Stratigraphy of Reference Sections in the Popotosa Formation, Socorro County, New Mexico

U.S. GEOLOGICAL SURVEY BULLETIN 1800

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By SIGRID ASHER-BOLINDER

Description and interpretation of late Oligocene(?) and Miocene closed-basin rocks of the Rio Grande rift

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Stratigraphy of Reference Sections in the Popotosa Formation, Socorro County, New Mexico

By Sigrid Asher-Bolinder

Abstract

The Popotosa Formation of Socorro County, New Mexico, consists of detritus derived mainly from volcanic units of the Datil-Mogollon volcanic field to the southwest and of some interbedded, locally derived volcanic units. The Popotosa was named by C.S. Denny in 1940 to encompass sedimentary rocks of late Tertiary age between the Ladron and Lemitar Mountains. No type section was named, but Denny ascribed the formation's origins to alluviation in a closed basin. The Popotosa's age range and areal extent have been expanded by various authors as the Socorro paleobasin's relation to the development of the Rio Grande rift has become better understood.

Two measured sections are described in this report; a principal reference section is designated at Silver Creek, and a reference section is designated 11 km to the south at Cañoncito de las Cabras. The reference sections consist of 1,316 and 1,447 meters, respectively, of conglomerate, granulestone, sandstone, siltstone, and mudstone. Thirteen airfall and waterlaid tuffs at Silver Creek and seven airfall and waterlaid tuffs at Cañoncito de las Cabras are interbedded with the detrital units; one may serve as a marker bed between the two measured sections. Lithologic correlation between sections is otherwise difficult.

Low in the Silver Creek section, the Popotosa is interbedded with a flow of the La Jara Peak Basaltic Andesite of late Oligocene age. At Cañoncito de las Cabras, the Popotosa rests in unconformable and fault(?) contact with the La Jara Peak Basaltic Andesite. At Silver Creek, the west-dipping Popotosa is truncated by the flat-lying Pliocene and Pleistocene Sierra Ladrones Formation; at Cañoncito de las Cabras east-tilting Popotosa is truncated by Holocene alluvium.

These two reference sections reflect sedimentation near the depositional center of the closed paleobasin. Sedimentary structures, lateral and vertical successions, and chemical alterations of original lithologies suggest that the sediments were deposited on alluvial fans and flats and on mostly dry playas.

Dated volcanic units in contact with the Popotosa show that the closed paleobasin was faulted and filled, beginning probably more than 26.4 m.y. to probably less than 7 m.y. ago; no one section shows a complete range of ages. Laterally varied lithologies, limited sections, episodes of postdepositional faulting and tilting, and truncation by Pliocene and later through-flowing drainage make basinwide correlations within the Popotosa difficult at best.

INTRODUCTION AND ACKNOWLEDGMENTS

The Popotosa Formation was named by C.S. Denny in 1940. Denny (1940) specified no type section but based many of his interpretations on exposures in the Silver Creek area of Socorro County, N. Mex. As the Socorro paleobasin's history has become better understood, Denny's definition of the Popotosa has become incomplete. The formation shows rapid lateral facies variations and is interbedded locally with volcanic units; it also has undergone syndepositional and postdepositional faulting, rotation, and geochemical alteration. Age interpretations, thicknesses, and elevations of various outcrops throughout the paleobasin suggest a complex basin history. Airfall and waterlaid tuffs within the reference sections provide general time correlations between the two reference sections where lithologic successions do not.

G.O. Bachman first noted high lithium values from the Popotosa Formation (unpub. data); Brenner-Tourtelot and Machette (1979) surveyed the tuffs and clays in the southern part of the basin for lithium and other elements. Chamberlin (1980, 1981) provided a detailed picture of the stratigraphy and structural history of the formation in the Socorro and southern Lemitar Mountains. Chapin and others (1978) have also given a regional picture of Popotosa sedimentation in the southern part of the basin.

The purpose of this report is fourfold. (1) It reviews usages of the formation name, Popotosa. (2) It brings together previously published data from sections throughout the basin to provide a more complete picture of the formation's depositional and structural history. (3) The new, detailed lithologic descriptions of the reference sections provide a framework for understanding the depositional and geochemical histories of tuffs which contain anomalous amounts of lithium (Asher-Bolinder, 1982). (4) Brief interpretations of environments of deposition of informal units are presented.

I thank M.N. Machette and R.M. Chamberlin for their time in the field clarifying regional relationships between structure and sedimentation. C.E. Chapin provided insight into the influences of volcanic activity of the Socorro caldera system on Popotosa sedimentation. Permission to study the rocks along Silver Creek was given by Mike Kiger, Sevilleta National Wildlife Refuge. And C.H. Maxwell's knowledge of Socorro area geology and of volcanic eruptions made fieldwork more productive and enjoyable.

Reviews of this manuscript by P.L. Hansley and Fred Peterson served to clarify both my concepts and my writing. The correlations and conclusions, however, are my own.

METHOD OF STUDY

The lithologies of 1,316 m of exposure along Silver Creek are herein described, and this exposure is named the principal reference section of the Popotosa Formation. Lithologies of 1,447 m of exposure along the Cañoncito de las Cabras are described as a reference section of the Popotosa Formation.

Most of the reference section exposures were measured by Jacob's staff and inclinometer in the fall of 1979 and in the spring and fall of 1980 (fig 1). The La Jara Peak Basaltic Andesite and units 8 and 9 of the Silver Creek principal reference section were measured on aerial photographs and corrected for dip.

Rock colors were determined in the field using the Rock Color Chart (Goddard and others, 1975); colors were named from fresh, dry surfaces unless otherwise indicated. Lithologies were determined in the field using a grain-size and roundness chart. Very few beds contain a single lithology; beds were named for their principal lithology. The lithologies of a unit are listed in their order of decreasing abundance unless otherwise noted. Units were sampled for geochemical and petrologic investigation, both at the reference sections and throughout the basin, with careful sampling of the tuffs.

Unit boundaries were picked in the field; most were chosen to reflect differences in weathering styles, principal rock types, or groups of rock types. Most contacts between units are gradational and are conformable unless otherwise noted.

The Silver Creek principal reference section dips 30°–42° W. and strikes essentially north. The Cañoncito de las Cabras reference section dips 30°–36° E. and also strikes north. The opposing dips of the sections, their thicknesses, the commonly transitional nature of contacts between units, and their central positions in the paleobasin (fig. 3) combine to pose a problem in interpretation: how much of the lithologic-sequence differences between the sections are artifacts of different locations in the paleobasin, created by measuring across the beds?

If one assumes a constant 30° dip of beds, measuring 1,500 m of true thickness requires 3,000 m of lateral movement into or out of the paleobasin. In a broad, mature basin 3 km of lateral movement might be negligible; in a small, tectonically active basin, 3 km of movement could cross depositional boundaries. Thus, these two reference sections may show rather dissimilar lithologies due to artifacts of measurement as well as due to intrinsic differences in their depositional histories.

PREVIOUS STUDIES OF POPOTOSA FORMATION

The Popotosa Formation was named by Denny (1940) for outcrops near Arroyo Popotosa (fig. 1). He was aware of the extent and variability of the formation within his study area, and he understood its origins and its complexly faulted nature. His study of the San Acacia area, which includes the Silver Creek principal reference section of this report, did not extend north to the Cañoncito de las Cabras section of this report. He assigned the Popotosa to the late Miocene(?) on the basis of its stratigraphic position, and he noted regional variations in clast composition.

Bruning (1973) mapped the Popotosa's extent in the Socorro paleobasin, described three facies, provided petrographic studies of individual localities, and named, but did not describe, a type locality along the informally named Cañada de Tortola, T. 1 N., R. 1 W. (about 3 km southeast of the base of the Silver Creek principal reference section shown on fig. 1). His dissertation contains descriptions of clast compositions, sedimentary structures, unit thicknesses, pebble counts, and current and source indicators.

Machette (1978), in his map of the San Acacia 7½-minute quadrangle to the east of Silver Creek, recognized four major facies: the volcaniclastic fanglomerate facies, the playa bed facies, transitional beds, and a facies of conglomerate derived from detritus shed off the Ladron Mountains. His transitional units represent the mixture of sandstone and pebbles that accumulate at the toes of alluvial fans and upon alluvial flats adjacent to playas. Machette's playa beds are upper? Miocene to middle? Miocene only, and they apparently represent a single episode of playa development.

Osburn and Chapin (1983) described and placed several formally and informally named synrift volcanic units, as well as the Popotosa and the Sierra Ladrones Formations, within the Santa Fe Group. Their correlation chart applies to the northeast portion of the Datil–Mogollon volcanic field south of Magdalena. They characterized the sedimentary rocks of the Popotosa Formation as a sequence of mudflow deposits overlain by playa claystones. They recognized the intertonguing

