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Gary A. Smith

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PALEOGEOGRAPHIC, VOLCANOLOGIC AND TECTONIC SIGNIFICANCE OF THE UPPER ABIQUIU FORMATION AT ARROYO DEL COBRE, NEW MEXICO

GARY A. SMITH

Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131

Abstract—Detailed study of the sedimentology and petrology of the upper member of the Abiquiu Formation west of Abiquiu, New Mexico, indicates that this member is composed of three stratigraphic intervals reflecting distinctive provenance and depositional processes. Interval I consists of fluvial sandstone and siltstone derived from erosion of volcanic rocks in the San Juan Mountains and Precambrian rocks of the Tusas Mountains north of Abiquiu. Interval II consists primarily of pumiceous debris-flow deposits derived from erosion of the 26.5 Ma Amalia Tuff, erupted in the Latir volcanic field northeast of Taos. This interval also contains detritus indicative of San Juan and Tusas Mountains provenance, suggesting drainage from the north across the distal outflow sheet of the Amalia Tuff that was dispersed at least 60 km westward from its source at the Questa caldera. Interval III is characterized by fluvial facies, notably finer grained than those of interval I, with petrographic characteristics consistent with derivation entirely from the Latir volcanic field. This study suggests that the petrosomes defined by Ingersoll and Cavazza (1991) and the paleogeographic reconstruction of Ingersoll et al (1990) require revision. Interval I of the upper Abiquiu Formation is a variant of the Esquibel petrosome that contains significant (> 25%) basement-derived detritus. Interval II is a mixture of the Esquibel and Cordito petrosomes. The presence of the Cordito petrosome in interval III along the far western margin of the Rio Grande rift suggests that development of accommodation space due to eastward tilting of the San Luis basin in the late Oligocene (~26 Ma) was small compared to the sediment supplied from the Latir volcanic field; therefore a westward paleoslope was maintained across most of the basin and into the Abiquiu embayment. Southward dispersal of Latir-derived sediment near Abiquiu suggests, however, that faulting along the western margin of the rift influenced drainage patterns

INTRODUCTION

The upper Oligocene–lower Miocene Abiquiu Formation (Abiquiu Tuff of Smith, 1938) forms prominent white, castellated outcrops in the western Rio Grande rift in north-central New Mexico. The lower member (as designated by Vazzana, 1980, and Vazzana and Ingersoll, 1981) is conglomerate and sandstone with a primarily Precambrian basement provenance. It is correlated to the Ritito Conglomerate of Barker (1958) and Kelley (1978). The upper member is dominated by tuffaceous volcanic materials. Although the physical sedimentology and stratigraphy of this volcaniclastic apron remain largely unknown, the provenance of its constituents have played a significant role in understanding the middle Tertiary paleogeography of north-central New Mexico (Vazzana, 1980; Vazzana and Ingersoll, 1981; Manley, 1981; Ingersoll et al., 1990; Ingersoll and Cavazza, 1991). The principal outcrop belt of the Abiquiu Formation is in the Abiquiu embayment, a structurally shallow bench along the western margin of the Rio Grande rift adjacent to the deeper west-tilted Española basin and east-tilted San Luis basin (Fig. 1; e.g., Baldridge et al., 1994).

Smith (1938) first noted, on the basis of areal grain-size variations, that the likely source of the Abiquiu Formation volcaniclastic debris was the San Juan Mountains volcanic field of southern Colorado and northernmost New Mexico (Fig.1). Vazzana (1980) and Vazzana and Ingersoll (1981) concurred with Smith (1938) that a San Juan source was most probable on the basis of southerly paleocurrent measurements and petrographic examination of 18 thin sections indicating a provenance of quartz-poor, plagioclase-rich volcanic rocks typical of the lavas and tuffs exposed in the southeastern San Juan Mountains (Lipman, 1975a, b).

Manley (1981) proposed correlation of the Abiquiu Formation to the Los Pinos Formation of the Tusas Mountains and southern San Juan Mountains (Fig. 1). The Los Pinos Formation includes a lower Esquibel Member, derived from the San Juan volcanics, and an upper Cordito Member, derived principally from the Latir volcanic field near Taos (Manley, 1981; Fig. 1). At the contact of these two members Manley (1981) and Manley and Wobus (1982) mapped discontinuous outcrops of a welded ignimbrite, the tuff of Canada del Agua, which was later established (Manley and May, 1984, p. 357) as being the 26.5 Ma Amalia Tuff erupted from the Questa caldera in the Latir volcanic field (Lipman et al., 1986; Fig. 1).

The relative contribution of detritus from the San Juan Mountains and the Latir volcanic fields to the Abiquiu Formation and the paleogeographic significance of contributions from these two sources remain unclear. Although Vazzana (1980) and Vazzana and Ingersoll (1981) reported no indication of quartz- and alkali–feldspar-rich detritus in the Abiquiu Formation that might be derived from the Amalia Tuff and related alkali rhyolites of the Latir volcanic field, Manley (1981) reported the presence of clasts of the Amalia Tuff within the upper Abiquiu Formation, suggesting correlation of the upper Abiquiu Formation with the Cordito Member of the Los Pinos Formation. Citing Manley (1981), Ingersoll et al. (1990) noted that the presence of sediment eroded from the Amalia Tuff and "local sources" is likely in the uppermost Abiquiu Formation. However, on the basis of petrographic studies of the Abiquiu Formation and other volcaniclastic strata in northern New Mexico, Ingersoll et al. (1990) and Ingersoll and Cavazza (1991) assigned the Abiquiu Formation entirely to their Esquibel petrosome, representing sediment eroded from the San Juan Mountains, and restricted their Cordito petrosome of Latir-derived volcaniclastics to the Cordito Member of the Los Pinos Formation.

OVERVIEW OF THE ABIQUIU FORMATION AT ARROYO DEL COBRE

In order to better understand the relationship of Abiquiu Formation deposition to the volcanic histories of the San Juan and Latir volcanic fields, detailed study of an 80-m thick section of the upper Abiquiu Formation was undertaken at superb exposures along Arroyo del Cobre, 2 km west of Abiquiu (Figs. 1–3). The complete thickness of the upper member is not known because of the lack of previously identified stratigraphic markers and the numerous faults that displace the unit. Smith (1938) estimated a thickness of about 300 m, whereas Vazzana (1980) estimated the thickness at only 180 m. The section described here, therefore, represents 25% to 45% of the upper member.

Along Arroyo del Cobre, the Abiquiu Formation dips southeastward at about 12° and is capped, at several levels, by ancestral Rio Chama and Arroyo del Cobre terraces. Near the western edge of the arroyo the upper Abiquiu Formation is faulted against older Abiquiu strata and the Eocene El Rito Formation. In this area, the upper Abiquiu Formation is characterized by two intervals of light gray, relatively thick-bedded strata, con-

