar (OG-1 and OG-2, OG-3, and 012189-2, Fig. 4A).

The late stages of eruption of the tuff of Pajarito were marked by two hiatuses, during which time minor fluvial activity reworked unconsolidated tuff of Pajarito, and eolian sand accu-

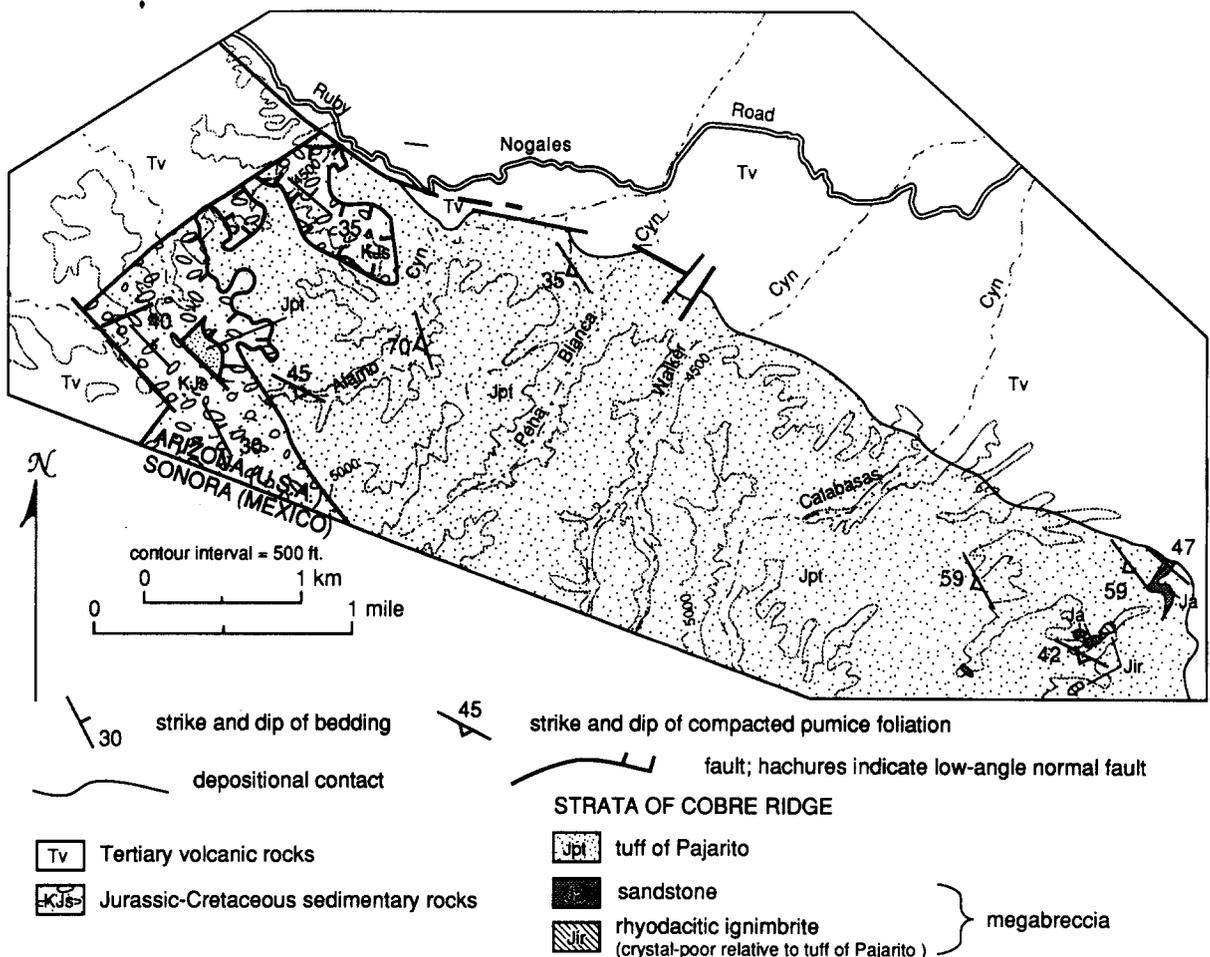


Fig. 9. Generalized geologic map of the Pajarito Mountains after Riggs (1987). See Fig. 1 for location.

mulated in horizons as much as 50 m thick (Fig. 8A). Abrupt lateral discontinuity of the lower of these sandstones and local changes in thickness (Fig. 10) may be indicative of irregularities on the surface of the tuff of Pajarito or of deposition on fault blocks caused by piecemeal subsidence.

The amount of time implied by deposition of 50 m of eolian sand is not clear. Accumulation of eolian sand is controlled by the sediment saturation level of wind as it enters the area of deposition, and the deceleration in wind velocity across the depocenter (Havholm and Kocurek, 1991).