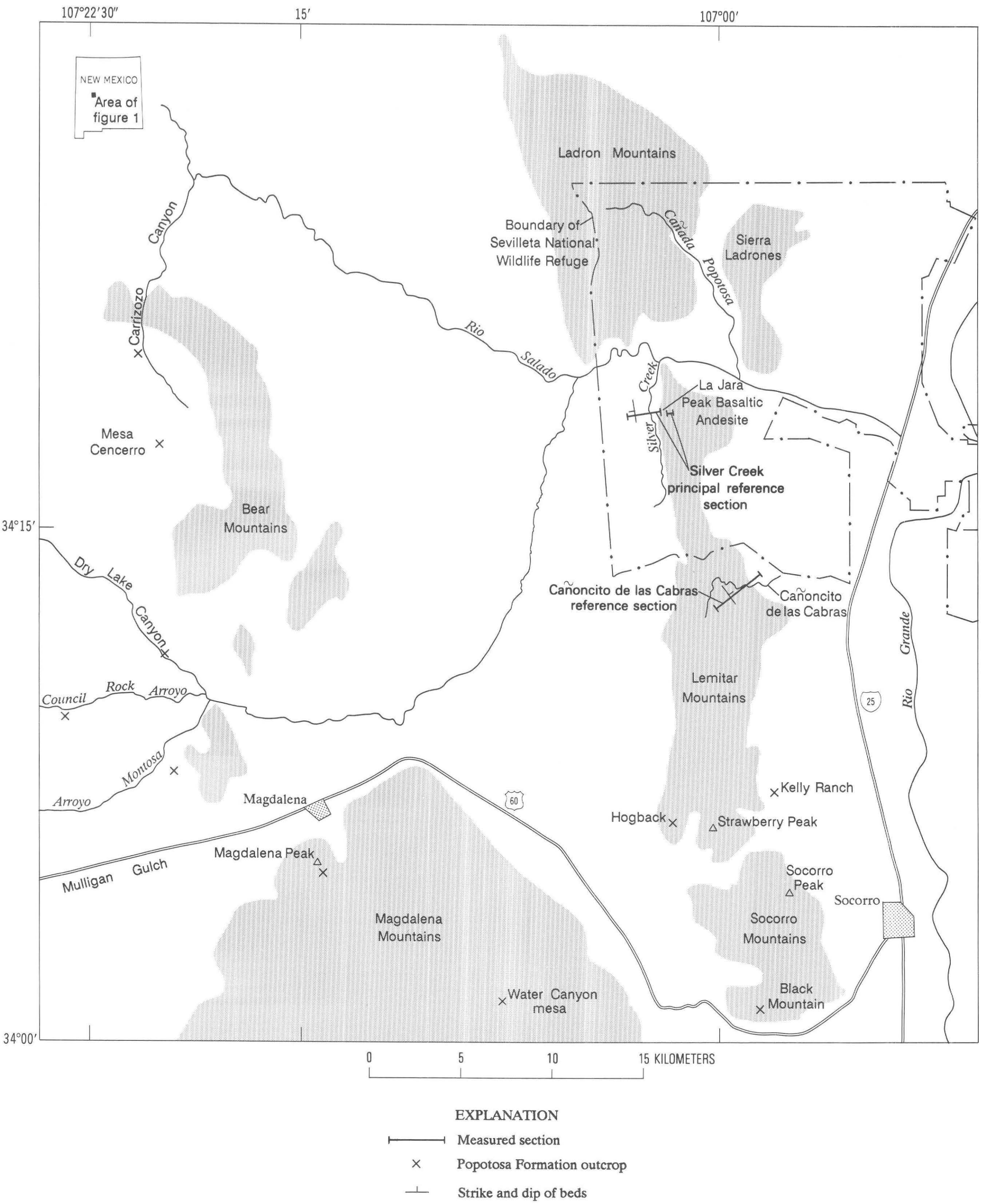


Figure 1. Popotosa Formation outcrops, names mentioned in text, and locations of reference sections.

nature of Popotosa facies with one another outside the Socorro area but separated the fanglomerate of Dry Lake Canyon from the description of the Popotosa Formation entirely. Although these descriptions fit volcanic and sedimentary relations in the area around the Socorro and Sawmill Canyon–Magdalena cauldrons, such relationships do not exist throughout the rest of the basin.

POPOTOSA FORMATION

The Socorro Paleobasin

The Rio Grande rift in New Mexico first formed as a series of closed basins, younging northward, later integrated by through-flowing drainage of the Rio Grande in Pliocene time (Machette, 1978). The Socorro paleobasin, a discrete subbasin of the Albuquerque paleobasin, developed during late Oligocene through most of Pliocene time in response to evolution of the Rio Grande rift. Its location is outlined on figure 3. The Popotosa Formation is a sedimentary response to inception and development of the downdropping and widening Socorro paleobasin (fig. 3). The formation includes the first rocks laid down in various subbasins that later integrated to form a broad sag basin. It also includes much younger rocks on the western margin not appreciably different from the overlying Pliocene and Pleistocene Sierra Ladrones Formation. Most of Popotosa detritus is derived from caldera and caldera-related volcanic rocks of the Datil–Mogollon volcanic field, which was cut by the paleobasin. Popotosa rocks of these two measured sections were deposited near

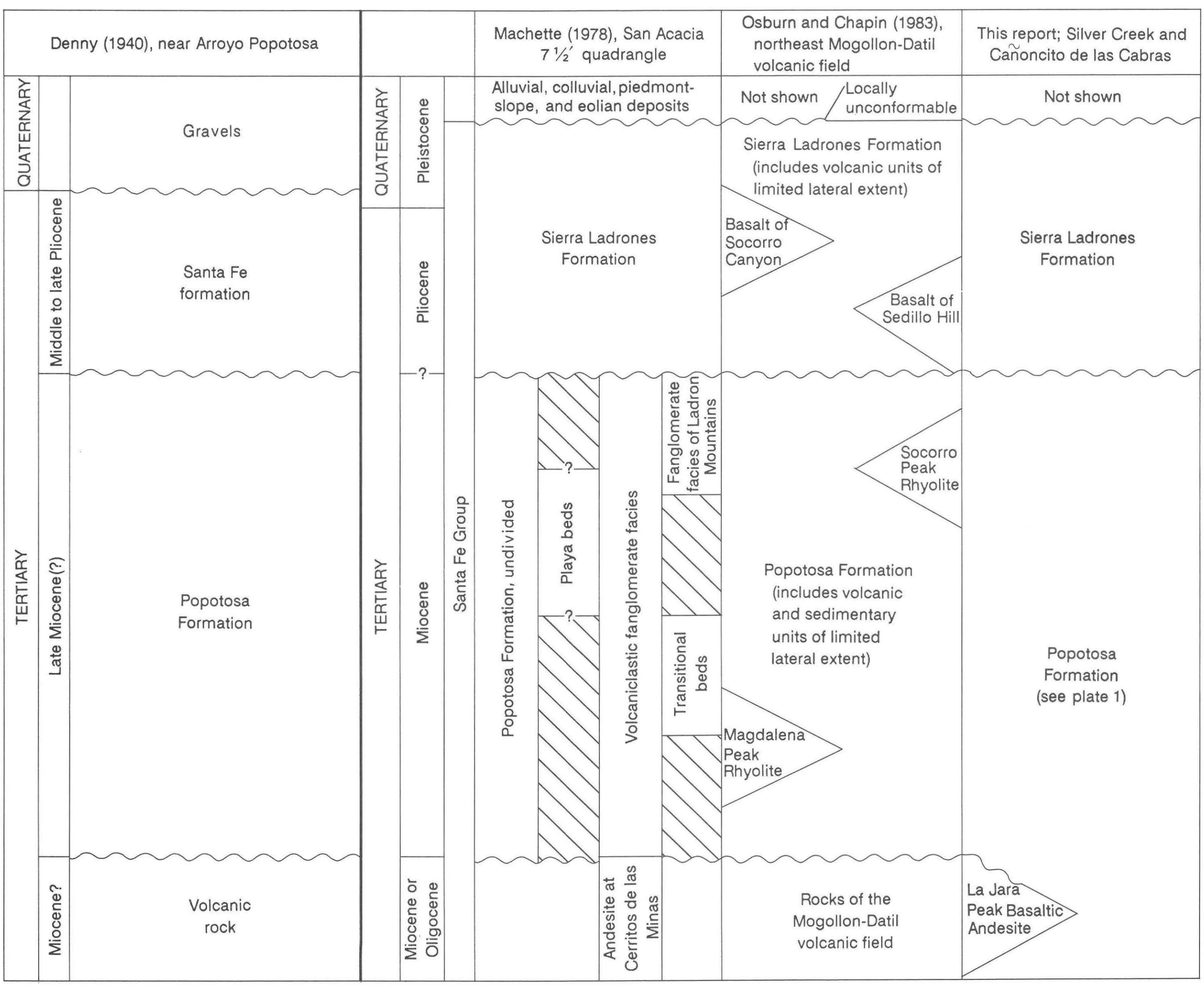


Figure 2. Popotosa Formation and Santa Fe Group names throughout Socorro paleobasin as used by various authors. Chart does not imply relative thickness or correlative age between rocks of one column and another. Wavy line, unconformity. Diagonal line pattern, no lithology of that age present.

the basin center, as indicated by their thicknesses, elevations, and older ages (fig. 4).

The Popotosa Formation is now exposed on the western side of the former paleobasin in a series of upthrown blocks, the mountain ranges shown in figure 3. Although no exposures of the Popotosa are known east of the Rio Grande, geophysical data suggest that the Popotosa is present in the subsurface (Jurdy and Brocher, 1980). Provenance studies by Chamberlin (1980) indicate that nearby sediment sources to the east existed during Popotosa time. If Chapin and Seager's (1975) inferred east edge of the paleobasin is anywhere near its actual locality (fig. 3), the Silver Creek and Cañoncito sections were deposited near the paleobasin center.

Age of the Formation

Figure 5 shows the ages of dated volcanic units in depositional or erosional contact with the Popotosa Formation throughout the Socorro paleobasin. Although erosional contacts provide limited information, an overall picture of the age of the rocks appears. The variety of volcanic ages indicates that sedimentation during Popotosa time was repeatedly affected by ashfalls, volcanic outflows, and intrusive domes. While no area remained a depocenter for the entire history of the Popotosa, these reference sections record the most complete depositional history, least complicated by local volcanism and faulting.

Machette (1978) listed a radiometric date of 26.4±0.5 m.y. for a flow of La Jara Peak Basaltic Andesite near the Silver Creek section. At the Silver Creek section, 112 m of tuff- and andesite-bearing granulestone occurs below the (same?) andesite flow. Thus, the lowermost Popotosa may predate that andesite and may well be late Oligocene in age. Chapin and others (1978, p. 122) suggested that these andesite flows accumulated on downthrown blocks during early rifting, further indicating that rocks of the reference sections were deposited near the origin of the Rio Grande rift.