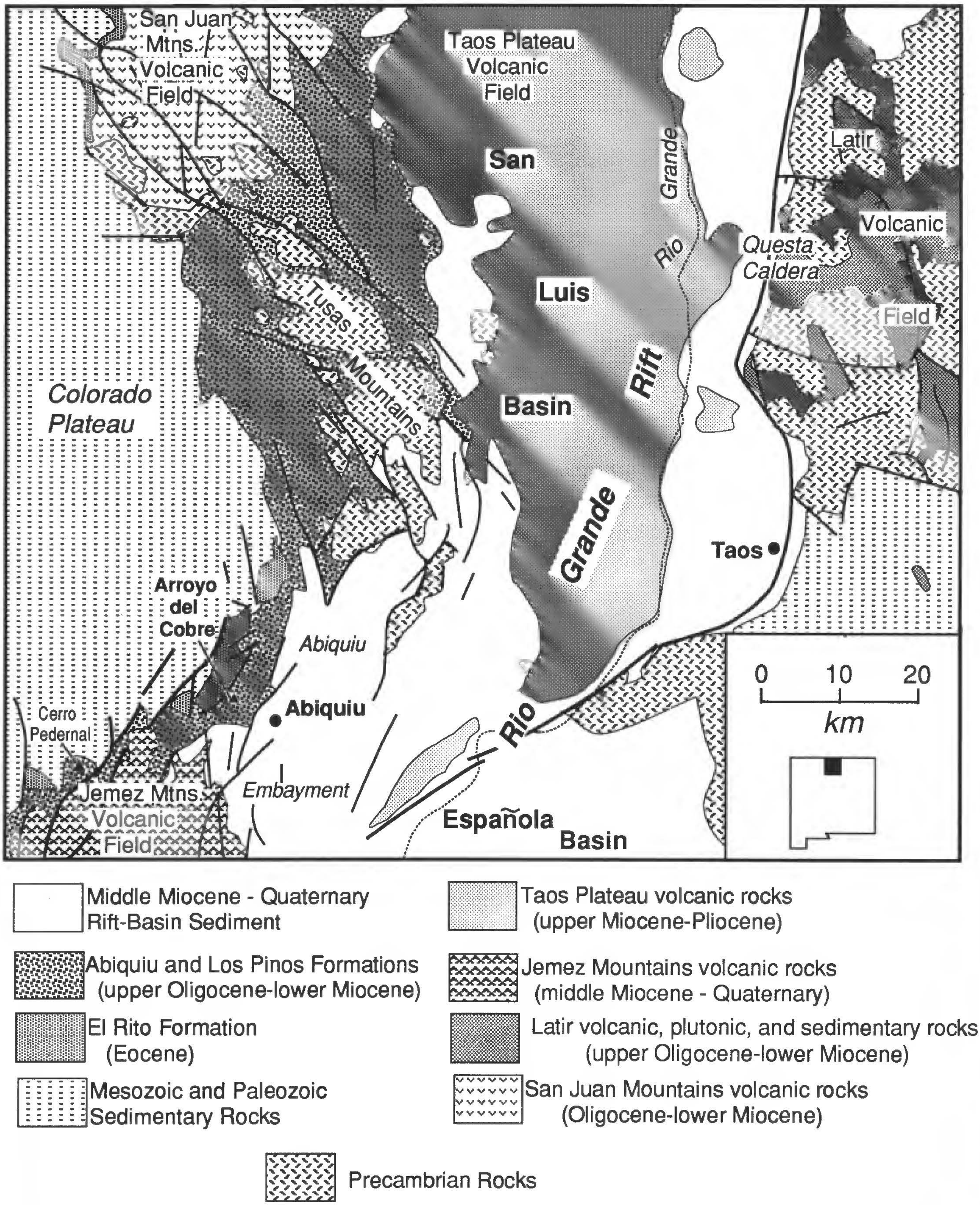

FIGURE 1. Generalized geologic map of north-central New Mexico showing locations mentioned in the text.

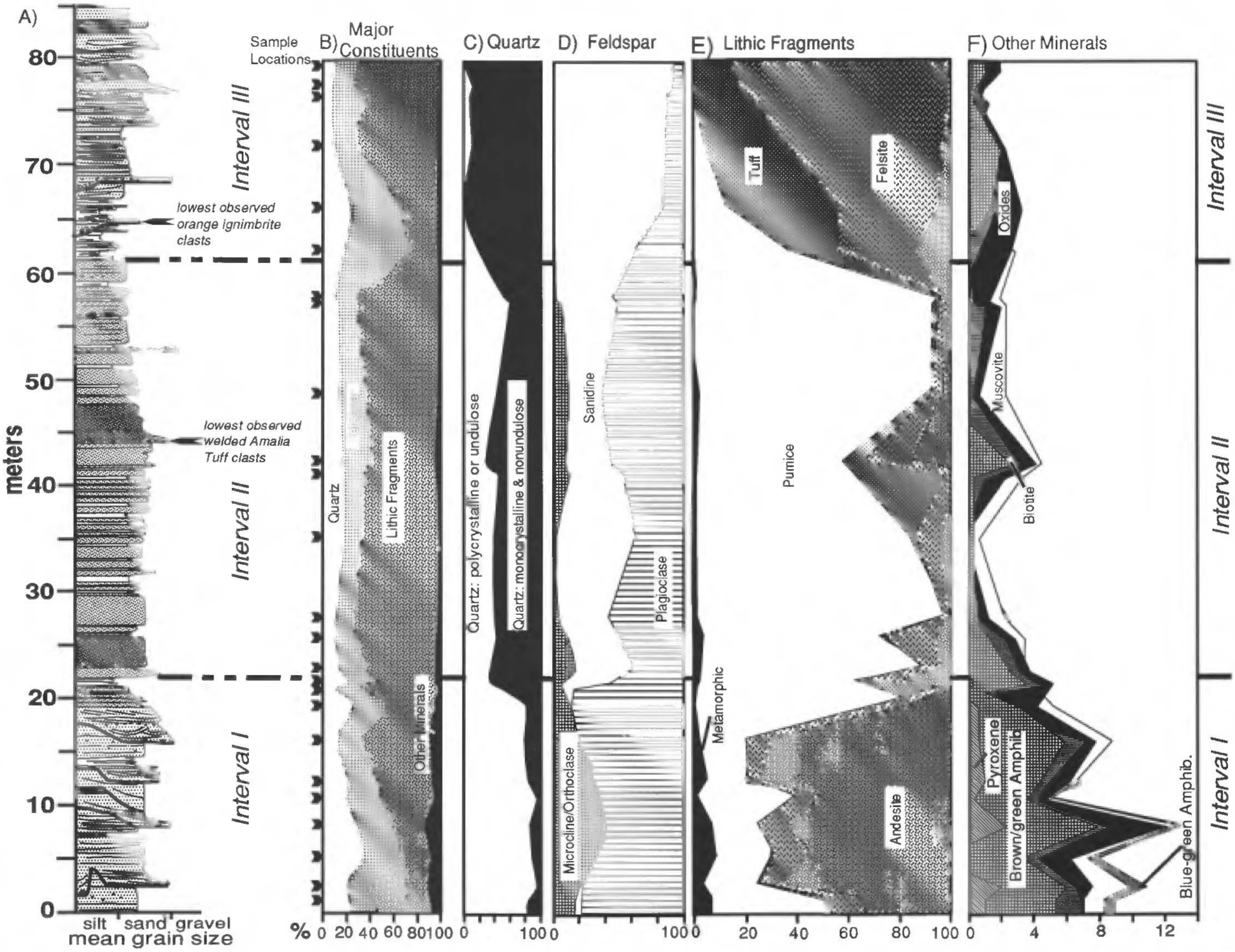

FIGURE 2. Stratigraphy and sedimentary petrology (see Table 1 for definition of categories) of the upper member of the Abiquiu Formation at Arroyo del Cobre. (A) Generalized lithostratigraphy. (B) General composition of sandstones. (C) Relative abundance of quartz types (total quartz normalized to 100%). (D) Relative abundance of feldspar species (total feldspar normalized to 100%). (E) Relative abundance of lithic-fragment types (total lithic fragments normalized to 100%). (F) Stratigraphic variation in trace-mineral components.