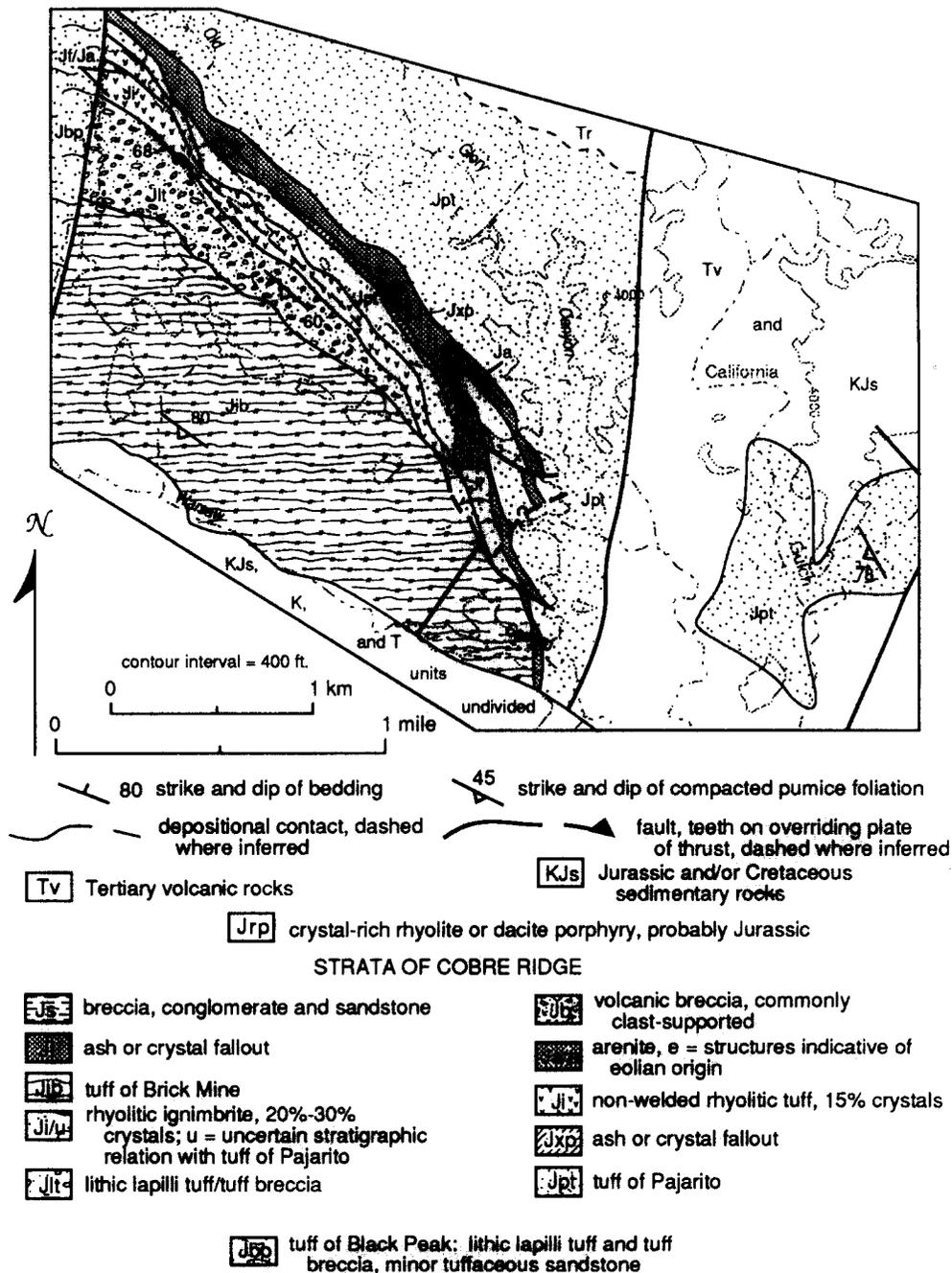


Fig. 10. Geologic map of the Old Glory area, Cobre Ridge. See Fig. 1 for location.

Within those parameters, certain calculations can be made on the potential rate of deposition, although these can only be considered a best estimate. Fryberger et al. (1984) and Illenberger and Rust (1988) documented depositional rates in modern dune fields of 0.15 cm/yr and 0.018 cm/yr. These data correspond to accumulation times of  $\sim 33,000$  yr to  $\sim 280,000$  yr for 50 m-thick eolian deposits at Cobre Ridge; extreme conditions of sediment saturation and/or wind velocity deceleration could yield much higher or lower numbers. Because the ignimbrites separated by eolian deposits in the Old Glory area are identical in outcrop and similar in modal composition, they are assumed to be part of the same eruptive process, and we infer an accumulation time nearer to the lower end of the range indicated.

Lithic lapilli tuff/tuff breccia that overlies the tuff of Pajarito (Fig. 8A; Jlt, Fig. 10) in the Old Glory fault block contains cobbles and blocks of the tuff of Pajarito. These cobbles and blocks locally constitute as much as 75% of the clasts in this tuff and are in some cases rounded (Fig. 11). The matrix composition of the tuff is rhyolitic and similar to the tuff of Pajarito, but with smaller

and fewer crystals. Pumice fragments and rare shards suggest that the tuff was deposited as a pyroclastic flow. This lithic lapilli tuff/tuff breccia unit occurs only in the Old Glory fault block.

The Old Glory section is capped by 700 m of the tuff of Brick Mine (Jib, Fig. 10), which mixed locally with the lithic lapilli tuff/tuff breccia that underlies it. Angular, brecciated clasts of the tuff of Brick Mine, a few to several cm in diameter, occur in the underlying lithic tuff/tuff breccia, demonstrating a close age relationship between the two flows. The tuff of Brick Mine is as much as 750 m thick in the fault block immediately to the north of the Old Glory fault block (Fig. 2).

#### *South Chimney Ridge fault block*

The Chimney Ridge fault block is divided into north and south blocks (Fig. 12) due to the very dissimilar structure and stratigraphy of each block. The south Chimney Ridge fault block is stratigraphically similar to caldera-fill sequences described thus far; the north Chimney Ridge fault block contains a disparate facies association and is described in a later section.

The south Chimney Ridge fault block (Figs. 2, 3, 8B and 12) is characterized by laterally contin-

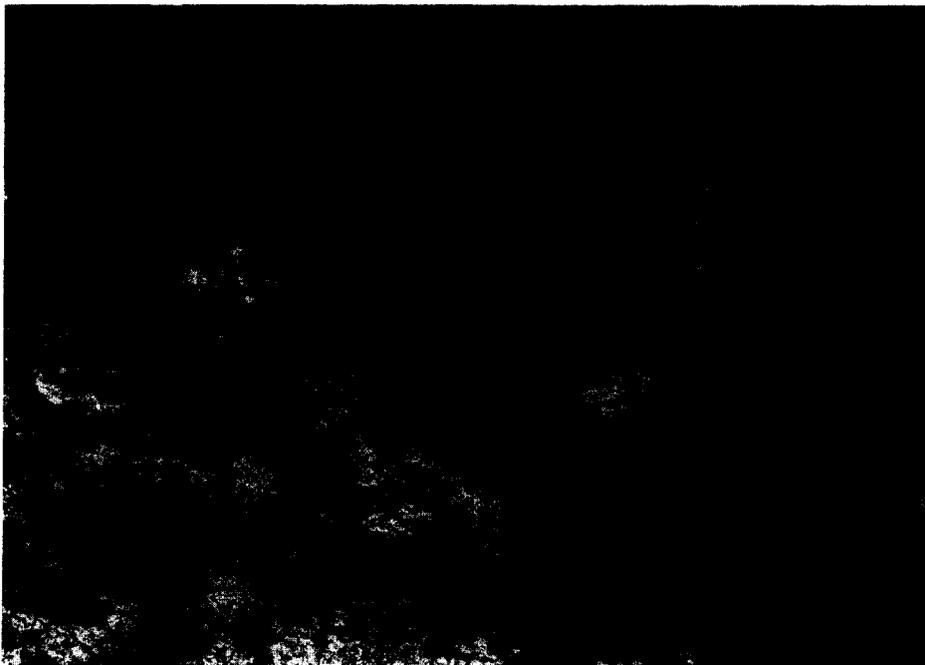


Fig. 11. Photograph of lithic lapilli tuff/tuff breccia in the Old Glory area. Dominant clast composition is the tuff of Pajarito.