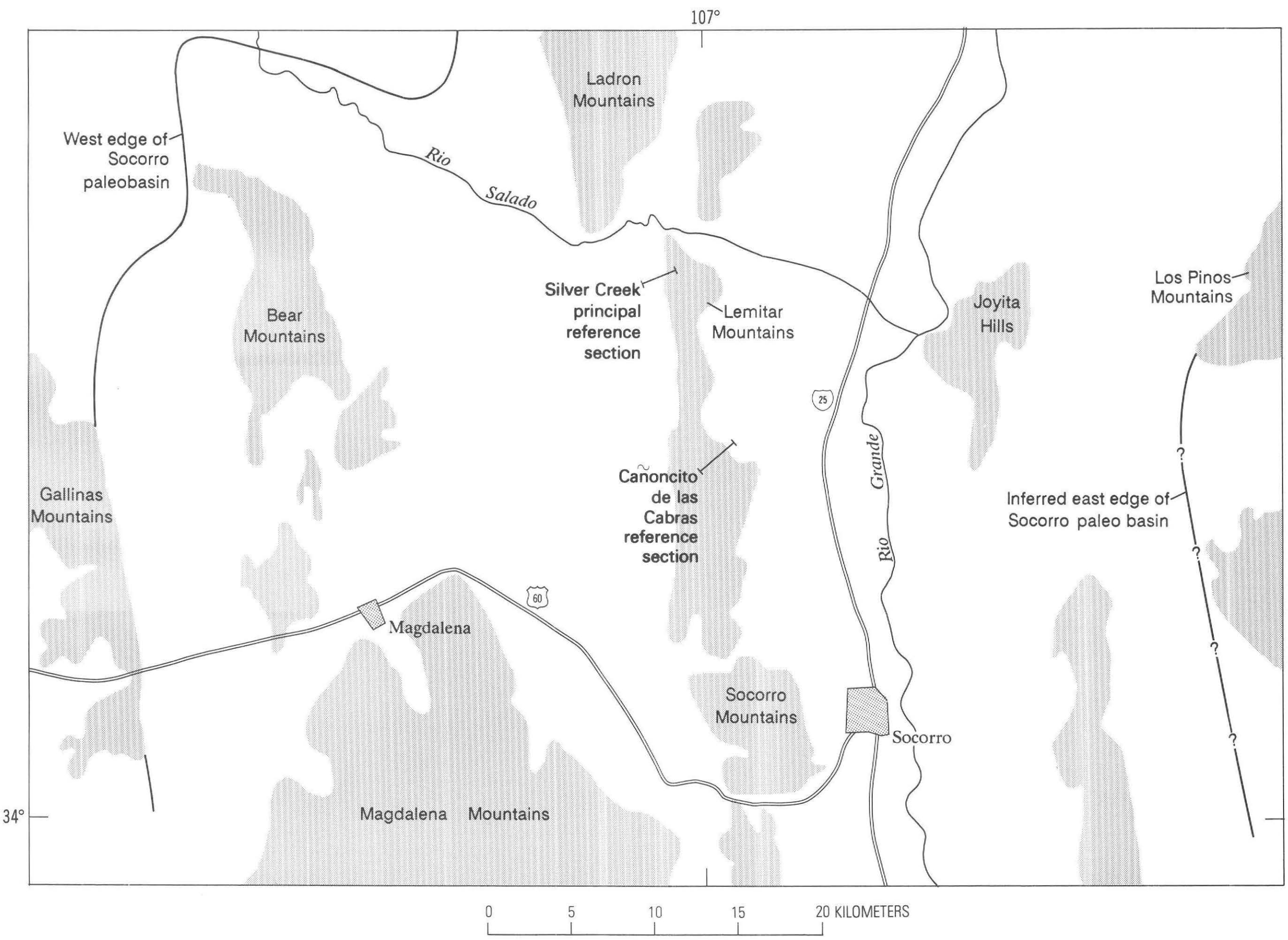
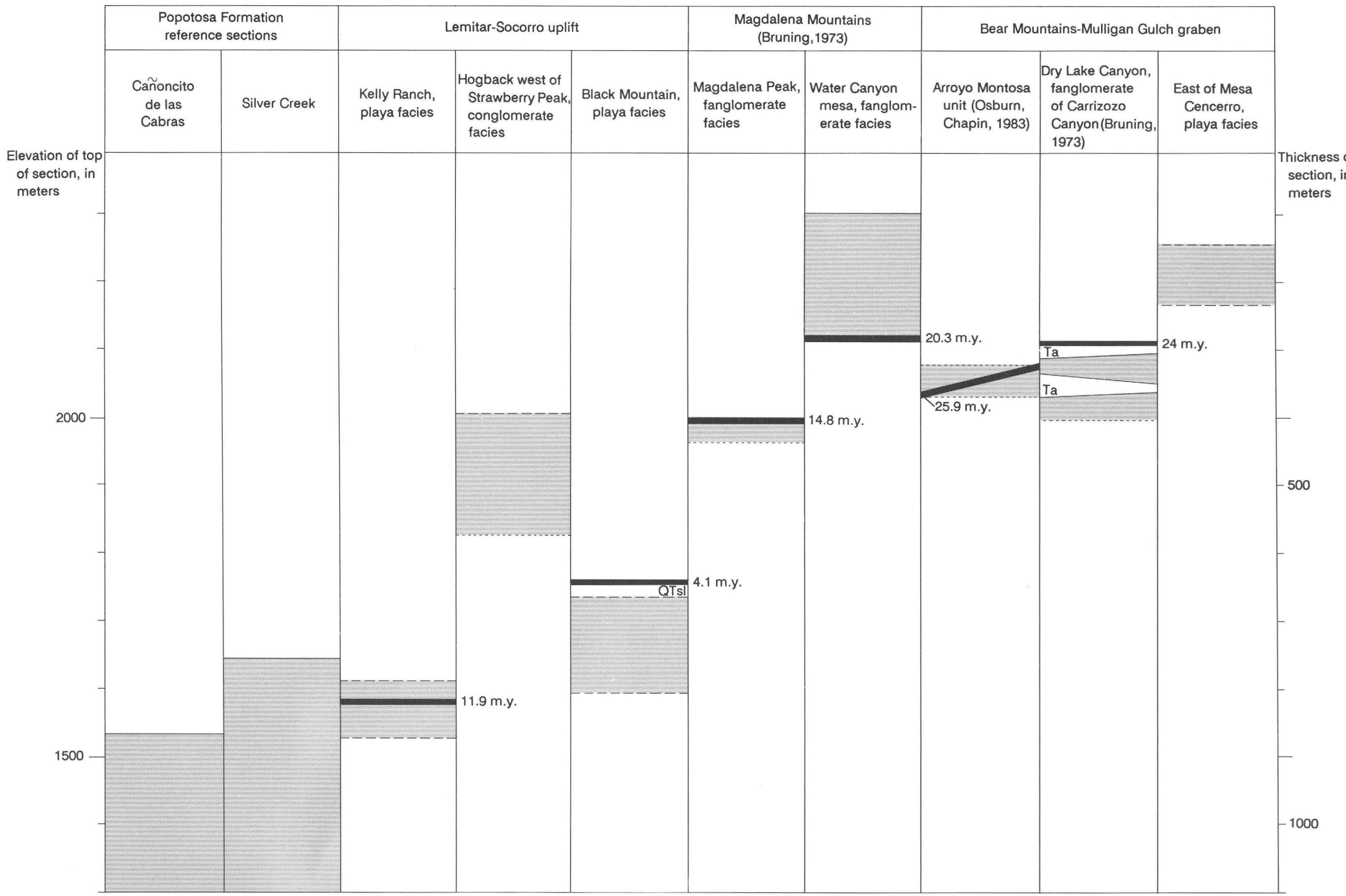


Figure 3. Schematic map showing Socorro paleobasin at its fullest development (modified from Chapin and Seager, 1975).



Popotosa Formation reference sections
Lemitar-Socorro uplift
Magdalena Mountains (Bruning, 1973)
Bear Mountains-Mulligan Gulch graben
Cañoncito de las Cabras
Silver Creek
Kelly Ranch, playa facies
Hogback west of Strawberry Peak, conglomerate facies
Black Mountain, playa facies
Magdalena Peak, fanglomerate facies
Water Canyon mesa, fanglomerate facies
Arroyo Montosa unit (Osburn, Chapin, 1983)
Dry Lake Canyon, fanglomerate of Carrizozo Canyon (Bruning, 1973)
East of Mesa Cencerro, playa facies
Elevation of top of section, in meters
Thickness of section, in meters
2000
1500
500
1000
20.3 m.y.
24 m.y.
Ta
Ta
25.9 m.y.
14.8 m.y.
4.1 m.y.
QTsl
11.9 m.y.