FIGURE 3. Photograph, looking northwest, of the Arroyo del Cobre section of the upper Abiquiu Formation. Arrows mark the base and top of interval II. Interval I is visible at lower left; interval II is visible in upper right and in the foreground.

taining prominent channelform paleoerosion surfaces. These intervals are separated by a 40-m thick sequence of white, thinner-bedded and more tabular strata. These three intervals were the focus of this study (Fig. 3).

PHYSICAL SEDIMENTOLOGY

Interval I

The lower interval is characterized by interbedded pebbly sandstone and tuffaceous siltstone with conspicuous channel forms (Fig. 4). Where laterally traceable, channels are on the order of 50–100 m wide and 2–4 m deep. Smaller channel-form sand bodies are nested within larger channels. Low-angle cross-stratification and horizontal lamination are the dominant sedimentary structures. Most of these structures indicate flow parallel to the south to south-southeast orientation of the channels, consistent with the paleoflow mean azimuth of 164° measured by Vazzana (1980). Some low-angle crossbeds, however, are inclined into channels, suggesting deposition on point bars. Pebbles and cobbles, 4 to 20 cm in diameter, are present along the base of the deepest channel scours. These clasts are primarily vesicular, intermediate-composition volcanic rocks although quartzite clasts are ubiquitous. Small (0.5–3.0 cm) rounded pumice lapilli with conspicuous biotite crystals are scattered throughout

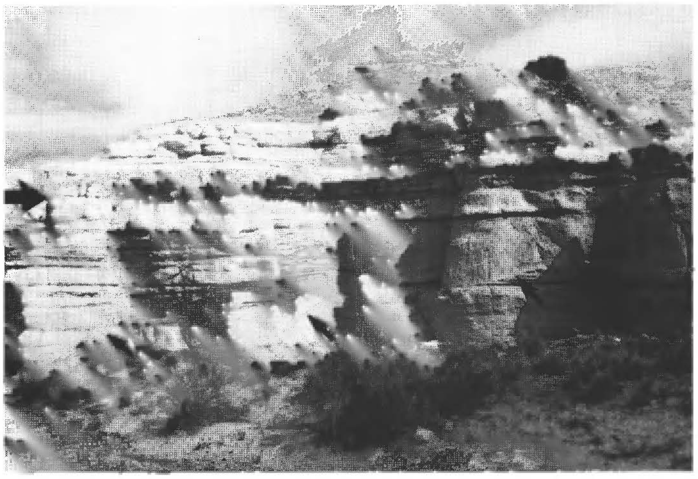

FIGURE 4. Outcrop photograph illustrating channel-form geometries of interval I sandstones (channel bases marked by small arrows). Large arrow at left marks contact between interval I and tabular pumiceous debris-flow deposits of interval II.

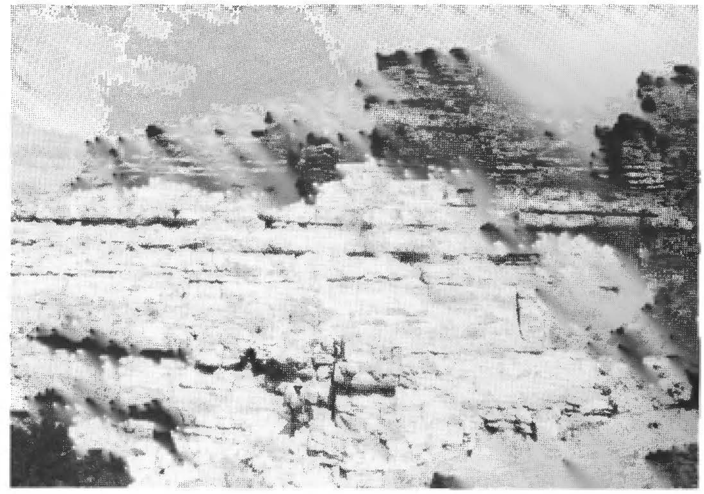

FIGURE 5. Massive, tabular pumiceous debris-flow deposits in interval II. Arrow marks contact between intervals II and III. Note general upward thinning of interval II beds. Photo by Megan Rhoads.

the sandstone and siltstone beds but rarely appear to represent more than 5% of the deposits. Siltstone beds are massive or laminated and typically contain burrow structures. Siltstone is present as 25–30-cm thick intervals overlying 3–4-m-thick sandstone intervals or as 2–4 cm strata interbedded with channel-filling sandstone (Fig. 2).

The uppermost 2.5 m of interval I is composed of tabular beds, 15–35 cm thick, that grade upward from massive bases to horizontally stratified tops. These beds are notably more pumiceous (~25% crystal-poor lapilli).

The sedimentological features of this interval suggest deposition by a mobile channel belt with a fluctuating base level. Absence of meter-scale crossbedding suggests that flows were much shallower than the 3–4 m depths exhibited by most channel scours. The pebbly sandstone strata not only fill these channels but also extend as sheets for 100 m or more adjacent to prominent channels. These characteristics suggest deposition by shallow, probably braided, streams that deposited sediment alternately in incised channels and on poorly confined sandflats. Siltstone beds within the channel-fill strata suggest unsteady and possibly ephemeral flows. The uppermost 2.5 m of graded-stratified beds may have been deposited by hyperconcentrated flows (Smith and Lowe, 1991).

Interval II

The overlying 38 m of section contains tabular pumiceous beds characterized by massive or crudely plane-bedded structure (Fig. 5). The thickest of the massive sandstone beds are 2–3 m thick and are found near the base of this sequence of strata. Other massive to crudely stratified beds are 15 cm to 1 m thick and separated by 5–20-cm-thick sandy siltstones. Some massive beds are notable for normal grading of dark lithic fragments and inverse grading of white to pink pumice lapilli. No erosional channels are present at the base of any bed. Quartz- and feldspar-bearing pumice lapilli, 1–5 cm across, are the dominant clasts in this interval. Volcanic pebbles, like those in interval I, range in size from 5–15 cm and are most conspicuous in the lowermost 20 m. Above this level are rounded pebbles and cobbles, to 80 cm across, of densely welded quartz- and feldspar-bearing ignimbrite. The massive nature of strata in this interval preclude the measurement of paleocurrent directions.

The tabular and generally massive nature of beds in this interval suggest deposition by debris flows and sheetfloods or hyperconcentrated flows (Smith and Lowe, 1991). The massive sandstones contain a finer ash matrix but little or no detrital clay. Volcaniclastic debris-flow deposits are typically clay poor (Smith and Lowe, 1991) because of derivation from erosion of nonconsolidated and nonweathered pyroclastic material shortly following eruptions. Grading patterns of lithic and pumice clasts may reflect negative and positive buoyancy, respectively, of these dominant clasts within the ashy debris-flow matrix.

Interval III

The uppermost strata exposed along Arroyo del Cobre are interbedded pebbly sandstone and siltstone (Fig. 2). Pebbly sandstone with low-angle and trough cross-stratification forms beds 1.0 to 2.0 m thick that are laterally persistant for 100 m or more but are thickest within 1.0–1.5 m deep erosional scours that are only 10–20 m across. These channels trend toward the south and southeast, as also indicated by Vazzana's (1981) paleocurrent data. The sandstones contain conspicuous clasts of orange, crystal-poor, lithic-rich, nonwelded, devitrified ignimbrite, 2–25 cm across.

More than half of this stratigraphic interval is composed of alternating laminated sandy siltstone and massive or horizontally stratified fine- to medium-grained sandstone in beds 4–40 cm thick. These beds are broadly lenticular and locally interrupted by channels filled with the pebbly sandstone facies. The siltstone intervals contain current-ripple laminations, mudcracks, and rare rain-drop impressions. Most of these laminated intervals also exhibit convolute laminations suggesting rapid deposition and dewatering.