uous strata that dip steeply and face to the southwest (Fig. 12). The section is overlain by Jurassic to Cretaceous sedimentary strata and is intruded or faulted against Tertiary strata at its base. Approximately 1500 m of the tuff of Pajarito is overlain by a section that differs from the Old Glory section only in that the sandstone horizon at the top of the tuff of Pajarito is fluvial, rather than largely eolian in origin, with abundant channels and low-angle cross-stratification. Finely planar laminated, well-sorted, very fine-grained tuffs a few cm thick also occur within the upper horizon of tuff of Pajarito; these tuffs probably represent subaqueous fallout deposits. Units above the uppermost tuff of Pajarito do not appear to correlate with units in the Old Glory section (Fig. 8A); although the upper sandstone is overlain by lithic lapilli tuff, this tuff is in general much poorer in crystals, is far richer in pumice, and has a different clast population than the lithic lapilli tuff at Old Glory (i.e. clasts of the tuff of Pajarito are rare, and fine-grained crystal-poor volcanic clasts dominate).

The rare presence of very thinly laminated tuffs, both in the south Chimney Ridge fault block and in a few other exposures in the caldera complex, indicates local deposition in standing water, but there is no evidence that an areally extensive caldera lake formed. An arid or hyper-arid environment documented for southwestern North America in Middle Jurassic time (Kocurek and Dott, 1983) would tend to discourage the accumulation of standing water. Fluvial sandstone, debris-flow deposits, and rare reworked ignimbrites demonstrate movement, if not accumulation, of water.

#### *Cañoncito fault block*

The Cañoncito fault block contains a megabreccia block encased in tuff of Pajarito. The megablock is approximately 250 m thick and ~ 500 m along strike, and comprises crystal-rich ignimbrite (Ji, Fig. 13) overlain by fluvial sandstone (Ja, Fig. 13) and breccia (Jb, Fig. 13). These strata dip shallowly to the southwest. Compacted pumice foliation within the tuff of Pajarito in the

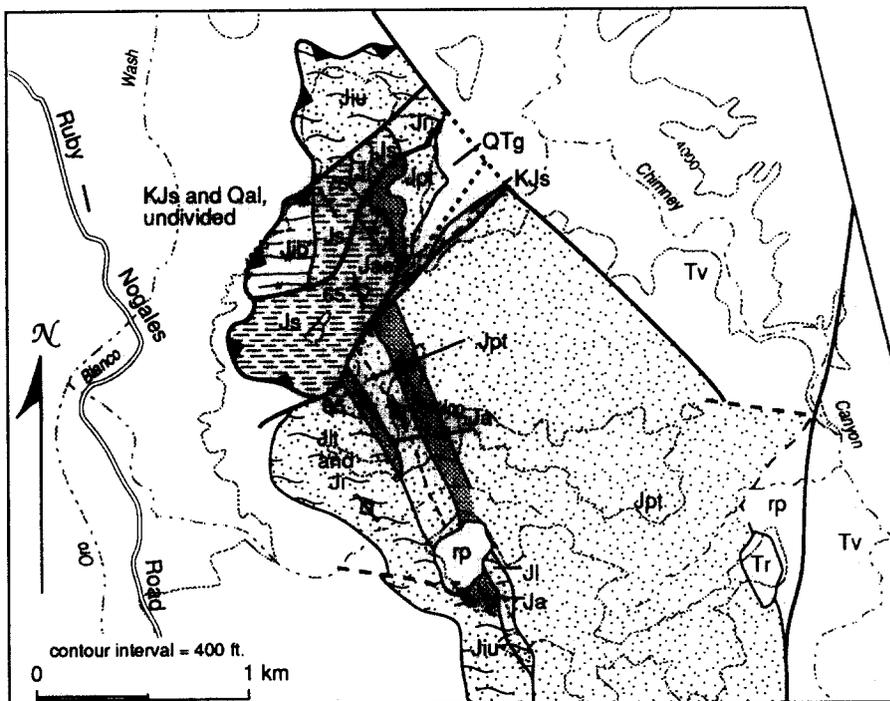


Fig. 12. Geologic map of north and south Chimney Ridge fault blocks. Strata in the south Chimney Ridge fault block dip to the southwest, whereas strata in the north Chimney Ridge fault block dip to the northeast. Explanation is as for Fig. 10; for location of these fault blocks see Fig. 2.

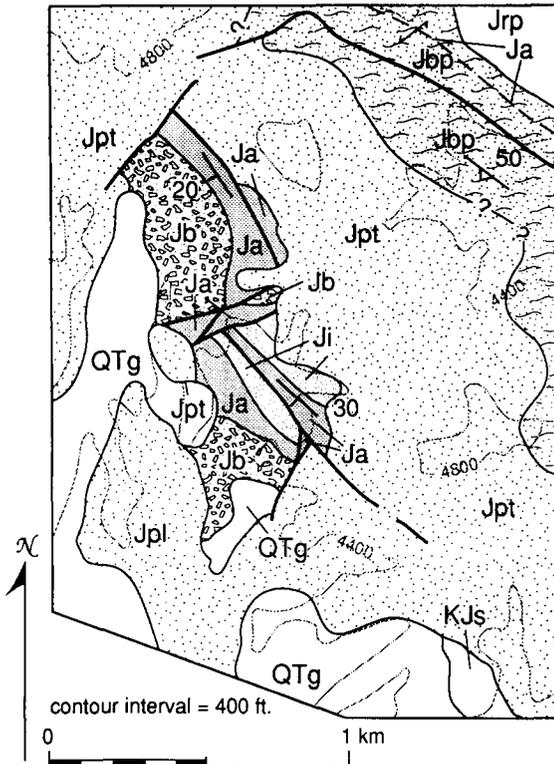


Fig. 13. Geologic map of the Cañoncito area. Explanation is as for Fig. 10; for location of this fault block see Fig. 2.