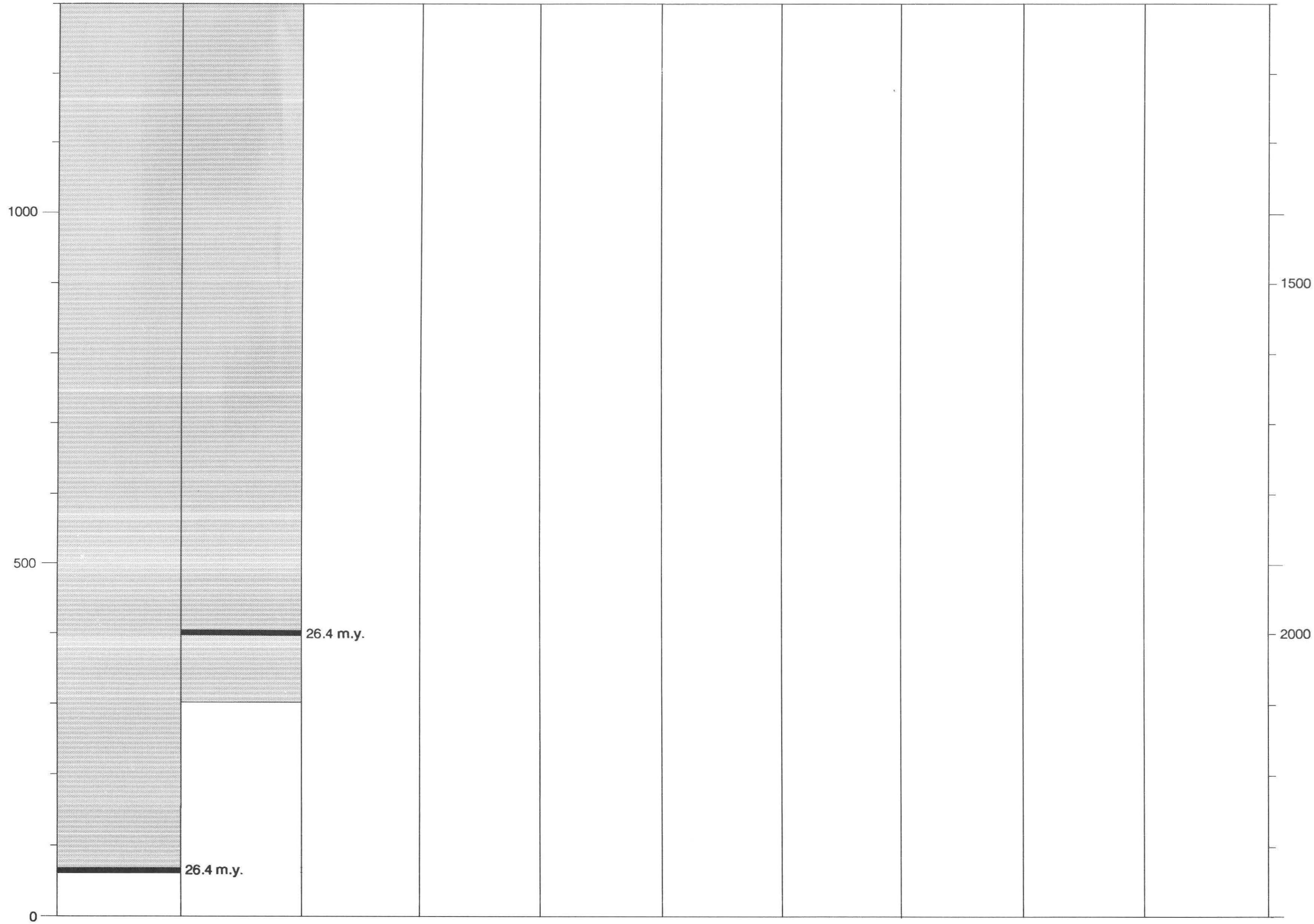
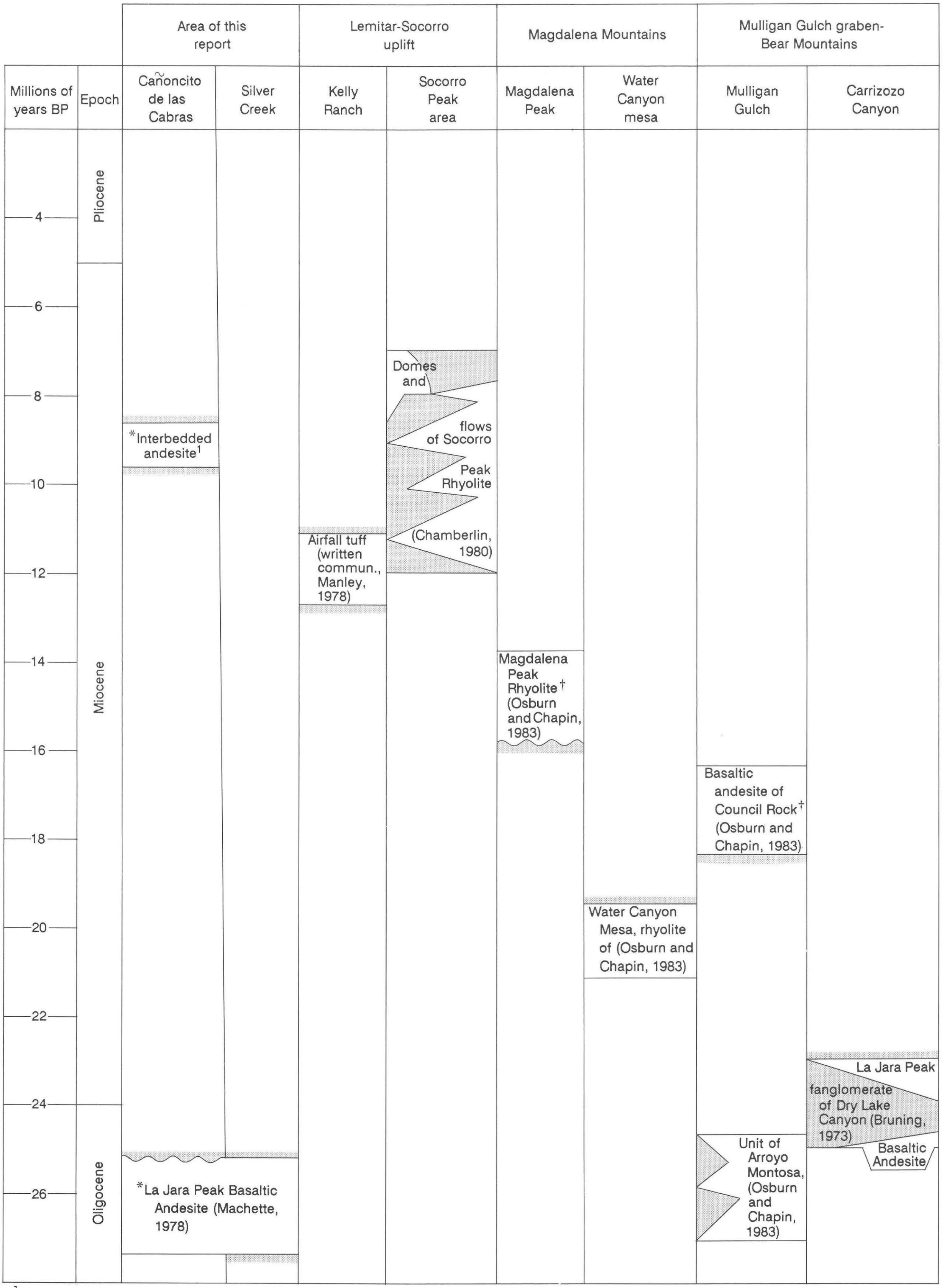


Figure 4. Elevations (left scale) and thicknesses (right scale) of Popotosa outcrops (patterned) throughout paleobasin. Thicknesses greatest near center of paleobasin (Cañoncito de las Cabras and Silver Creek reference sections); tops of those sections have lowest elevations. Elevations higher and thicknesses smaller near edges of paleobasin. Older dates of Bear Mountains–Mulligan Gulch graben suggest that it served as a separate depocenter early in Socorro paleobasin history, before it was integrated with overall basin. Dashed line, elevation or thickness estimated; dotted line, elevation or thickness inferred; heavy line, age of associated volcanic unit in millions of years; **QTsl**, Sierra Ladrones Formation; **Ta**, Tertiary basaltic andesite.



[1]Machette (1978)

Figure 5. Ages of dated volcanic rocks within or adjacent to the Popotosa Formation (patterned) throughout paleobasin. Wavy line, erosional contact between Popotosa Formation and volcanic unit. Jagged line between volcanic unit and Popotosa indicates interbedded relationship. Thicknesses of units not implied; only age range of date is indicated by thickness; *, dates from nearby flows; †, averaged dates given with range of ±1.0 m.y.

Chamberlin (1980) reported the youngest dates on the formation, near Socorro, at about 7 m.y. ago (late Miocene). Assuming more or less continuous deposition for the the entire formation, the Popotosa ranges in age probably from late Oligocene to late Miocene.

Environments of Deposition

Interpretations of environments of deposition for the units of the reference sections appear at the end of each unit. (See section, "Measured reference sections.") Plate 1 supplies a summary of those interpretations and possible correlations between the sections, as well as lithologies.

Although individual beds cannot be precisely correlated (excepting tuff 7 or 13), units or groups of units display similar sedimentary and lithologic responses to tectonic and (or) climatic events. For example, unit 8 of the Silver Creek section is the finer grained equivalent of units 5 and 6 of the Cañoncito section. Although the contact between units 4 and 5 of the Cañoncito section is erosional, that between 7 and 8 of the Silver Creek section is gradational, suggesting that the Cañoncito section was nearer the active rift-edge at that time, leading to deposition of coarser detritus.

Environment of deposition creates differences in diagenesis, as well as in original lithology. For example, units 3 through 6 at Silver Creek are generally fine grained; tuffs are zeolitic smectites characteristic of alteration in saline lacustrine lakes; and those tuffs are more numerous than seen in units 2 and 4, Cañoncito section. These factors suggest that the rocks at Silver Creek were deposited closer to the depocenter, on the playa, than were the ones at Cañoncito section.

The playas of Popotosa time show little evidence that they held standing water for long periods. No beds of salt and few examples of mudcracks, salt casts, or oscillation ripples exist. Gypsum occurs as thin vein fillings, as efflorescences, or as a few thin (0.5- to 1-cm) beds. Beds rarely contain only mudstone; most contain some silt and sand. Such a system might best be described as a dry playa.

Correlation of Lithologic Units Between Reference Sections

The difficulty in correlation between beds or units of the Cañoncito de las Cabras and Silver Creek sections that are only 11 km apart seems puzzling at first, yet their disparity may reflect the tectonic history of a rapidly subsiding rift basin. Anderson and others (1983) indicated that, early in the history of a rift basin, subbasins may exist, subject to their own local depositional histories. As subbasins coalesce or broaden, basin history becomes more uniform from place to place. But repeated back-faulting in the ever-widening rift can reactivate alluvial fan development in one area and not another. (Repeated back-faulting has led to basin-center Popotosa at greater dips, whereas western-margin Popotosa is more flat-lying; Chapin and Seager, 1975.) Playa depocenters shift with tectonic adjustments, or they may shrink and swell due to climatic variations. All these factors can limit correlation of beds or lithologic units of sections not far distant from one another.

However, the Popotosa contains several airfall and waterlaid altered ashes (tuffs). Chamberlin (1982) considered them intrabasinal, representing renewed volcanism from caldera-related vents to the south near Socorro. Both sections contain a series of several tuff beds within a few hundred meters of each other, then an interval of several hundred meters of non-tuff-bearing rock, and finally, a single tuff bed much higher in both sections (pl. 1). The uppermost tuffs in both sections appear to be equivalent to one another in terms of stratigraphic position; they represent a time line (pl. 1). The lack of direct correlation between individual tuffs lower in the sections is a function of a tuff's preservation at that outcrop's original position on the alluvial fan, flat, or playa, plus erosion and postburial alteration at that site; tuffs are more likely to be preserved in playa sediments than higher on an alluvial fan.

Interpretations of Alteration Patterns and Lithium Accumulation

The sections differ from one another in the degrees and kinds of alteration each shows. The Silver Peak section is less indurated overall, it is richer in calcite cement and gypsum near its base, and its tuff beds are altered to zeolitic smectites. The Cañoncito section is markedly better indurated and reddened low in the section, it has more siliceous cement, and its tuffs are siliceous smectites altered to greens, pinks, and yellows. The gypsum present in many beds at Cañoncito is found only in the playa sediments of unit 8. Unit 4 of the Cañoncito section contains either pisolites or accretionary lapilli deposited in limestone-altered-to-chert beds of a playa lake (fig. 6); these distinctive playa lake beds of limestone and chert are not seen at Silver Creek.

The tuffs at Silver Creek contain, by atomic-absorption and semiquantitative spectrographic analysis methods, three to ten times as much lithium, on the average, as those at Cañoncito. Plate 1 suggests that a playa was centered nearer the Silver Creek section during deposition of unit 6 at Silver Creek. A playa was centered nearer the Cañoncito section during deposition of the upper 165 m of unit 8, Cañoncito section. Thus,

Figure 6. Pisolites or accretionary lapilli, whole (W) and fragments (F), from limestone-and-chert bed, unit 4, Cañoncito de las Cabras reference section, Popotosa Formation.

accumulation of tuffs in the older Silver Creek playa provided a source for the lithium (easily leached from volcanic glass), a site for concentration (evaporative concentration on the playa lake), and a mechanism for entrapment (altering tuffs incorporating lithium into their smectite structures). The younger playa at Cañoncito did not have the source and mechanism for lithium entrapment provided by the presence of ashes.

Differences in the mineralogies of the two sections may also reflect their distances from the Socorro caldera that Chapin and others (1978) suggested was the site of a late Miocene (7–12 m.y. ago) geothermal system that created massive potassium metasomatism in the Socorro area. Part of their evidence for the geothermal system is that, around Socorro, Popotosa fan conglomerates are anomalously reddened and show high induration, as does unit 5, Cañoncito section (and, to a lesser extent, the units below it). The originally porous nature of the fan conglomerates of unit 5 would make it an excellent aquifer, with warm ground waters supplying the cementing and reddening agents of silica and iron. Lithium driven off from tuffs 1 through 6 by the thermal waters may have been transported along the tuffs to lower positions in the playa containing tuffs 1 through 12, Silver Creek section.