Deposition of this interval was probably associated with narrow and shallow sand and gravel bedload channels and on adjacent, rapidly aggrading floodplains that were frequently inundated because peak flows were not confined within the shallow channels.

SANDSTONE PETROLOGY AND PROVENANCE

Twenty-five medium- and coarse-grained sandstone samples were subjected to thin-section petrographic study. Nine of these samples are from interval I, 10 are from interval II, and 6 are from interval III. Using the Gazzi–Dickinson point counting technique (Ingersoll et al., 1984), 300 points were counted on each slide after staining to assist recognition of potassium feldspar. Point-count categories and the likely provenance of each grain type are summarized in Table 1. Petrographic data are graphically summarized in Figure 2.

In terms of major groups of components (Fig. 2B), the sandstones appear to be similar lithic-feldspathic sandstones with 10–30% quartz. Closer examination of grain types (Figs. 2C–2F), however, illustrates important compositional differences that correspond to the three stratigraphic intervals that are distinct in outcrop.

Interval I

The lowest interval is characterized by components suggesting derivation from a mixed provenance of intermediate-composition volcanic rocks and Precambrian crystalline rocks, consistent with the observed pebble types. More than 80% of the quartz in this interval is polycrystalline and/or exhibits undulose extinction, characteristic of quartz derived

TABLE 1. Description and interpretation of grain types used for modal analysis.

Categories and Description	Provenance
Quartz (Q):	
Monocrytalline/nonundulose: All monocrystalline quartz grains that exhibit complete optical extinct at a single position of the microscope stage.	Volcanic or plutonic rocks; most grains lack inclusions, many are euhedral or embayed as typical of volcanic quartz, especially in intervals II and III (Fig. 7A).
Polycrystalline or undulose: All polycrystalline grains and all of those exhibiting undulose extinction, whether mono- or polycrystalline.	Plutonic or metamorphic rocks; possibly sedimentary chert. Most polycrystalline grains are aligned suggesting a metamorphic rather than sedimentary origin.
Feldspar (F):	
Microcline/Orthoclase (K): All potassium feldspars exhibiting albite-pericline twins, perthitic texture, and/or untwinned or Carlsbad-twin grains with 2V>50° and typically partly altered to clays or sericite.	Plutonic or metamorphic rocks or recycled sedimentary grains from such a source.
Sanidine (K): All fresh potassium feldspar grains with 2V<25° and typically lacking twinning or rarely exhibiting Carlsbad twins; typically euhedral or subhedral (Fig. 7B).	Felsic volcanic rocks. [Note: some of these grains are probably anorthoclase because they are only faintly stained for K-feldspar and some are microperthitic.]
Plagioclase (P): All feldspars lacking stain for potassium; always exhibiting albite twins and typically zoned and fresh.	Not indicative of provenance. However, most such grains exhibit complex zoning suggestive of volcanic origin.
Micas:	
Biotite: (both brown and green varieties)	Not indicative of provenance.
Muscovite:	Most likely derived from metamorphic rocks, less likely from granitic plutonic rocks.
Dense, nonphyllosilicate minerals (D):	
Pyroxene: (both orthopyroxene and clinopyroxene)	Probably derived from intermediate volcanic rocks.
Amphibole:	
Brown/ yellow-brown amphibole: oxyhornblende, hornblende with both brown and green pleochroism; typically partly rimmed with opaque minerals (Fig. 6A).	Most likely derived from volcanic or hypabyssal plutonic rocks.
Blue-green amphibole: amphibole (probably hornblende) strongly pleochroic in shades of dark green and blue-green.	Most likely derived from plutonic or metamorphic rocks.
Opaque Minerals:	Not indicative of provenance.
Lithic Fragments (L):	
Andesite: volcanic fragments exhibiting pilotaxitic and intergranular textures with abundant microlites of plagioclase and, typically, oxyhornblende, pyroxene, and oxides (Fig. 6A).	Intermediate (i.e., basaltic andesite to dacite) lava flows
Felsite: volcanic fragments lacking pyroclastic texture; typically vitric, spherulitic, or exhibiting anhedral microcrystalline mosaics of silica minerals and potassium feldspar (Figs. 7B, 8A).	Rhyodacitic or rhyolitic lava flows and possibly devitrified tuffs (in sand-size fragments of devitrified tuffs in which vitroclastic texture is largely destroyed, distinction from lava-flow fragments is not reliable).
Tuff: volcanic fragments, vitric or devitrified, with well developed vitroclastic or axiolitic textures (Fig. 5B).	Ignimbrites consolidated as a consequence of welding or vapor-phase mineralization during devitrification.
Pumice: colorless vesicular fragments, partly to mostly vitric with fine-grained alteration to clay and carbonate (Fig. 7A).	Fragments eroded from unconsolidated pyroclastic deposits.
Metamorphic: fine-grained, foliated, quartz-mica rock fragments; contains blue-green amphibole in some cases (Fig. 6B).	Metasedimentary or metavolcanic rocks.

from plutonic and metamorphic rather than volcanic rocks (Pettijohn et al., 1987). Some of the monocrystalline, nonundulose quartz is likely derived from similar sources. Nearly all of the potassium feldspar in these sandstones is microcline or orthoclase, also derived from metamorphic and plutonic rocks; sanidine from volcanic rocks is present in some sandstones but is not more abundant than 1.3%.

The lithic fragments in these sandstones are mostly volcanic. Andesite fragments (Fig. 6A) comprise the largest proportion of these grains, followed by felsite volcanic grains, and pumice. Fragments of devitrified tuff are present in a few samples. Fine-grained, foliated quartz–mica grains of metamorphic origin are present in all samples. Coarser-grained quartzite and granitic fragments (Fig. 6B) are also present but are not included as lithic fragments by the Gazzi–Dickinson point-counting method.

Accessory minerals, comprising more than 10% of some samples, also indicate a mixed volcanic and basement provenance. Amphibole with brown or brown-green pleochroism typical of volcanic hornblende or oxyhornblende is the dominant accessory mineral. Orthopyroxene and clinopyroxene, also typical of intermediate volcanic rocks and present within some of the andesite lithic fragments, are present in nearly all samples from this interval. Blue-green hornblende, typical of metamorphic and plutonic rocks, and muscovite are also present in nearly all samples and represent basement sources.

The composition of these sandstones does not match the Esquibel petrosome of Ingersoll and Cavazza (1991; Table 2). The high

TABLE 2. Means and standard deviations for recalculated variables for petrosomes of Ingersoll and Cavazza (1991) and Abiquiu Fm.