Cañoncito fault block is not apparent, but the tuff is underlain by lithic lapilli tuff of Black Peak with compacted pumice foliation that dips more steeply than strata in the megablock (Fig. 13).

The upper ~150 m of the megablock consists of massive breccia (Jb, Fig. 13) that comprises tightly packed clasts of crystal-rich rhyolite. Although poly lithologic and matrix-supported in its basal few meters, the breccia is predominantly clast-supported and monolithologic, with very poorly sorted angular to subrounded, randomly oriented clasts commonly 5–10 cm in diameter (Fig. 7). Thin ( $\leq 10$  m) tongues of lava occur throughout the breccia. Matrix composes as much as about 10% of the breccia and is made up of crystals and finely comminuted fragments of the rhyolite.

#### *Las Guijas Mountains*

The lower part of the Las Guijas section (Figs. 1 and 8D) correlates with the lower part of the Old Glory section; the tuff of Pajarito is approxi-

mately 350 m thick, and sandstone in the Las Guijas section is eolian in origin. The tuff of Pajarito and overlying sandstone are continuous along strike up to ~2 km, but apparently only one unit of tuff of Pajarito is preserved, and overlying ignimbrites in the Las Guijas Mountains are laterally discontinuous. The base of the tuff of Pajarito is intruded by granite porphyry and faulted, and the top is overlain by Jurassic and/or Cretaceous sedimentary strata.

#### *North Chimney Ridge fault block*

The north Chimney Ridge fault block contains a great preponderance of sedimentary strata and very few pyroclastic flow deposits (Figs. 12 and 14). Where the base is exposed, this section overlies the tuff of Brick Mine. The top of the section is faulted (Fig. 14B) or a large block of the tuff of Pajarito (Fig. 14A). Strata in the north Chimney Ridge fault block form the youngest units in the strata of Cobre Ridge. The section is >450 m thick, and consists of primarily breccia, conglomerate, and sandstone debris-flow deposits with very little fine-grained component, and no lateral or vertical organization (Fig. 14). Many of the conglomerates and breccias are monolithologic, or nearly so, but changes in clast composition between debris-flow deposits are neither systematic nor gradational. With the exception of the basal tuff of Brick Mine and overlying eolian sandstone (Fig. 14B), units are rarely laterally continuous over more than a few meters. Channels, cross-lamination, and other sedimentary structures are rare, although the presence of channels is suggested by the lenticularity of breccias and conglomerates. Grain and clast size in the sandstones, breccias, and conglomerates varies randomly, but the grains are always coarser than fine sand.

Non-eolian deposits within the north Chimney Ridge section are broadly divisible into five lithofacies. (1) Matrix-supported massive breccia, non-graded but generally characterized by a basal layer of outsized clasts. (2) Clast-supported massive, monolithologic conglomerate or scarce breccia, rarely reversely graded at the base. Clasts are nearly always tuff of Pajarito, and the matrix is composed of sand- to granule-sized fragments of

tuff of Pajarito and lesser sand-sized material comprising rounded quartz grains or volcanic fragments. (3) Clast-supported polyolithic,

massive breccia. (4) Fine- to medium-grained massive sandstone, commonly containing volcanic granules and pebbles, with very rare planar lami-