Definition of the Formation

The Popotosa Formation was described by Denny (1940) as a

> transition between the Miocene (?) epoch of volcanic activity and the period of basin deposition which is dominantly of Pliocene (Santa Fe) age. The formation consists of debris eroded from volcanic rocks, plus a slight amount of tuff which was contributed to the basin by relatively small contemporaneous eruptions. The formation is confined to an area on the east side of the Sierra Ladron [(p. 77). Also,] The Popotosa formation is an alluvial deposit which was laid down in an enclosed basin under arid or semiarid climatic conditions. The conglomerate, sand and sandy silt are alluvial fan deposits. The silt and silty clay accumulated in a playa, in the center of an enclosed basin* * * [p. 81 and 83].

This definition generally fits the sequences of sedimentary rocks seen in the two reference sections, but it does not address the complex relationships between volcanic outflow and sedimentary units that are characteristic in the Socorro and Magdalena areas. Osburn and Chapin (1983) have expanded the definition of the Popotosa Formation in the northeast Datil–Mogollon volcanic field to include five extrusive volcanic members, one sedimentary member, and one interbedded volcanic and sedimentary member. They elected, as have I, to retain the La Jara Peak Basaltic Andesite as a separate formation. The various members they named do not extend into the reference sections of this paper; their units' geographic extent is limited to areas around the Socorro cauldron. Likewise the individual tuffs in these reference sections have limited areal extent and cannot be tied to specific events or named units related to the Socorro cauldron.

The Popotosa Formation in the two reference sections typically consists of a mixture of lithologies from coarse conglomerates to sandstones to claystones derived from alluvial fans, alluvial flats, and playas, including tuffs from intrabasinal sources, deposited in the Socorro paleobasin or subbasins before breaching by through-flowing drainage occurred.

CONCLUSIONS

The 1,316 m of conglomerate, granulestone, sandstone, siltstone, mudstone, and tuffs of the Silver Creek principal reference section are somewhat lithologically similar to, but not sequentially or temporally identical to, the 1,447 m of rock that constitute the Cañoncito de las Cabras reference section 11 km to the south. Both sections represent deposition of detritus by mudflow, streamflow, and sheetflow on the proximal and distal portions of alluvial fans, alluvial flats, and on playas (fig. 7) in portions of the paleobasin that seldom contained bodies of standing water.

The sequences of tuffs in the reference sections provide a tool for correlation, showing that lithologies of comparable age vary significantly from one part of the paleobasin to another, even near the center of the actively subsiding Rio Grande rift.

Limited continuous exposures, few age constraints, and circum- and postdepositional tilting and erosion preclude basinwide correlation or naming of units within the Popotosa Formation.

MEASURED REFERENCE SECTIONS

The Silver Creek principal reference section and the Cañoncito de las Cabras reference section are thick and lithologically diverse. Units within each section were separated from one another, not solely on the basis of lithology (a single bed may contain three or more lithologies), but on the bases of overall color, weathering or exposure characteristics, or marked differences in grain size or bedding forms.

Individual units chosen by such criteria often reflect local tectonic events, sedimentary responses to localized storms, local ground-water conditions, or nearby source terrains. Thus units in one reference section may not be directly correlatable with units in the other; they should not be thought of as formal divisions, but as devices for breaking down unwieldy thicknesses of rock into comprehensible records of events.

Principal Reference Section—Silver Creek Section

[Approximate location of base of section 3,797,600 m north, 313,150 m east; top of section 3,798,100 m north, 310,750 m east, UTM grid zone 13, Riley 15′ quadrangle; lat 34°18′00″ N., long 107°02′30″ W., Sevilleta National Wildlife Refuge, Socorro County, New Mexico (fig. 1)]

Sierra Ladrones Formation.

Angular unconformity.

Popotosa Formation (part): Meters

9. Sandstone, granulestone, minor siltstone to mudstone, and conglomerate; gray brown to red brown. Unit forms poorly resistant small hogbacks to debris-covered surfaces. Base of unit is tuff 13; 1 m of light-greenish-gray altered tuff that grades upward into ashy sandstone. Tuff 13 is correlated with tuff 7, Cañoncito section.

   Some sandstones are tuffaceous and form noncalcareous medium- to coarse-grained salt-and-pepper beds containing pumice fragments. Other light-brown to grayish-orange-pink finer grained sandstones have calcareous and clayey cements. These two types of sandstone interbed; beds in both have broad lateral extent.

   Near the unit's top, the thick-bedded, featureless, lighter colored sandstones contain irregular-edged horizontally and vertically

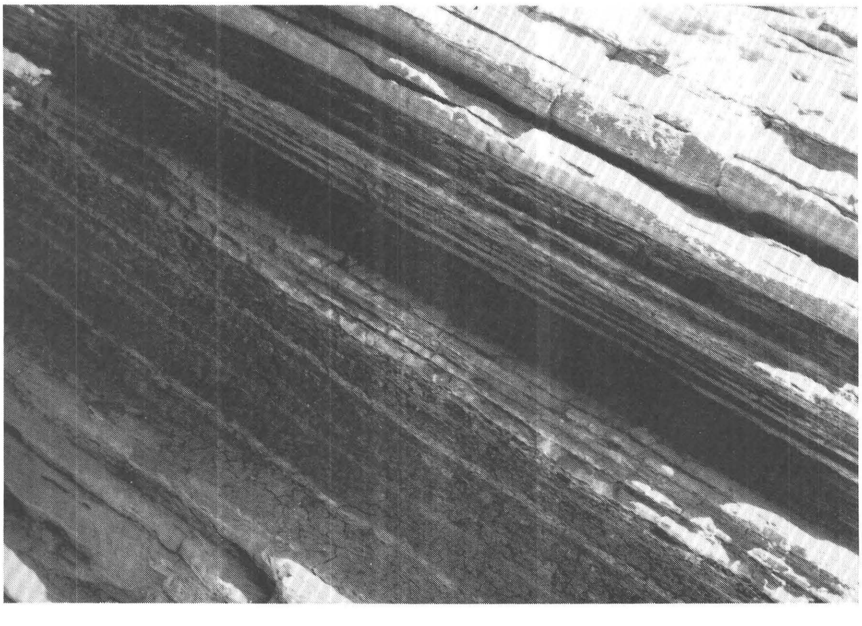


Figure 7. Silty mudstones and calcareous claystones of unit 8, Cañoncito de las Cabras reference section. Great diversity of rock types is characteristic of both this section and the Silver Creek principal reference section. Lens cap is 5.5 cm across.

Popotosa Formation (part)—Continued Meters

oriented patches of darker, coarser sandstone 5–30 cm wide or long that resemble burrows. Clasts in a rare conglomeratic channel were 34 percent unknown igneous rock (trachyte?), 30 percent andesite, 20 percent dark-red welded tuff(?), 10 percent siltstone, and 5 percent gray welded tuff.

Near the base of the unit are faintly laminated red-brown siltstones to mudstones containing (formerly) vertical burrows and horizontal trails (now tilted). These beds are 10–15 cm thick with 3–10 m lateral extent and interbed with the sandstones.

The unit is cut by channel-form beds of sandstone and granulestone that occur in tangential and planar low-angle crossbed units as much as 60 cm thick and 3 m wide.

Alluvial-flat mudstones and siltstones grade upward into distal alluvial-fan beds with two types of sheetwash, perhaps reflecting different source terrains. Lenticular fan-channel deposits cut through the more planar sheetwash beds, and the overall upward-coarsening effect represents renewed uplift on the basin margin ....approximately 160

8. Upward-fining unit composed of sandstone, granulestone, less than 15 percent conglomerate, and a few mudstone beds; pale red to pale reddish brown. Thick irregular beds and channels form prominent cliffs and hills with deep slotlike canyons. Unit may be a finer grained equivalent of units 5 and 6, Cañoncito de las Cabras reference section, this report.

The sandstones are medium to fine grained, moderately well cemented with calcite and clay, and show iron staining along bedding planes. Bedding is indistinct to featureless; beds are 5–90 cm thick.

Reverse- to normally graded beds of coarse sandstone to granulestone extend a few meters horizontally and are 10–20 cm thick. They appear darker than surrounding rocks because of their higher detrital andesite content. Within these broad, thin beds are clasts of milky quartz as much as 1 cm wide.

The conglomerates' composition is approximately 80 percent welded tuff, 15 percent andesite, and about 5 percent gneiss, granite, and quartz, perhaps derived during the unroofing of the Ladron Mountains to the north (fig. 1). Conglomerates occur in thick, irregular, laterally continuous beds.

Channels 60–80 cm deep and about 5 m wide contain about 70 percent andesite as larger clasts; the remainder are smaller clasts of welded tuff and unidentified clasts. Clasts are supported by a granulestone, sandstone, and mudstone matrix; imbricated clasts dip from the southwest to the northeast.

Popotosa Formation (part)—Continued Meters

Proximal to distal alluvial-fan deposits characterize this unit. The thick, irregular beds of granulestone that fine upward represent deposition in response to regional basin-margin uplift that also produced unit 5 in the Cañoncito de las Cabras section. Andesite channel clasts suggest that the uplift or the resulting erosion reexhumed a valley-center La Jara Peak Basaltic Andesite body such as that below unit 2, this section........approximately 395

7. This unit is characterized by poor exposure because Silver Creek and a tributary flow along its strike. Exposure varies from nonexistent to perhaps 60 percent exposed near the unit's top; beds that do rise above the alluvium are mainly well cemented sandstones, granulestones, and conglomerates; gray brown to pale red to pale yellowish brown. Unit is lithologically similar to unit 6, and it reddens upward into unit 8. The transitional nature of units 6, 7, and 8 is further reinforced by upward coarsening in 7.

Sandstones are pale red to yellowish brown, friable, calcareous cemented, fine to medium grained, poorly sorted and subangular. They form 60- to 100-cm-thick beds that pinch and swell and contain some low-angle planar crossbeds.

The sandstones may be cut by broad channels filled with coarse granulestone-to-conglomerate. These granulestone-to-conglomerate channels are normally graded and contain a mud- to silt-sized matrix. Grains within them may be clast or matrix supported. Pebbles within channels consist of 60–70 percent smaller clasts of welded tuff; the remainder are larger, better rounded andesite cobbles as large as 10×30 cm. At 283 m above the base of the unit, one clast of quartzite was noted in a channel, suggesting unroofing of the Precambrian-cored Ladron Mountains to the north.