	Ingersoll & Cavazza (1991)		Abiquiu Fm. (this study)		
	Esquibel Petrosome	Cordito Petrosome	Interval I	Interval II	Interval III
No. of samples	26	17	9	10	6
Variable *					
QFL%Q	6±8	18±11	25±8	15±4	14±7
QFL%F	41±16	28±13	25±5	19±4	33±13
QFL%L	53±15	54±22	50±13	66±7	53±19
P/F	0.92±0.09	0.20±0.12	0.72±0.10	0.51±0.08	0.18±0.10
%D	10±4	2±1	6±3	2±1	2±1

* see Table 1 for abbreviations

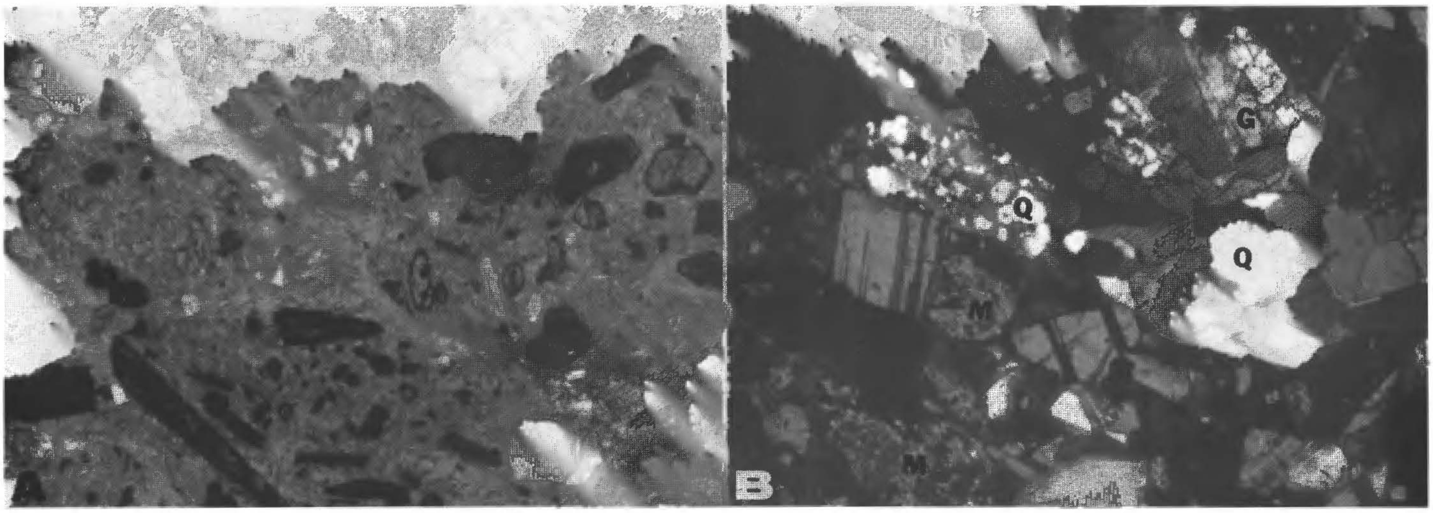

FIGURE 6. Photomicrographs of interval I sandstones (field of view, 3.5 mm). A, Three andesitic rock fragments, containing microphenocrysts of plagioclase and oxyhornblende (rimmed by opaque oxides), surrounded by plagioclase grains, smaller rock fragments, and minor calcite cement (plane-polarized light). B, Metaquartzite (Q), granitic (G), and foliated metamorphic (M) rock fragments among plagioclase grains and small volcanic-rock fragments (crossed polars).

plagioclase:total feldspar (P/F) ratio and abundance of volcanic lithic fragments are consistent with a San Juan Mountains provenance but the quartz content of the Abiquiu Formation sandstones is significantly higher (25% vs 6 %) than the Esquibel petrosome and the Abiquiu Formation has more potassium feldspar.

Andesite and dacite lavas comprise most of the southeastern San Juan Mountains volcanic field and both predate and postdate dacitic and rhyodacitic ignimbrites associated with formation of the composite Platoro–Summitville caldera complex, about 120 km north of Arroyo del Cobre (Lipman, 1975a). The ignimbrites are quartz-poor, biotite-bearing rocks in which sanidine:plagioclase ratios typically are less than 0.5; the few tuffs with more abundant sanidine (e.g., Carpenter Ridge Tuff) are also crystal poor (2–3% total crystals) (Lipman, 1975a). Erosion of these tuffs and associated lavas can explain the abundance of biotite-bearing pumice, andesite-lithic fragments, rarity of sanidine, and low abundance of quartz of possible volcanic origin.

Contribution of quartz and potassium feldspar from Precambrian basement rocks accounts for the discrepency between the compositions of Abiquiu Formation sandstones and the Esquibel petrosome of Ingersoll and Cavazza (1991). Detritus was probably derived from basement rocks in the Tusas Mountains, 25 to 60 km to the north (Fig. 1). As part of the Laramide Brazos–Sangre de Cristo uplift, the Tusas Mountains had undergone Eocene and Oligocene erosion represented by strata of the Eocene El Rito Formation and the lower member of the Abiquiu Formation. Dissection of these older sedimentary strata could account for the crystalline basement components in the upper member of the Abiquiu Formation, but derivation from direct erosion of Precambrian rocks is likely because the upper Abiquiu Formation, and correlative Los Pinos Formation to the north, locally rest with profound erosional relief (up to 300 m; May, 1980) upon basement rocks.

The Tusas Mountains provided considerable detritus to the Abiquiu Formation. Not including monocrystalline-nonundulose quartz, plagioclase, oxides and biotite that are also probably derived in some part from Precambrian rocks, the sum of other constituents of nonvolcanic origin (polycrystalline or undulose quartz, microcline, orthoclase, metamorphic lithics, muscovite, blue-green amphibole) comprise 10% to 45% (average 28%) of the interval I sandstones.

Interval II

Coincident with the abrupt sedimentological transition from interval I to II is a complementary change in sandstone petrology. Interval II shows evidence of mixing of sediment derived from volcanic and basement sources but the volcanic source includes a more quartz- and sanidine-rich component than reflected in interval I (Fig. 2). Pumice and tuff fragments dominate the lithic fraction of interval II sandstones (Fig. 7A). Andesite fragments, representing 15 to 41 % of most interval I sand-

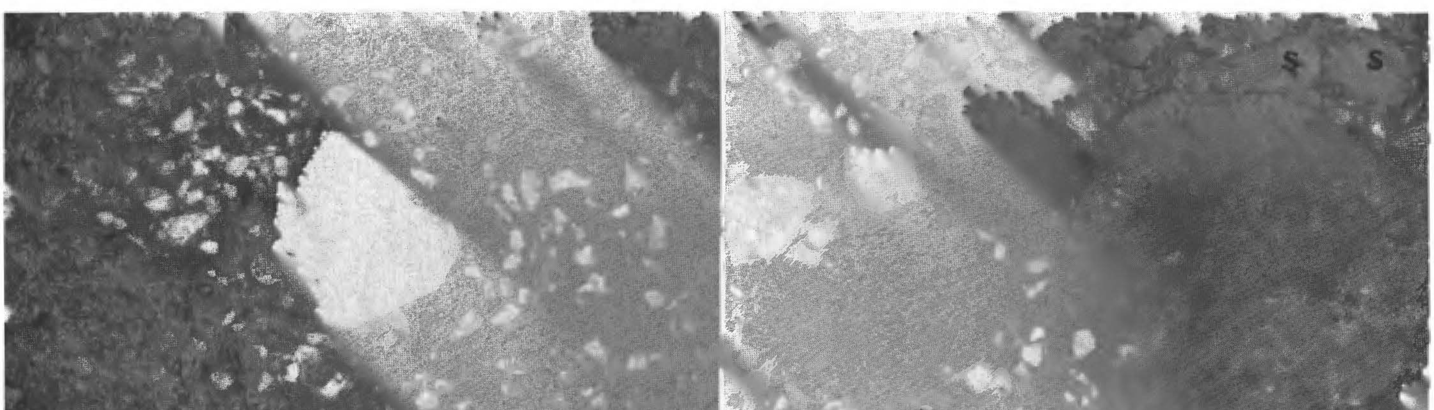

FIGURE 7. Photomicrographs of interval II sandstones (plane-polarized light; 3.5 mm across). A, Subhedral, embayed-margin volcanic quartz grain surrounded by smaller quartz and feldspar grains and darker vitric-pumice grains with elongate vesicles. B, Finely crystalline felsite fragments surrounded by stained sanidine (S), quartz, plagioclase, and ashy matrix.