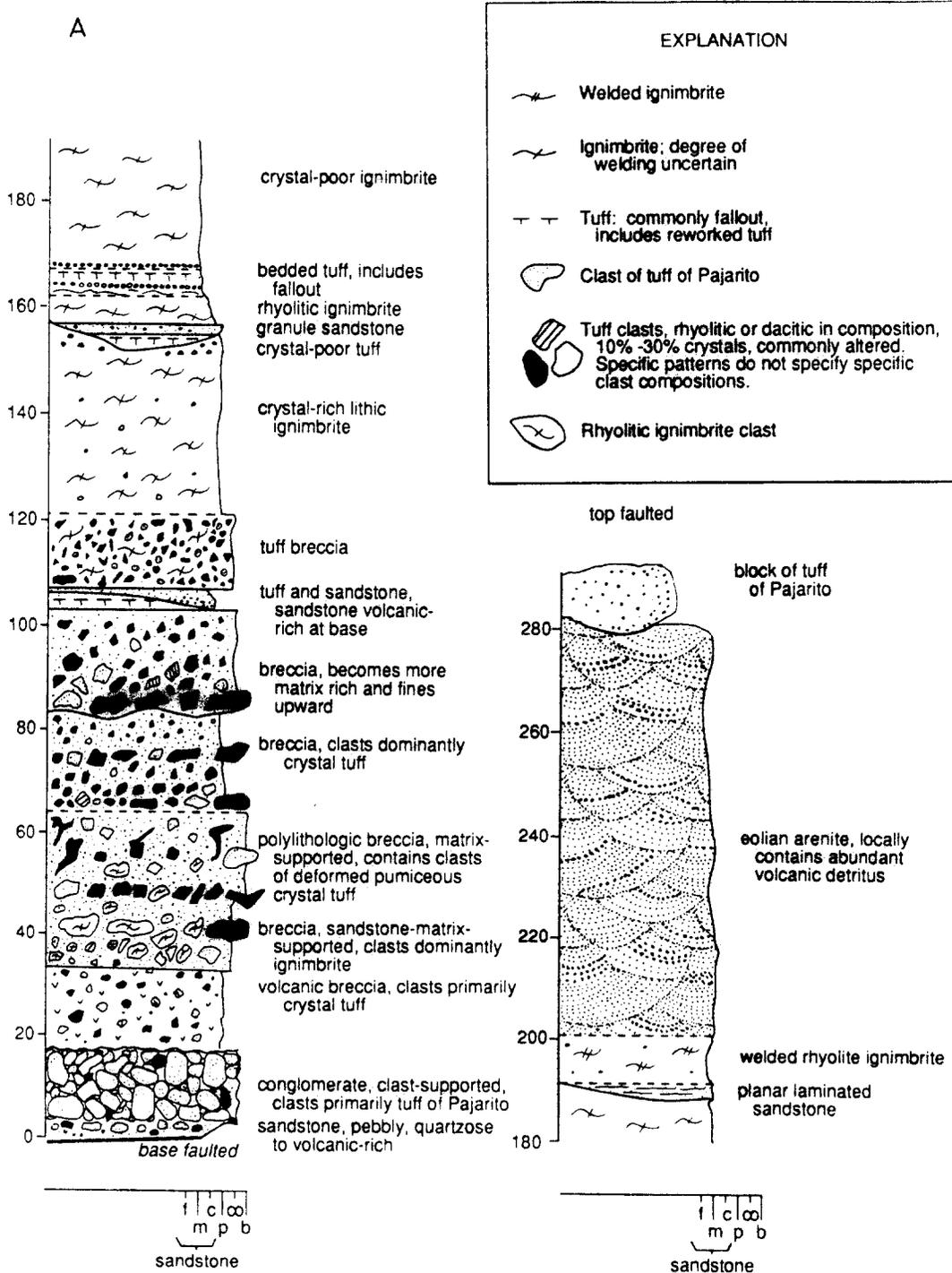


Fig. 14. Stratigraphic sections of the debris apron at north Chimney Ridge. Stratigraphic sections were measured in the southern and central sub-blocks of the north Chimney Ridge fault block (see Fig. 12).

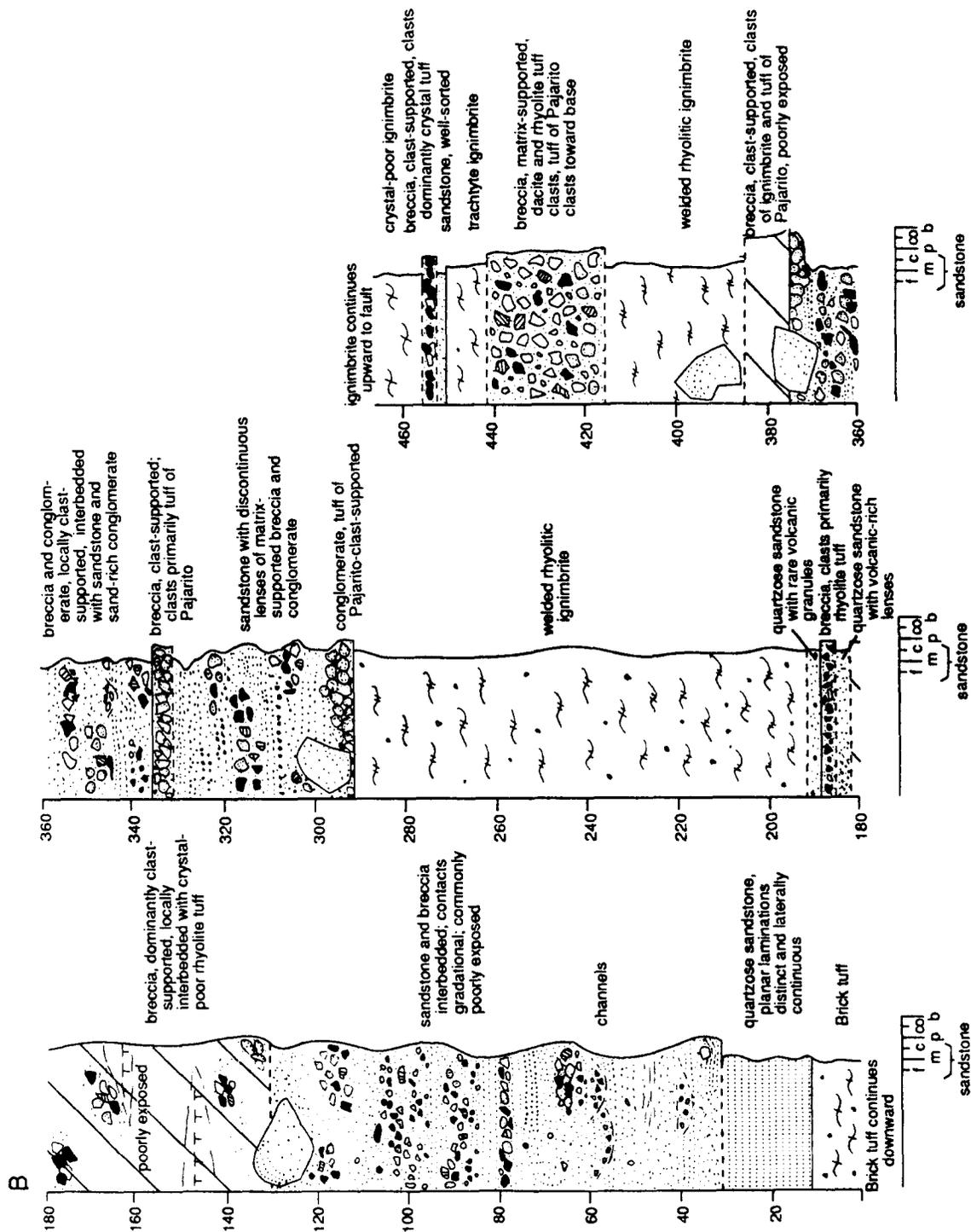


Fig. 14 (continued).

nation. (5) Fine- to medium-grained laminated sandstone, locally channelled, and interbedded with discontinuous lenses of breccia.

Debris flows, which deposited the breccias of Facies 1 and 3(?) and structureless sandstone (Facies 4), were the primary mechanism of transport in the north Chimney Ridge section. Fluvial flow (Group 5) was of lesser importance, and may locally have reworked tops of debris-flow deposits. Massive clast-supported deposits of Facies 2 and possibly 3 may represent hyperconcentrated flood flow deposits, resulting from high-sediment-load floods that occur where debris flows are diluted by water (Smith, 1986).

### **Interpretation of lithofacies of the Cobre Ridge Group**

We suggest that a caldera facies model (e.g. Fisher and Schmincke, 1984; Cas and Wright, 1987) best provides a cohesive basis for interpreting the distribution and importance of lithofacies described above. Although individual fault blocks are not uniquely indicative of caldera-related deposition, the great thickness of tuff of Pajarito ( $\geq 600\text{--}3000$  m) throughout the area strongly suggests accumulation within a caldera, and other lithofacies within the fault blocks provide information on the syn- and post-eruptive history of the caldera.