Fluvial and mudflow channels derived from farther up the fan surface were incised into the broad sheetwash deposits of midfan. The continued presence of large, well-rounded basaltic andesite cobbles in channels suggests that an andesite body remained exposed nearby.........322

6. Unit is characterized by a deeply incised badlands topography in which clay may drape underlying rocks, and sandstone or coarser fractions may stand out as sharp flatirons. Tuff beds form brilliant white zigzags across the landscape.

Three cycles of generally upward coarsening mudstones, sandstones, and granulestones and conglomerates; pale yellowish brown in finer fractions, to gray brown, to dark reddish brown in coarser fractions. Cycles are, from bottom to top, 48, 45, and 102 m thick. Unit contains 12 altered tuffs consisting of swelling clays and zeolites. Gypsum and mudcracks are present in the first cycle, and the unit contains sparse to abundant mica flakes, both in tuffs 2 through 10 and in adjacent clastic rocks. Pumice shards are sparsely admixed into any of the lithologies.

Cycles begin with basal, thin, laterally continuous silty mudstones. Some swell upon weathering, and some have calcareous cement. Mudstones may be yellow gray, gray brown, or red brown and may contain ripplemarks. Small lenses of sandstone in the silty mudstones grade upward into more continuous thin, and then thicker, beds of light-gray, yellow-gray, and gray-brown, lithic- and biotite-rich laminated sandstones. These sandstones are moderately indurated, clay and calcite cemented, and may show soft-sediment deformation and burrowing. These sandstones are similar to type-2 sandstones in unit 7 of the Cañoncito de las Cabras reference section (see p. 17 for definition).

Cycles pass from type-2 sandstones upward to thinly laminated red-brown to dark-brown stringers, lenses, beds, and channels of fine-grained, well-indurated, calcareous-cemented sandstones similar to those called type 1 in unit 7, Cañoncito de las Cabras reference section. Asymmetric ripples suggest sediment transport from the west-southwest. Vertical burrows, churned beds created by biota or loading, and ripple marks are common in the middle portions of the cycles.

The top portion of each cycle consists of granulestone beds and a few matrix-supported conglomerates similar in appearance to type-2 sandstones; these are interbedded with a few silty mudstones. The top portion of each cycle shows no crossbedding, loading, ripples, or burrows. Lastly, the top of the uppermost cycle contains an increased percentage of andesite clasts.

The contact between the uppermost conglomerate and the overlying finer lithology of the next-higher cycle is abrupt but nonerosive, representing continuous deposition. These upward-coarsening cycles are similar to those of the Hornelen Basin, Norway (Steel and others, 1977), which are ascribed to repeated faulting along the basin margin. Stream-transported sandstones of distal alluvial fans overwhelmed playa sediments, followed by ever-coarser fractions as larger fans with coarser materials built out over the former playa surface. Most of the rocks above the playa mudstones show soft-sediment deformation and vertical burrows, suggesting they were deposited within the water table of the former playa. The last cycle's increased andesite clast content suggests that faulting or erosion had reexposed a buried La Jara Peak Basaltic Andesite body.

The 12 altered tuff beds are white, yellow green, yellow white, gray white, and light brown. They vary from 5 to 120 cm thick; most of the purely tuffaceous portions are 30–40 cm thick. Their bases are in sharp depositional contact with underlying units; their tops usually grade upward into tuffaceous mudstones to sandstones. Mudstone balls may occur in the tuffs. Pumice shards and balls occur in any lithology and in the tuffs themselves. The tuffs grade upward into detrital units showing complex flaser bedding, interlaminations and crossbedding, pumices aligned on parting surfaces, and differential loading. C.H. Maxwell (oral commun., 1981) suggested that these tuffs grading into waterlaid sediments may have been created by the torrential rains that commonly follow volcanic eruptions.

The tuff beds are altered to mixtures of swelling clays; talclike, shardy, or porcellaneous zeolites, primarily clinoptilolite; and varying amounts of siliceous and calcareous cements 195

5. Sandstone, granulestone, conglomerate, and rare muddy siltstones; light brownish gray to grayish pink on fresh surfaces; pale red to pale yellowish brown on weathered. Unit passes from cliff-forming beds in lower 9 m to more diversely laminated and less well exposed beds in upper 24 m. Sandstones and granulestones form lenses and planar units; matrix-supported conglomerates generally occur in channels. Rare muddy siltstones form planar thinly laminated beds with 20–1,000 m lateral extent in uppermost third of unit.

The bottom 9 m of the unit contains thinly laminated (0.5–cm), thick-bedded (5- to 50–cm) sandstone, granulestone, and (rare) conglomerate. Sedimentary features include formerly vertical burrows and horizontal trails, normal grading, soft-sediment deformation, and low-angle and low-amplitude crossbeds. Sandstones are light brownish gray, fine to coarse grained, contain abundant lithic fragments, and are moderately indurated by clayey (tuffaceous?) cement.

The top 24 m is thinly to thickly (0.5- to 40–cm) bedded, poorly sorted to normally graded sandstones and granulestones that become more muddy upward. Coarser sandstone and granulestone beds contain lenses less than 3 m wide and show some soft-sediment deformation.

The finer grained red-brown rippled and ripple-crossbedded sandstones are better indurated and show soft-sediment deformation and vertical burrowing; they are similar to the type-1 sandstones in unit 7, Cañoncito de las Cabras reference section.

The thinly laminated, normally graded, less well indurated muddy siltstone-to-sandstone beds near the top of the unit contain stringers of sandstone and mudstone; they are laterally continuous over tens of meters, except where cut by channels.

Conglomerate-filled channels in the upper 24 m decrease in size and number upward. Conglomerates of approximately 70 percent basaltic andesite (largest clasts) and 30 percent welded tuffs and unknowns float in a matrix of granulestone and muddy sandstone. Pebble imbrications in one channel dip to the east-southeast.

The unit reflects deposition of coarse to fine alluvial-fan and alluvial-flat material into a playa, as indicated by burrowing, soft-sediment deformation, rippling, laminations, and normal grading. The better and less well indurated sandstones suggest the interplay of fluvial and sheetflood deposits, respectively, on the distal portions of a fan or fans. Stringers of laminated and graded muddy siltstone-to-sandstone intervals may represent overbank deposits on the fan, or temporary resurgence of playa conditions. This unit is similar in appearance to unit 3, this section 33

4. Heterogeneous mixture of primarily sandstone, conglomerate, and granulestone at base, fining upward to mainly muddy sandstone at top of section; unit is grayish orange to grayish orange pink. Forms moderately to poorly exposed (clay-draped) cliffs to slopes with indistinct bedding. Base of unit shows reworking of materials from unit 3 into gravel-filled channels. Channels of sandstone and conglomerate are common throughout unit, becoming smaller and finer grained in the top third.

The conglomerate channels near the base contain cobbles less than 20 cm in diameter of about three-quarters andesite and a quarter welded tuff. Channels in the upper third are less than a meter wide and are about 20 cm deep; the pebbles contained therein are less than 7 cm in diameter, are subangular to subround, and are matrix supported. These pebbles are 60–70 percent basaltic andesite; the remainder are welded tuff.

A third variety of red-brown sandstone channels, greater than 10 m wide and less than 40 cm thick, contains asymmetric ripples and low-angle crossbeds; ripple orientation suggests water flow from west to east.

The laterally continuous lithologies include massive, thin-bedded, medium- to fine-grained, angular to subangular, quartz-poor and andesite-rich sandstone that is light gray on fresh surfaces and weathers to pale red with areas of green alteration. Also occurring are friable, poorly indurated, mud-cemented sandstones in which the clay weathers out to form clay drape. Thinly laminated to massive silty grayish-orange-pink mudstone forms stringers-to-beds in medium-light-gray clay-rich fine sandstone.

Unit 4's upward-fining sequences are cut by channels of sandstone and conglomerate that also become smaller and finer grained upward. This suggests alluvial fan deposition on a lessening gradient. The high clay content in the sandstone indicates poor sorting of materials delivered to the distal ends of fans or to an alluvial flat by distributary channels 60

3. Primarily silty mudstones and sandstones containing conglomeratic lenses, pale-red to grayish-pink on fresh surfaces. Unit weathers to brownish gray to grayish red purple; it forms sandy, clayey, poorly exposed slopes and platy to spherical knobs and chunks of sandstone. The unit's well-indurated and sparkly nature and its distinctive knobs, plates, and chunks are due to overgrowth by calcite and (or) gypsum cements.

The mudstones are slightly silty and calcareous, thinly laminated, and break into blocky fragments. The sandstones are medium to fine grained, subangular, and have calcareous cement; they contain quartz, feldspar, andesite lithic fragments, and granules of various compositions. Sandstone beds are thin (2–5 cm) and either pinch out over less than 20 cm or extend for more than 5 m. Ripple crossbedding in the sandstones was seen. A channel 70 cm deep by 15 m wide contained 80 percent basaltic andesite cobbles as much as 20 cm in diameter and about 20 percent welded tuff. Crude pebble imbrications dip to the east-northeast.

The mudstones and sandstones were deposited on a dry playa or alluvial flat subject to sporadic deposition of coarser sediments from nearby alluvial fans. The channel of mainly basaltic andesite cobbles represents storm runoff from a local exposure of La Jara Peak Basaltic Andesite, probably to the east 34

2. Sandstone, granulestone, and conglomerate at base grading up into half sandstone, granulestone, and conglomerate and half clayey sandstone at top; pale red to grayish red on fresh surfaces. Thick (15 cm to 1 m) interlayered beds at base contain low-angle crossbeds, featureless beds, and normally graded beds; unit passes upward into thinner, more laterally continuous beds. Granules of andesite occur together in green-altered forms and unaltered forms.

Popotosa Formation (part)—Continued Meters

Sandstones are well sorted, slightly calcareous, lithic rich, and form thinner beds than those mentioned in the previous paragraph. Granulestones and conglomerate clasts appear to float in a noncalcareous sandy, clayey matrix. Average composition of clasts at base was estimated to be 60 percent basaltic andesite, 35 percent welded tuff, and 5 percent other rock types. Pebble imbrications at base dip to the west.

Unit is in unconformable, angular, and sometimes-faulted contact with the underlying La Jara Peak Basaltic Andesite. This upward-fining sequence of alluvial-fan to alluvial-flat rocks was deposited rapidly over the volcanic flow. The angular unconformity, the relatively high percentage of welded tuffs in granulestones and conglomerates that directly overlie andesite, and the western source implied by pebble imbrications at the base of the unit suggest that rapid tectonic uplift of the basin margin to the west inundated the exposed La Jara Peak Basaltic Andesite 5

La Jara Peak Basaltic Andesite, approximately 300 m thick; within but not part of Popotosa Formation (figs. 8, 9). Unit shows individual west-dipping tongues of autobrecciated and stacked flows ½ to 3 or more meters thick. Zeolites and calcite fill small gas cavities; alteration of the basaltic andesite to an unknown green mineral occurs in patches and blebs.