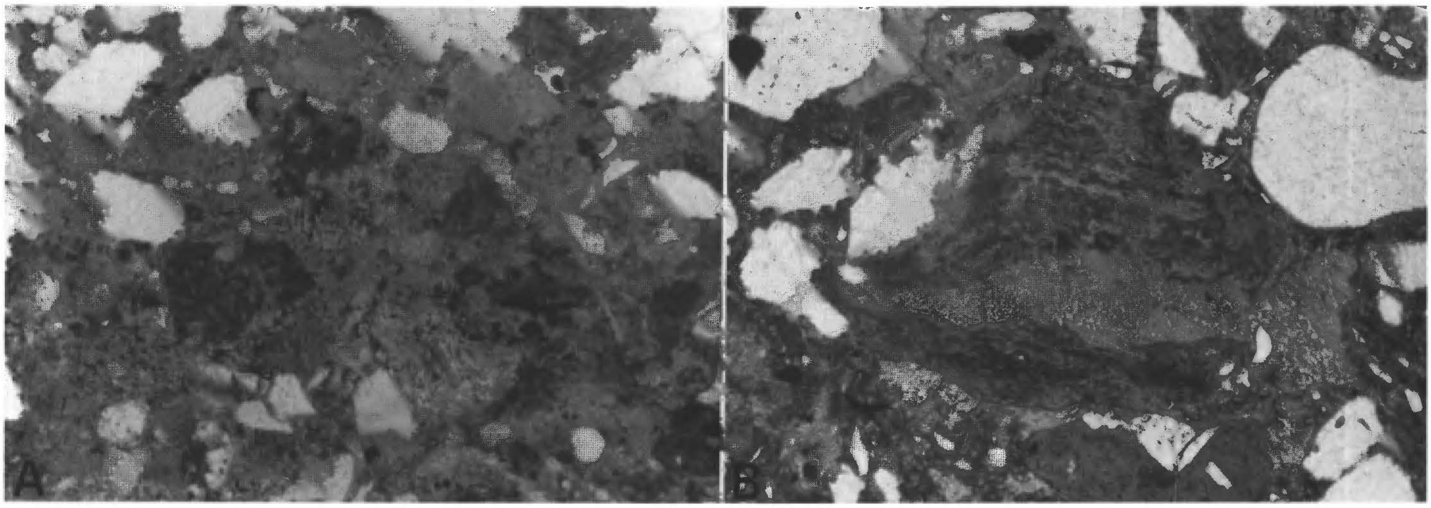

FIGURE 8. Photomicrographs of interval III sandstones (plane-polarized light; 3.5 mm across). A, Fine-grained felsites along with quartz and sanidine grains. B, Devitrified welded tuff grain (probably Amalia Tuff) surrounded by felsite, quartz, and sanidine grains.

stones, comprise only 1–9% of interval II samples. Biotite and probable volcanic hornblende are greatly reduced in abundance and pyroxene was observed in only one sample. The abrupt increase in the abundance of monocrystalline, nonundulose quartz and sanidine (Fig. 2) are consistent with an influx of rhyolitic detritus. The hyperconcentrated-flow deposits near the top of interval I (19 to 22 m in the section; Fig. 2A) have compositions intermediate between those of the remainder of interval I and interval II and may reflect deposition in the transition from one dominant volcanic provenance to another.

A basement-rock provenance is also recorded in the composition of interval II sandstone, although the volumetric importance of this source is reduced relative to interval I. Polycrystalline and/or undulose quartz comprise 4.6% to 8.6% of sandstone in this interval. Microcline and orthoclase are present in small amounts (0.3–3.6%) in all of the sandstone in this interval subjected to point counting. Muscovite is present in all but two samples from this interval, and blue-green amphibole was observed in one sample. On average, interval II sandstones contain 10% grains that must be derived from nonvolcanic sources.

The petrology of interval II sandstones does not match any of the petrosomes of Ingersoll and Cavazza (1991). P/F ratio is intermediate between the Esquibel and Cordito petrosomes (Table 2). The high lithic content is a result of the abundance of pumice in these samples. A contribution from the Latir volcanic field is indicated not only by the abundance of volcanic quartz and sanidine atypical of San Juan Mountains sources but also by hand-sample and thin-section identification of the welded-ignimbrite clasts in this interval as the distinctive Amalia Tuff (P. W. Lipman, personal commun., 1994). The abundant pumice in this interval, typically containing quartz and sanidine and no biotite, is probably derived from erosion of nonwelded zones of the Amalia Tuff. This detritus is mixed with sediment derived from the San Juan Mountains volcanic field and Tusas Mountains to the north. Most grains in interval II are of pyroclastic origin and the sandstones could just as appropriately be called tuffs (classification of Fisher, 1981; Schmid, 1981).

Interval III

Samples from the uppermost interval represent derivation almost entirely from a felsic volcanic source and closely resemble the Cordito petrosome of Ingersoll and Cavazza (1991; Table 2). Pumice content of sandstone diminishes and fragments of felsic tuffs and lavas increase (Fig. 8). Sanidine strongly dominates over the other feldspars (Fig. 2D). Monocrystalline, nonundulose quartz comprises about 5–24% of these samples. Although some of this quartz may be derived from nonvolcanic sources, the decrease of polycrystalline or undulose quartz (averages: 19.1% in interval I, 4.9% in interval II, 0.9% in interval III) and the bipyramidal and embayed outlines of volcanic quartz preserved in many of the monocrystalline quartz grains suggest a voluminous influx of volcanic quartz.

Tuff grains in the sandstones include recognizable fragments of Amalia Tuff (Fig. 8B) and grains of the orange, crystal-poor, lithic-rich ignimbrite that is also prominent as pebbles and cobbles in interval III. Petrographic examination of a clast of this latter ignimbrite (e.g., Fig. 9B) indicates that it contains sparse (<1%) quartz and alkali feldspar (possibly anorthoclase rather than sanidine, because the grains do not stain well), rare amphibole, and no plagioclase. Amalia Tuff fragments are present within the ignimbrite. This ignimbrite does not resemble any tuffs known to crop out within the San Juan Mountains or Latir volcanic fields; its crystal-poor nature with quartz and alkali feldspar suggest, however, a possible relationship to eruptions within and adjacent to the Questa caldera after eruption of the Amalia Tuff (P. W. Lipman, personal commun., 1994).

Most of the voluminous felsite fragments in interval III sandstones were probably eroded from lava flows but some fraction of these grains may also be fragments of Amalia Tuff. Petrographic examination of Amalia Tuff clasts (Fig. 9A) in the Abiquiu Formation indicates the presence of zones of coarse-grained devitrification in which all vitroclastic texture has been destroyed. Sand grains eroded from such zones might not be recognizeable as tuff fragments.

Detrital contributions from basement rocks are negligible in interval III. The stratigraphically lowest sandstone examined in this interval contains 3.6% polycrystalline quartz, 1% microcline/orthoclase, and 0.3% muscovite. Only 8 other grains of known basement provenance (7 of which are quartz) were counted among the other 6 samples from interval III.

SYNTHESIS

The combination of physical sedimentology and sandstone petrology indicate complex influences of explosive volcanism and paleodrainage changes to construct the Abiquiu Formation section at Arroyo del Cobre (Fig. 10).