#### *Initial collapse of the Cobre Ridge caldera and erosion of the caldera walls*

The homogeneity of  $\sim 3000$  m of the tuff of Pajarito in the Pajarito Mountains suggests that the initial eruption of the tuff produced a single, locally extremely thick, flow unit. Although the caldera floor is not exposed in the Pajarito Mountains, stratigraphic relations indicate that the tuff of Black Peak underlay most of the Cobre Ridge area at the time of initial collapse. The apparent lack of precursor fallout in areas where the tuff of Pajarito overlies the tuff of Black Peak suggests that conditions of vent diameter and gas content required to maintain a Plinian column

were not sustained (Sparks et al., 1978; Wilson et al., 1980).

The variation in the thickness of the tuff of Pajarito, from  $> 600\text{--}3000$  m over the width of the Cobre Ridge caldera, suggesting either trap-door collapse (cf. Trans-Pecos, Texas, USA, Henry and Price, 1984; Valles caldera, New Mexico, Nielson and Hulen 1984; Heiken et al., 1986) or piecemeal collapse (cf. English Lake District, Branney and Soper, 1988; Branney et al., 1991; Questa caldera, New Mexico, USA, J.M. Meyer, Univ. of California, pers. commun., 1990) of the caldera floor. Lipman (1984) noted that most trapdoor calderas are associated with eruptive volumes of  $25\text{--}100$  km<sup>3</sup>, far less than the estimated volume of the tuff of Pajarito. The apparently irregular nature of thickness changes in the tuff of Pajarito may be due in part to exposure, but a wedge-like variation in thickness is not apparent, suggesting that subsidence was not hinged. Additionally, the minimum thickness of the tuff of Pajarito is 350 m, unlike documented trap-door calderas in which intra-caldera deposits near the hinge are very thin. Intra-caldera faults clearly related to collapse, however, have not been found.

Caldera collapse was apparently accompanied by rapid erosion and sloughing of caldera walls. Blocks of sandstone and ignimbrite in the eastern Pajarito Mountains are probably megabreccia blocks within the tuff of Pajarito (Drewes, 1980, interpreted these blocks as exotic within a caldera-related hypabyssal intrusion). In the Cobre Ridge area, the stratigraphically lower parts of the tuff contain numerous beds of sandstone, ignimbrite, and/or reworked pyroclastic deposits commonly less than 5 m long along strike and less than 5 m thick; these thin horizons are shown schematically in Fig. 2 as Jpte. Although these horizons may represent deposits between flows of the tuff of Pajarito, we interpret them as meso- and megabreccia blocks due to their abrupt lateral discontinuity. There is little or no stratigraphic continuity between proximal megabreccia blocks, similar to the setting described by Lipman (1976).

The megabreccia block within the Cañoncito fault block (Figs. 2 and 13) is the largest of the

megabreccia blocks, and provides information on pre-tuff of Pajarito volcanic activity. The clast-supported breccia in the Cañoncito block is inferred to be part of a lava dome talus cone. Tight packing of clasts and very low matrix content, together with rare occurrence of massive lava suggest that this talus was shed from a growing lava dome, rather than representing a series of flow-top breccias. The thinness of the rare lava flows suggests deposition of the breccia near the edge of a lava dome rather than atop one. This lava dome deposit could represent precursory volcanism to the tuff of Pajarito, although its stratigraphic relation to the tuff of Pajarito is uncertain. Faults within the megablock that do not extend into the surrounding tuff of Pajarito may have formed by internal fracturing as the megablock fell into the caldera.

Megabreccia blocks of similar size to the Cañoncito megablock have been documented in the mid-Tertiary Uncompahgre and Lake City calderas in southwestern Colorado, in the Cretaceous Tucson Mountains in Arizona (Lipman and Fridrich, 1990), and in the early Mesozoic Vandever Mountain caldera in the Sierra Nevada of California (Busby-Spera, 1984b). Formation of such megabreccias has been attributed to oversteepening and failure of caldera walls during collapse (Lipman, 1976). We suggest that megabreccia blocks such as those in the eastern Pajarito Mountains and the Cañoncito block were formed in a similar way. Megabreccias described by Lipman (1976) and Busby-Spera (1984b) commonly grade to mesobreccia from caldera margin toward the interior of the caldera. Blocks of sandstone and tuff in the eastern Pajarito Mountains become progressively smaller (~ 500 m along strike to ~ 10 m along strike) to the west over approximately 3 km, suggesting that the topographic wall lay towards the east. In the Cobre Ridge area, post-Jurassic faulting has disrupted the original geometry of the caldera, but blocks of sandstone and pyroclastic deposits < 5 m in thickness within the tuff of Pajarito may be remnant megabreccia blocks that slid to more interior parts of the caldera.

The size of the Cobre Ridge caldera remains uncertain. Caldera margins probably lay close to

areas of megabreccia in the eastern Pajarito Mountains and the Cañoncito area, giving an approximate length of the caldera as ~ 50 km. We infer an approximate width of ~ 25 km, based on present-day exposures of strata of Cobre Ridge. Caldera-bounding structures, however, are nowhere exposed.

#### *Secondary collapse and post-collapse volcanism*

Stratigraphic relations preserved in the Old Glory fault block indicate that total subsidence in the northwestern part of the caldera was greater than that in the Pajarito Mountains. Accumulation and preservation of 1.5 km of post-tuff of Pajarito strata in this area indicate that although the Old Glory area subsided less during eruption of the tuff of Pajarito, subsequent eruptions were concentrated in that area. The presence of abundant clasts of tuff of Pajarito within the lithic-lapilli tuff/tuff breccia suggests that fault scarps exposed the tuff of Pajarito and that eroded blocks were easily carried in the tuff. These fault scarps may have formed during secondary collapse associated with the smaller eruptions of tuff of Pajarito. Alternatively, many of these Pajarito tuff clasts may have been accidental clasts derived from the vent area or conduit walls.

As discussed earlier, the thickness of the tuff of Brick Mine ( $\geq 600$  m) strongly suggests a caldera-forming eruption, and its association with the strata of Cobre Ridge suggests that eruption of this tuff occurred within or very near to the Cobre Ridge caldera. Eruption of the tuff of Brick Mine may have enlarged much of the northwestern caldera area, or it may have caused subsidence of a smaller caldera nested within the Cobre Ridge caldera.