Popotosa Formation, lower part:

1. Granulestone, grayish-orange-pink to red-brown. Thick (1- to 2-m) beds of featureless to crudely normally graded, 1-mm to 1-cm, subangular clasts of altered andesite and welded tuff are suspended in a matrix of red-brown siltstone and mudstone. Proportion of welded-tuff clasts increases upward. Top of unit is in nonangular, but unconformable, contact with La Jara Peak Basaltic Andesite. Base of unit is in fault contact with unknown portion of Popotosa Formation.

   Unit contains remnant of a formerly vertical intrusive basaltic andesite dike that appears to have fed the overlying La Jara Peak Basaltic Andesite flows. Rust-colored clay alteration of beds in contact with the dike extends as much as 50–100 cm into the granulestone. Likewise, alteration and bleaching by the overlying basaltic andesite body extend about 1 m down-section into unit 1 of the Popotosa.

   The graded granulestone clasts floating in a siltstone and mudstone matrix suggest rapid deposition of sediment into a trough near the basin center that later held the considerable thickness of basaltic andesite. The presence of the dike within the unit suggests the source of the La Jara Peak was nearby. Because the granulestone clasts are welded tuff and andesite, the basaltic andesite flow that overlies unit 1 and its associated dike is not the oldest basaltic andesite in this portion of the paleovalley 112

Total thickness of Popotosa Formation, not including La Jara Peak Basaltic Andesite 1,316

Unmeasured Popotosa Formation of unknown stratigraphic position in fault contact with unit 1.

Reference Section—Cañoncito de las Cabras Section

[Approximate location of section NW¼SE¼ sec. 13, T. 1 S., R. 1 W. and secs. 17 and 18, T. 1 S., R. 2 W., Magdalena 15′ quadrangle and Lemitar 7½′ quadrangle; lat 34°13′30″ N., long 106°59′00″ W.; Socorro County, New Mexico (fig. 1)]

Quaternary stream alluvium.

Angular unconformity.

Popotosa Formation (part): Meters

8. Siltstone, mudstone, and sandstone, grayish-red, light-olive-gray, moderate-olive-brown, grayish-brown, and red-brown. Unit becomes more gypsiferous and sandstone rich upsection. Lithologies interbed and grade from one to another vertically and laterally. Unit is poorly to moderately indurated and weathers to subdued flats mostly covered with smectitic clay intermixed with loose sand and silt.

   Siltstones are thin bedded, grayish red to red brown, thinly laminated, and contain calcareous cement. Beds extend laterally over more than 100 m. Mudstones are olive brown, gray brown, and red brown and often contain silt-sized grains and vein-filling gypsum; they are finely laminated and their cement may be slightly calcareous. The sandstone beds resemble type-2 sandstone beds from unit 7 (defined in this reference section) and are cemented with gypsum and calcareous and clayey cement. Some sandstone beds contain bright-orange-red grains of unknown composition.

   Base of unit is chosen at top of last type-1 sandstone; increasing gypsum and very poorly indurated sandstone upsection from the last type-1 sandstone represents the fullest development of the detritus-rich playa. Some of the sandstones may be of eolian origin; rarely did water stand on the playa 165

7. Interbedded sandstone, siltstone and mudstone, and conglomerate and granulestone that weather to subdued light and grayish tones of brown, orange, red, pink, olive, green, and

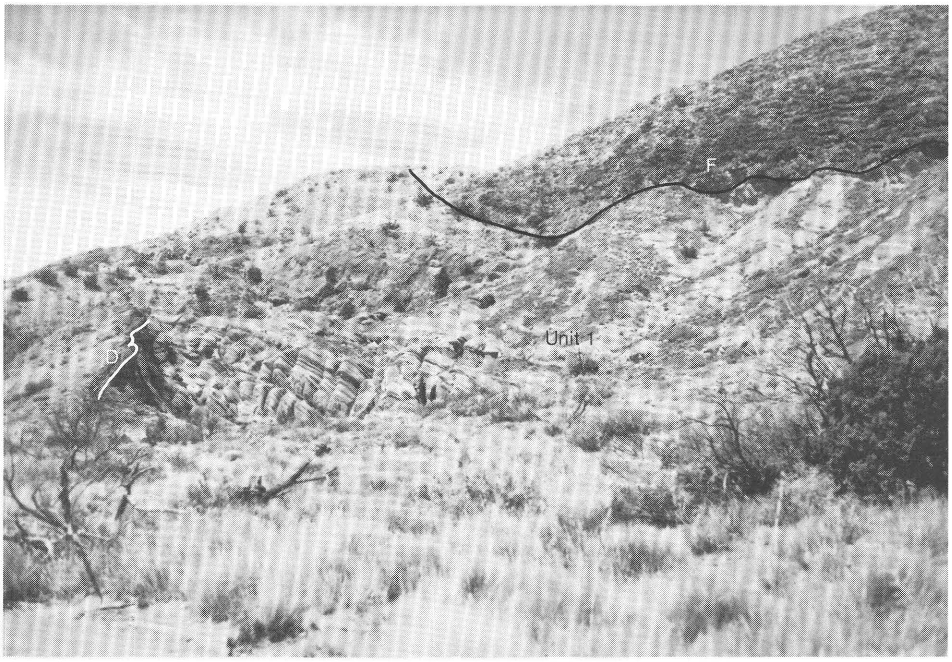


Figure 8. Silver Creek principal reference section showing intrusive nature of basaltic andesite dike (D) into unit 1 of Popotosa Formation that underlies flow of La Jara Peak Basaltic Andesite (F). These relationships suggest that the beginning of the Popotosa Formation and, hence, opening of the Socorro paleobasin may be as early as late Oligocene in age.

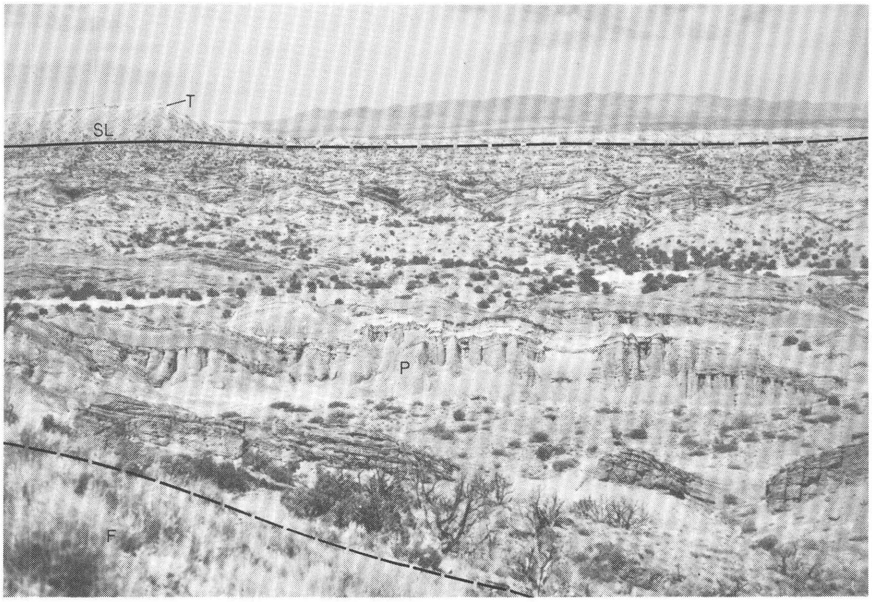


Figure 9. Overview of Silver Creek principal reference section showing flow of La Jara Peak Basaltic Andesite (F); units 2 (above F) through 9 (below SL) of the reference section (P); Sierra Ladrones Formation (SL); and capping travertine bed (T). Altered tuffs in unit 6 show up as white beds. Contacts dashed where indistinct or approximate.

yellow. Unit is about one-quarter covered by slightly smectitic clay and detritus and forms low hills and swales; individual beds or packets of well-indurated sandstone or conglomerate and granulestone may form distinct hogbacks. Unit is in gradational contact with underlying unit 6 and is differentiated from it by its poorer exposure and induration and by its increase in finer detritus and the presence of thin gypsum laminae.

Conglomerates decrease and type–2 sandstone beds, mudstone beds, and gypsum increase in occurrence upsection. At 160 m above its base, no more conglomerates exist. Although vein-filling gypsum appears at 30 m above the base, thin laminae of gypsum first occur at 115 m.

The sandstones and few remaining conglomerates develop into two fairly distinct lithologies (types 1 and 2) at about 160 m above the unit's base. Type 1 is a red-brown to orange-pink, thinly laminated to graded to featureless, medium- to fine-grained, moderately sorted, calcareous-cemented well-indurated ridge-forming sandstone or conglomerate. Composition is quartz, feldspars, dark minerals, and some flakes of biotite. Some beds contain coarse pyrite grains that weather to rust stains. Type–1 sandstone shows ripple crossbedding, current lineations on parting surfaces, and soft-sediment deformation features. The ripple crossbedding and lineation features indicate current directions from the south and from the east. Type–1 sandstones grade from beds with wide lateral extent upward into channelized deposits.

Type–1 conglomerates and granulestones are clast supported; their beds are mainly 2 m or less thick; they form channels or laterally continuous beds. Clasts are generally welded tuffs and subordinate basaltic andesites 2 cm or less in diameter. Type–1 sandstone decreases to about 10 percent by 300 m above unit's base. Channel deposits may show reworking of angular type–1 conglomerate clasts into poorly consolidated type–2 matrix.

Type–2 sandstone and its subordinate granulestone and conglomerate beds are lighter colored than type–1 beds; they are light olive gray, grayish orange pink, and light brownish gray. They are poorly to moderately indurated and are porous. Their cement is calcareous; the grains appear to nearly float in a matrix of clay, gypsum, and altered tuff(?). Sandstone grains are medium, subangular, and contain abundant lithic fragments and pumice grains. No micas were seen. The conglomerates of type 2 are crossbedded (planar crossbeds 20–60 cm high) to featureless beds 1-3 m thick and 20–30 m wide. The clasts (generally less than 1 cm long) are supported by a matrix of type–2 sandstone or granulestone. Type–2 beds are moderately exposed to covered; they weather to detritus-covered swelling clay-containing slopes and swales.

Siltstone and mudstone beds are dark greenish gray to grayish brown and weather to grayish red. They are noncalcareous to slightly calcareous and show gradations in composition of, and interlamination between, siltstone and mudstone end members. These lithologies increase upward in thickness and abundance and make up 60–75 percent of the upper third of unit 7. Some siltstone and mudstone beds are well indurated, 1 to 2 cm thick, and extend tens of meters laterally. These beds weather to poorly exposed to covered slopes and swales blanketed by detritus and swelling clays.