Interval I records deposition on a braidplain draining southward from the San Juan Mountains volcanic field across the remnant Brazos uplift (Fig. 10A). The petrography of this interval generally supports correlation to the Esquibel Member of the Los Pinos Formation. The composition of these sandstones differ, however, from the Esquibel petrosome of Ingersoll and Cavazza (1990) because of the addition of significant basement-derived detritus to the dominant volcaniclastic debris.

Channel forms in interval I are deeper than the flows required to produce the observed sedimentary structures. This suggests incision of channels and deposition within them under different hydraulic regimes. The origin of these aggradation-degradation cycles is not known. Possibilities include climatic fluctuations causing imbalances in stream discharges and sediment load or aggradation driven by large sediment fluxes generated by explosive eruptions, then followed by degradation during inter-

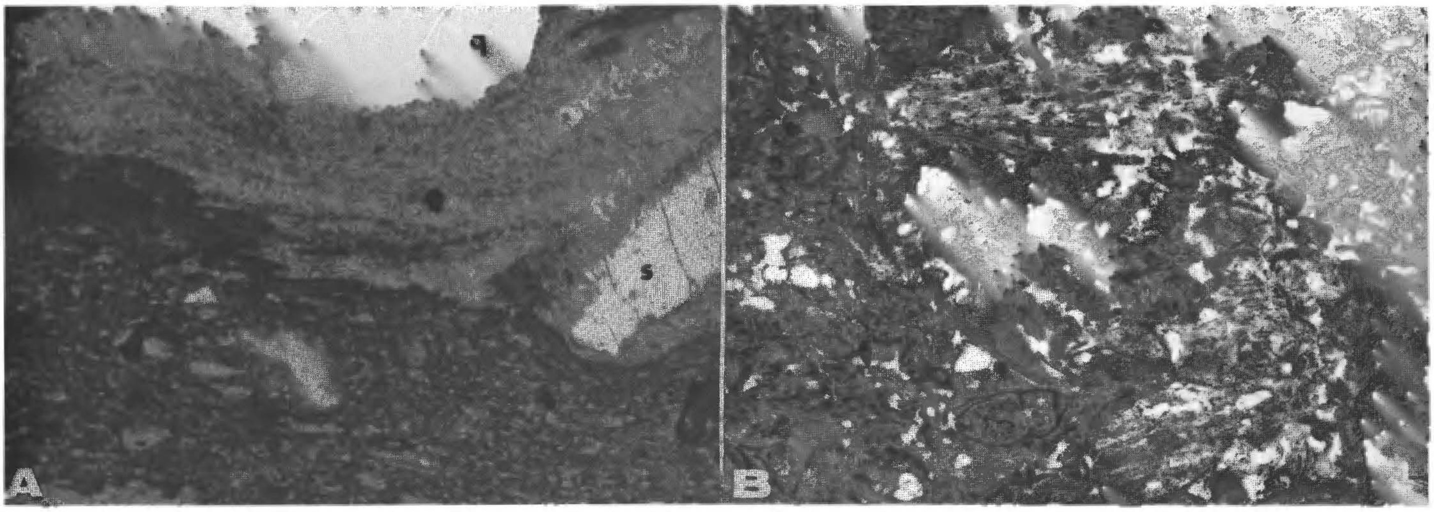

FIGURE 9. Photomicrographs of ignimbrite clasts (plane-polarized light; 3.5 mm across). A, Densely welded Amalia Tuff with quartz (q) and sanidine (s). Light-colored upper part of photo is a coarsely devitrified pumice fiamme. B, Devitrified shards and intershard vapor-phase feldspar and silica minerals typical of the orange, crystal-poor, lithic-rich ignimbrite fragments that are abundant in interval III.

eruption periods when sediment loads were reduced (Smith, 1991). Cycles of syneruption aggradation and inter-eruption degradation have been previously documented only in relatively proximal volcaniclastic sedimentary successions (e.g., Vessel and Davies, 1981; Smith, 1991), where syneruption facies are marked by debris-flow and hyperconcentrated-flow deposits largely lacking from interval I. The distal expressions of such volcanic influences on sedimentation remain undocumented in the stratigraphic record and cannot be argued for in this case without correlating the depositional cycles more closely to individual eruptions in the San Juan Mountains.

Interval II records the addition of pyroclastic debris derived from erosion of the Amalia Tuff to the distal San Juan volcaniclastic apron. The Amalia Tuff eruption not only led to collapse of the Questa caldera but also to widespread emplacement of outflow sheet ignimbrite. The extent of this ignimbrite is now largely obscured because of subsequent burial in the San Luis Basin of the Rio Grande rift. Outcrops in the Tusas Mountains (Manley and Wobus, 1982) indicate, however, that the pyroclastic flows traveled at least 60 km to the west of the source (Fig. 10B). Rapid erosion of the upper, poorly consolidated and nonwelded ignimbrite caused floods and debris flows transporting pyroclastic material to be flushed southward into the Abiquiu region. As dissection of the ignimbrite sheet progressed, clasts of welded and devitrified tuff from the interior of the ignimbrite were eroded and transported southward as well. The abrupt introduction of the distinctive Amalia Tuff detritus as flood and debris-flow facies probably represents deposition shortly (within weeks to years) of the eruption. Because basement-derived material comprises at least 10% and intermediate-composition volcanics at least 2–10% of the sandstones in this interval, it seems likely that drainage remained generally southward from the San Juan and Tusas Mountains and that the Amalia Tuff sediment was eroded from relatively distal outflow facies of the ignimbrite deposited on the Los Pinos–Abiquiu volcaniclastic apron north of Arroyo del Cobre (Fig. 10B).

Interval III represents renewed deposition by normal fluvial processes and sediment composition indicates correlation to the Cordito member