#### *Outflow facies*

If the probable megabreccia at Cañoncito marks proximity to a caldera margin, it appears likely that areas to the north and northwest of the Cañoncito block that contain strata of Cobre Ridge are remnant areas of outflow. The 350 m thickness of tuff of Pajarito in the Las Guijas

Mountains is much thinner than most exposures of the tuff. Although the base of the tuff is faulted or intruded, and thus its original thickness indeterminate, it is possible that exposures in the Las Guijas Mountains represent originally thinner outflow facies. Large parts of the Las Guijas Mountains are underlain by granite porphyry that was probably part of the batholith or pluton that supplied magma to the Cobre Ridge caldera. By analogy with younger caldera complexes (Long Valley caldera, Bailey et al., 1976; Yellowstone caldera complex, Christiansen, 1984) it is quite possible that related magmas spread beyond the margins of the caldera. Because of the thickness of the tuff of Pajarito in most areas (> 1000 m), it is not unreasonable to infer an extra-caldera thickness of 350 m. In comparison, outflow of the 1400 m-thick Fish Canyon Tuff in the San Juan Mountains of Colorado is locally up to 250 m thick (Steven and Lipman, 1976). Lateral discontinuity of units in the Las Guijas may be indicative of irregular topography either outside or near the margins of the caldera.

#### *Waning volcanism*

We interpret the strata at the north Chimney Ridge section as a debris apron, an unorganized accumulation of debris-flow and lesser fluvial deposits derived from a line source (Cook, 1982; Nelson et al., 1990), that formed as volcanism associated with the Cobre Ridge caldera waned. The large clast size and overall coarse-grained nature of the sedimentary deposits suggest substantial relief, and the overall poly lithologic clast composition of the deposits indicates multiple sources. Hyperconcentrated flood flow deposits containing rounded clasts of the tuff of Pajarito may have been derived from areas outside the caldera where outflow of the tuff of Pajarito provided the primary source. Many other clast types in debris-flow deposits are not definitively correlated with other ignimbrites in the post-collapse strata of Cobre Ridge, and may have been derived from ignimbrites exposed in caldera walls. Clasts very similar in appearance to the dome

breccia at Cañoncito may come from precursor lava domes. Alternatively, if piecemeal faulting was occurring within the caldera during continuing collapse, some of the debris flows, both mono- and poly lithologic, may have originated on topographically higher fault blocks within the caldera. Occasional outsize blocks of the tuff of Pajarito indicate that steep topographic walls lay proximal to the debris apron; these walls may have been either fault scarps or caldera topographic margins.

The fault-bounded nature of the debris apron prevents complete determination of the original size or shape of the apron, thus hindering our understanding of the processes that acted on it. Subaerial volcanic aprons described by most workers (e.g. Walton, 1979, 1986; Waresback and Turbeville, 1990) commonly contain a fine-grained component rare in the Cobre Ridge debris apron, ascribed to the constant supply of sand-sized material provided by explosive volcanism. These workers ascribe an increase in supply of coarse-grained material to cessation of explosive volcanism and ensuing erosion of consolidated volcanic deposits. By analogy, the Cobre Ridge debris apron would appear to represent sedimentation after explosive volcanism had largely ceased. The Cobre Ridge debris apron contains an interval approximately 100 m thick of dominant sandstone (Fig. 14B, ~ 30 to ~ 130 m) that reflects availability of unconsolidated detritus in one of the source areas, and some ongoing volcanic activity is clearly indicated by the presence of ignimbrites in the upper part of the section (Figs. 14A and 14B). It is unclear that these ignimbrites, emplaced on the apron rather than necessarily in a source area, affected depositional processes on the apron. Other evidence of ongoing explosive volcanism contemporaneous with formation of the debris apron is apparent in one debris-flow deposit (Fig. 14A, ~ 60 m), in which crystal-poor ignimbrite clasts were deformed plastically, apparently while still hot. Apron building may have ended with emplacement of pyroclastic flows and deposition of thick eolian strata (Fig. 14A, ~ 105 m to 280 m), perhaps contemporaneous with the overall erosion of the source areas. In general, however, it is apparent that explosive volcanism

was waning during the time of debris apron formation.

### Preservation of ancient sequences

Jurassic magmatic arc sequences in southern Arizona are representative of two distinct modes of preservation of ancient volcanic sequences. The Early Jurassic Mount Wrightson Formation, located 50 km northeast of the Cobre Ridge caldera (Fig. 1), represents a multiple vent volcanic complex deposited in a basin that evidently subsided in response to regional extensional or transtensional strain (Riggs and Busby-Spera, 1990). Multiple episodes of burial of vent regions by volcanic rocks derived both from within and outside of the complex and by eolian sandstone derived from the area of the present-day Colorado Plateau, indicate that the depocenter was continually subsiding. The paucity of mass flow deposits argues against either nearby basin margins, or high-standing volcanic edifices. Our interpretation of our U–Pb zircon data (Riggs et al., 1991) as well as that of Asmerom et al. (1990), together with the facies analysis described above, suggests that the Mount Wrightson Formation was deposited within ~15 m.y., and that subsidence was ongoing during most of that time. Although nearby caldera formation is evinced in thick, densely welded ignimbrites within the Mount Wrightson Formation, these calderas lay outside of the depocenter, and there is no evidence for volcanic-controlled subsidence within the Mount Wrightson basin. We thus infer that basin subsidence was tectonically controlled by intra-arc extension (Riggs and Busby-Spera, 1990; Busby-Spera et al., 1990).

In contrast, accumulation and preservation of volcanic and sedimentary units in the strata of Cobre Ridge were controlled by volcanic subsidence and deposition within a caldera. Segmentation of the caldera floor during eruption allowed deeper cumulative subsidence of the northwest part of the caldera, which then acted as a depocenter for accumulation of syn- and post-collapse strata. There is no evidence for tectonic influence on the formation and preservation of the depocenter within the Arivaca area, although

there is evidence for tectonically controlled subsidence during this time interval in other parts of the magmatic arc in Arizona and California (Busby-Spera, 1988; Busby-Spera et al., 1990).

### Conclusions

The Cobre Ridge caldera complex and possible outflow facies are presently exposed in fault blocks and mountain ranges over 1500 km<sup>2</sup>. Through recognition of the caldera facies described above, and identification of their distribution, we have established the following geologic history of the Cobre Ridge caldera (Fig. 15).