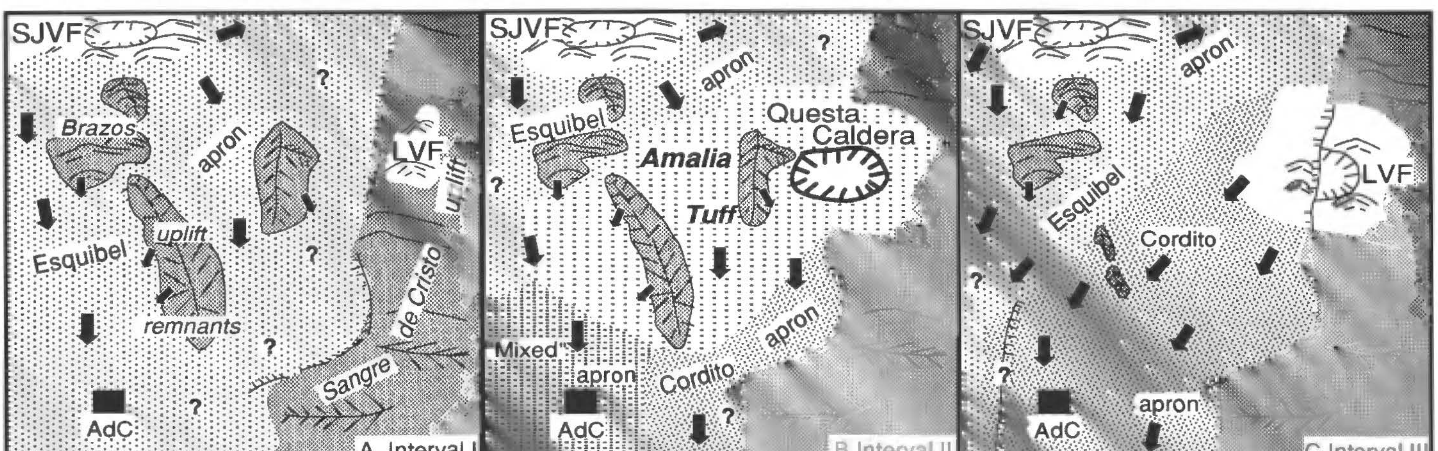

FIGURE 10. Generalized interpretations of paleogeography and paleodrainage during deposition of the upper member of the Abiquiu Formation. Interpretations are modified from Ingersoll et al. (1990) based on data from the Arroyo del Cobre (AdC) section. A, During deposition of interval I at Arroyo del Cobre, volcaniclastic debris from the San Juan Mountains volcanic field (SJVF) formed a broad apron (Esquibel petrosome within the Los Pinos and Abiquiu Formations) extending southward into New Mexico. Detritus was also eroded from Precambrian rocks exposed in remnants of the Laramide Brazos uplift. Subsidence and eastward tilting of the San Luis Basin may be initiated by this time, caused by faulting along the western front of the Sangre de Cristo Mountains. B, Interval II deposition records a mixture of Esquibel-petrosome sediment with Cordito-petrosome detritus eroded from the Amalia Tuff outflow sheet erupted from the Questa caldera. C, During interval III deposition, the Cordito apron derived from the Latir volcanic field (LVF) prograded across the entire early rift basin. Esquibel-petrosome detritus from the San Juan volcanic field was shed into the northern San Luis Basin of Colorado (Brister and Gries, 1994) and probably onto the Colorado Plateau to the west. Southward paleocurrents at Arroyo del Cobre suggest that subsidence along the boundary between the Colorado Plateau and Rio Grande rift may have influenced drainage patterns.

of the Los Pinos Formation, as suggested by Manley (1981). Two observations suggest that this sediment, although deposited in channels with local flow toward the south and south–southeast, was almost entirely derived from the Latir volcanic field to the northeast (Fig. 10C). First, nearly complete disappearance of basement-derived fragments and greatly diminished flux of plagioclase suggest minimal, if any, input from San Juan–Tusas sources to the north. Second, the unidentified orange tuff that is prominent as clasts in interval III is not known from outcrops to the north and has a mineralogy most consistent with erosion from an unknown ignimbrite in the Latir volcanic field that was locally distributed in what is now the eastern San Luis Basin.

It also seems unlikely that the Latir-derived, Cordito petrosome facies in interval III reflect deposition by streams of the pre-Amalia Tuff braidplain in which sediment supply from the previous San Juan and Tusas Mountains sources was considerably diluted by a more voluminous tributary sediment source from the Latir field. If such a dilution effect resulted, it should be more dramatically reflected in interval II, which represents deposition when the largest volume of nonconsolidated pyroclastic debris was being rapidly eroded from the ignimbrite outflow sheet. The sand in interval III is notably pyroclast-poor and composed almost entirely of epiclastic grains (i.e., those weathered and eroded from rocks rather than nonlithifed pyroclastic deposits). In facies representing mixing of Esquibel and Cordito petrosomes, therefore, the largest Cordito component would be expected in interval II, not in interval III, as observed. Therefore, interval III is interpreted to represent deposition on a rapidly aggrading braidplain that comprised a distal volcaniclastic apron from the Latir volcanic field without contributions from the San Juan and Tusas Mountains to the north.

The southward paleotransport of Cordito-petrosome debris at Arroyo del Cobre may reflect a control of subsidence along north–south-trending faults bounding the west side of the Rio Grande rift (Fig. 10C) thus accounting for local southward transport from sources located to the east, rather than the north. Subsidence of the San Luis Basin along the eastern rift margin is believed to have been initiated shortly after eruption of the 27.35 Ma Carpenter Ridge Tuff in the San Juan Mountains and before eruption of the 26.5 Ma Amalia Tuff (Brister and Gries, 1994; Chapin and Cather, 1994). Baldridge et al. (1994) interpreted faulting along the western edge of the Abiquiu embayment to be restricted to the time between about 10 Ma and 3 Ma, based on inferred relationships between faulting and basaltic volcanism. Some faulting along the margin embayment may have begun even earlier, however, in order to explain about 10° discordance between the El Rito and lower Abiquiu Formations 3 km farther west. Detritus from the San Juan and Tusas Mountains may have been diverted westward and southwestward onto the Colorado Plateau along the western and northern margin of the prograding Latir-derived apron. If this scenario is correct it has several implications for the early subsidence history of the Rio Grande rift. First, eastward tilting of the San Luis Basin block at this time was insufficient to prohibit extensive westward progradation of Latir volcaniclastic aprons. Second, subsidence along the western margin of the rift was adequate to induce a rift-parallel north–south grain to the drainage network but was inadequate to trap all volcaniclastic debris from the San Juan Mountains, and possibly Latir volcanic field, within the developing rift. Aspects of this last implication were apparent to Smith (1938) who noted that the erosional remnant of Abiquiu Formation at Cerro Pedernal (Fig. 1), west of the Rio Grande rift border faults, implies an originally extensive apron of volcaniclastic debris on the Colorado Plateau that has subsequently been eroded.

CONCLUSIONS

Detailed study of the sedimentology and petrology of an 85-m-thick part of the upper member of the Abiquiu Formation at Arroyo del Cobre suggests several revisions to the early Miocene paleogeography of north-central New Mexico and also raises important questions that require more extensive study of the Abiquiu and correlative Los Pinos Formations. The paleogeographic reconstruction presented by Ingersoll et al. (1990) and Ingersoll and Cavazza (1991) is generally supported by the results of this study, but important refinements are suggested:

(1) The Tusas Mountains, rather than an "incipient" feature during Abiquiu Formation deposition, as shown by Ingersoll et al. (1990), had sufficient relief to contribute significant detritus into the upper member of the Abiquiu Formation, despite the large volume of sediment being eroded from the San Juan Mountains volcanic field at this time. Left unresolved, however, is the matter of whether this relief was remnant topography from Laramide uplift or is indicative of uplift associated with eastward tilting of the San Luis Basin. Because the lower Abiquiu Formation is composed almost entirely of basement-derived detritus (Vazzana, 1980) and rests unconformably upon the Laramide El Rito Formation, it is possible that Abiquiu Formation deposition was initiated by early rift-basin subsidence that included rejuvenation of relief in the Tusas Mountains.

(2) A significant part of the upper member of the Abiquiu Formation was probably derived from the Latir volcanic field, indicating development of a widespread volcaniclastic apron that extended westward and southward from the Taos region. The presence of facies in the Abiquiu embayment representing this apron indicates that the subsidence volume due to eastward tilting of the San Luis Basin block was small relative to the large volume of volcaniclastic debris that was being shed westward into the basin, so that paleoslope remained toward the west. The southward dispersal of the Latir-derived detritus at Arroyo del Cobre suggests that drainage patterns in the Abiquiu embayment were influenced by subsidence along north–south trending rift-bounding faults.

(3) Detailed study of the petrography of upper Abiquiu Formation sandstones from Arroyo del Cobre indicates that the petrosomes defined by Ingersoll and Cavazza (1991) are inadequate to represent all Tertiary deposits in this area. These petrosomes were defined on the basis of 50 thin sections (Table 3 of Ingersoll and Cavazza, 1991) collected from strata representing approximately 20 Ma of deposition over an area of 20,000 km^2. More representative sampling of sandstones is required in this region in order to more tightly constrain the paleogeography.

Further study of the Abiquiu and Los Pinos Formations are required in order to more clearly evaluate the influence of ignimbrite-producing eruptions in the San Juan Mountains volcanic field on distal sedimentation in the Abiquiu embayment; and more closely define the timing and nature of early subsidence along the western margin of the Rio Grande rift.

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