(1) Initiation of caldera collapse was caused by eruption of the tuff of Pajarito. The primary caldera-forming unit, the tuff of Pajarito, is estimated to be  $\geq 1000$  km<sup>3</sup>, and possibly as much as 4000 km<sup>3</sup>, comparable in size to the largest-volume ignimbrites in the geologic record (Lipman, 1984). Structural failure of the caldera walls caused formation of megabreccia, with lithologically diverse clasts up to 0.5 km in strike length. We infer that the caldera subsided in two major structural blocks. The Pajarito Mountains in the southeast part of the caldera subsided during eruption of the tuff of Pajarito to approximately 3 km depth (Fig. 15A). The northwest part of the caldera, in the Cobre Ridge area, collapsed less during initial eruption, but subsided an additional ~1.5 km after eruption and deposition of the main body of the tuff of Pajarito. This additional subsidence may have occurred during the second and/or third eruptions of the tuff of Pajarito seen at Old Glory and north Chimney Ridge (Figs. 8A and 8B), and during eruption of the tuff of Brick Mine.

(2) We interpret strata that accumulated in the northwest half of the caldera as moat fill, including: (a) areally restricted ignimbrites such as the lithic lapilli tuff/tuff breccia at Old Glory, that were probably ponded between fault scarps and/or caldera walls to thicknesses of several tens of meters, and that in places transported cobbles and blocks of tuff of Pajarito; (b) a more continuous > 600 m-thick ignimbrite, the tuff of Brick Mine, whose eruption probably caused further collapse of the caldera or enlargement of the

caldera margins, or which may have been accidentally ponded within the caldera; (c) a localized debris apron deposit up to 450 m thick that

represents material reworked from intra-caldera blocks and/or possibly caldera walls; (d) eolian and fluvial sandstones and minor water-lain tuffs

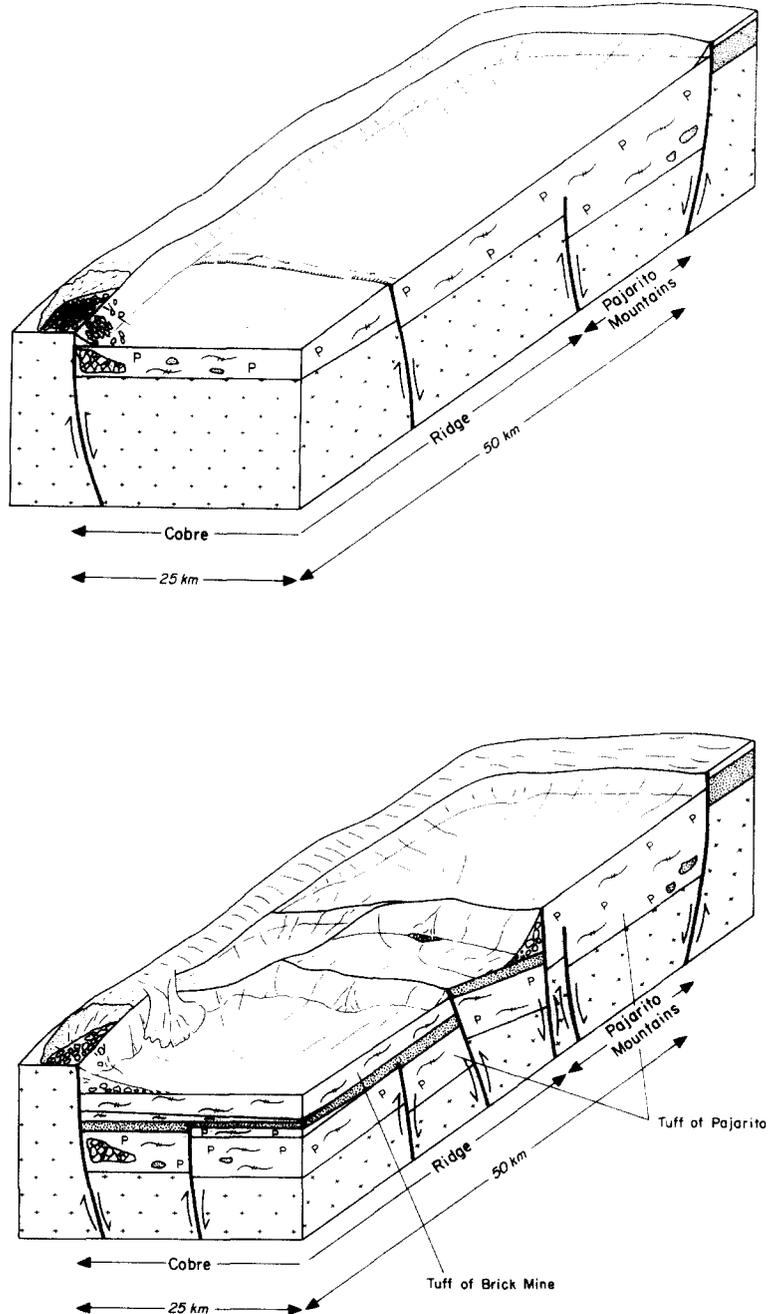


Fig. 15. Schematic evolution of the Cobre Ridge caldera. A. Initial caldera-forming eruption of the tuff of Pajarito with irregular subsidence of the caldera floor due to block faulting and/or trapdoor-style subsidence. B. Additional subsidence caused by the continued eruption of the tuff of Pajarito as well as later pyroclastic units. Local pyroclastic deposits trapped between fault scarps or banked against caldera walls. Debris apron shown schematically derived along caldera margin.

(Fig. 15B). The lack of lake deposits commonly found in calderas is attributed to a hyperarid climate that inhibited standing water.

Caldera collapse over a probable minimum area of 1500 km<sup>2</sup> provided the necessary depocenter for the accumulation and preservation of the strata of Cobre Ridge, in contrast to other, older parts of the Mesozoic magmatic arc in southern Arizona, where regional extensional tectonism created depositional basins (Mount Wrightson Formation—Riggs and Busby-Spera, 1990; Topawa Group—Haxel et al., 1984, and in prep.). Preserved remnants of Middle Jurassic arc-related rocks indicate that volcano-induced subsidence can be as important as regional tectonism in creating depositional basins.

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