Tuff 7, lying 300 m above the base of the unit, is a distinctive moderate-yellow altered tuff about 1 m thick, grading up into another meter of interlaminated tuff and detritus. This "golden ash" weathers to a flaky or chippy piecrustlike clayey, zeolitic material with a talclike texture and puffy surface. It is slightly calcareous on fresh surfaces, but not on weathered surfaces.

Unit 7 is transitional with and fines upward from unit 6. It is also transitional with unit 8, becoming ever more fine grained and gypsiferous near the top.

The two distinct types of sandstone were deposited in two different environments. Type–1 sandstones, granulestones, and conglomerates represent cleaner stream-channel detritus deposited in the alluvial-flat to playa environment. Type–2 sandstones, granulestones, and conglomerates are sheetwash deposits that spread over the unit in response to storms. The siltstone-to-mudstone beds and gypsum are characteristic of the playa facies. Unit 7 is characteristic of alluvial-flat to playa beds 417

6. Conglomerates, granulestones, and sandstones; intermediate in composition and proportions between units 5 and 7. Unit passes upward into less conglomeratic zones containing soft, light-gray-brown, poorly indurated, tuffaceous(?) sandstone. Cement is noncalcareous to slightly calcareous. Midway in the unit, rocks are about 80 percent granulestone and sandstone. Unit is appreciably grayer—pale yellowish brown—than is unit 5. Forms broken cliffs and rounded exposed hills of limited lateral extent.

Conglomerate clasts are generally smaller and grayer than those in unit 5; largest cobble seen was 12×6 cm. Clases are either in grain-to-grain contact or are supported by a matrix of noncalcareous sandy claystone. Some andesite clasts weather pervasively to dusky yellow green, yet adjacent andesite clasts may show no alteration. Half to three-quarters of all tuff clasts are broken. Conglomerate beds are less than 1 to as much as 5 m thick and may extend 5-30 m laterally.

Granulestone and sandstone beds may show 35- to 40-cm-thick sinusoidal crossbeds indicating currents generally from the south; they are laterally continuous over 3-10 m and have a noncalcareous to slightly calcareous, clay-rich cement. Sandstones are thickly to thinly bedded (5 m to 20 cm), finely laminated (0.5-4 cm), and contain quartz, feldspars, lithic fragments, and traces of mica.

Unit is distinctly less red than unit 7, and its base and top are gradational with units 5 and 7. It becomes less conglomeratic, less oxidized, and more calcareous upward, suggesting either progradation of distal-fan, alluvial-flat, and playa deposits onto the midfan; or unit 6 may indicate a decrease in overall basin-edge relief, leading to decreased grain-size and sediment load on the fan.

The high proportion of broken tuff clasts may represent frost-wedging of a colder climatic period. The sinusoidal crossbeds and fine laminations high in the section suggest current flow of suspended material such as streams might carry into a playa 96

5. Conglomerate, pale-reddish-brown to light-brown; unit lies in erosional but angularly conformable contact with underlying unit 4 and in gradational contact with unit 6. Unit contains no visible ash. Its high degree of induration (breaks primarily through large clasts), reddening, and thick bedding forms distinctive massive cliffs and deep slotlike canyons. Unit 5 may be a coarser grained equivalent of unit 8, Silver Creek principal reference section.

Broad sheets 1-2 m thick of coarse conglomerate (fig. 10), containing 10- to 20-cm subangular to subrounded cobbles, made up of 90 percent welded tuff and 10 percent scoriaceous basaltic andesite. This conglomerate grades up into pebble conglomerate of welded tuff. The scoriaceous cobbles are among the largest sized fraction (up to 40 cm) and show no downward size gradation; they make up less than 1 percent of the unit's clasts yet are 10-20 percent of the largest size fraction. Upward within the unit are granulestone and sandstone channels 50-70 cm deep and 1-3 m wide.

Within individual beds, the unit becomes redder as grain size decreases and as clay content increases. Clasts appear to float in a matrix at the base of beds; higher within the individual beds, the clasts may be in grain-to-grain contact in a matrix of noncalcareous granule-rich sandy claystone. Feldspars in andesite clasts show alteration to green chalky secondary minerals near the top of the unit.

Unit reflects deposition on the proximal portions of alluvial fans. The reddening is characteristic of well-oxidized sediments deposited by sheetflow and mudflow near the apices of fans. The erosional contact with underlying unit 4 suggests that the unit represents sudden renewed deposition from an uplifted basin margin into a lowered closed basin. The tendency of the coarsest conglomerate to float in the matrix argues against sieve deposition as a mechanism for accumulation. The presence of well-defined channels and finer materials higher in the section suggests lowering of gradient and development of channel flow as time passed. The presence of large, uniformly-sized basaltic andesite boulders suggests a nearby source was (re)exposed such as that above unit 1, Silver Creek principal reference section 95

4. Interbedded conglomerates, granulestones, sandstones, siltstones, and mudstones in approximately equal proportions; and three tuff beds. Altered ash and pumice may be admixed into other lithologies, making them grayer and more poorly consolidated. Unit's beds are thinly laminated to featureless or may show planar and low-angle crossbedding; coarser fractions occur as broad, thin sheets and channels. Unit is similar to but more tuffaceous than unit 2; its exposure is poorer than unit 2's.

Pisolites or accretionary lapilli are found in a distinctive 30-60-cm-thick limestone-to-chert bed of this unit. The oblate spheroids are compressed horizontally, with long axes from 0.5 to 1.3 cm wide. Fragments of broken spheroids are scattered throughout the bed, which is an upper and a lower limestone that passes laterally into a massive multicolored chert that also contains spheroids. Individual spheroids are made up of an apparently homogeneous core of material now altered to micritic limestone, or later chert, surrounded by thin, unevenly concentric rings of darker limestone, cherty limestone, or chert. The spheroids and their fragments occur in unlaminated or faintly laminated masses now cemented together with multicolored silica or dark-gray limestone. These spheroids are large by the standards presented by Moore and Peck (1962) for accretionary lapilli. However, the source for these possible accretionary lapilli is the nearby collapse vents of the Socorro caldera only 10-15 km to the south of the beds. A dark tuffaceous layer between the limestone beds and the presence of altered ash above the limestone-and-chert bed suggest that the unit was

Figure 10. Units 4 and 5, Cañoncito de las Cabras reference section. 30-60-cm-thick chert bed, **C**, in 4 and the coarse conglomerate beds of 5 show distinctive weathering. Contact between them (dashed line) is indistinct in photograph due to its erosional nature. Distance from chert bed to base of unit 5 is 80 m true section thickness.

Popotosa Formation (part)—Continued | Meters

originally tuffaceous. The limestone-and-chert bed shows 3 km of extent along its strike (M.N. Machette, oral commun., 1983).

Moderate-olive-brown to brown granulestones and conglomerates contain 90 percent welded tuff clasts with a few pumice balls and vesicular basaltic andesite clasts. The channel conglomerates contain well-rounded cobbles 5–10 cm across chaotically floating in a matrix that grades down into coarse sandstones within the channels. Other granulestones occur in 30–60-cm-thick sheets with lateral extents of less than 100 m.

Sandstones vary in tuff content, bedding characteristics, and composition. Lateral and vertical gradations into coarser granulestone and finer siltstone-to-mudstone fractions are common. A characteristic sandstone is tuffaceous to pumiceous, medium- to coarse-grained, salt-and-pepper sandstone; it is composed of angular grains of quartz, altered feldspar, abundant dark minerals and lithics, and tuff cemented with clay (altered tuff?) and calcium carbonate. These sandstones are thinly laminated and laterally continuous; they form poorly exposed beds with moderate to poor induration.

Other grayish-orange-pink medium-grained subrounded to subangular sandstones that contain quartz, feldspars, and minor dark minerals and lithic fragments form flaggy to massive well-indurated and rounded beds of 10–100 m lateral extent.

Popotosa Formation (part)—Continued | Meters

Siltstone and mudstone beds grade into sandstones and intergrade with each other. Siltstones are more similar to the grayish-orange-pink sandstone described in the previous paragraph than to the tuffaceous sandstones. Siltstones are grayish yellow green on weathered surfaces and pale red on fresh surfaces. They are finely laminated, slightly calcareous cemented, moderately to poorly indurated; and they pinch and swell over 5–50 m lateral extent. Some beds are grayer because of increased ash content. Beds may be covered by washdown from overlying claystones or may be thin ledges of clean siltstone; their degree of exposure is controlled by their mud, ash, and sand content. Mudstones form a nearly continuous compositional gradient with the siltstones and may show graying and swelling if their ash content is high. Purer mudstone beds are red brown, average less than 1 m thick, are slightly calcareous, and are poorly consolidated and exposed.

The featureless lower portions of the tuffs are grayish orange pink to salmon pink, white, and very pale green to light green in their purest forms. They may contain fragments of dark-gray country rock. They break with a hackly to chippy surface, weather to a popcorn texture, and show no residual glass structure. Tuff beds may be floored with airfall pumice shards pressed into the underlying beds. The contacts between the tuffs and underlying detrital beds are abrupt and nonerosive. The tuffs interbed upward with progressively more clastic-rich mudstones, siltstones, and sandstones containing pumice shards, ripples, flaser bedding, normal grading, and a few formerly vertical burrows.

These brilliantly colored tuffs, and the varying lithologies characteristic of this unit and unit 2, weather to intricate badlands of cliffs, flatirons, and twisted gullies. Unit 4 represents deposition on the distal portions of alluvial fans and on alluvial flats and playas. The diverse lithologies reflect the variety of environments as the playa and fan edges shifted at one another's expense in response to climate, tectonic events, and varying source areas. The lack of gypsum, yet the presence of ripples, flaser bedding, and small vertical burrows, suggests that standing water was not high salinity. The pervasive presence of ash or pumice shards suggests that volcanic activity occurred nearby in the Socorro area, but that tuff beds were not preserved on the higher gradient slopes of the distal fans. The presence of fragile accretionary lapilli in the limestone-and-chert bed represents a period of deposition of ash from a local eruptive event into a standing body of water with considerable area (3 km of strike) 389

3. Sandstone, pale-red; unit is distinctly redder and more massive than are rocks in units 2 and 4. Upper and lower contacts are abrupt but nonerosive. Sandstones are medium to massive bedded (10–50 cm); irregularly laminated; medium to fine grained; and contain subangular to subrounded grains of quartz, feldspars, dark minerals, micas, and lithic fragments. The beds are well indurated and calcium carbonate cemented; they contain formerly vertical burrows, clay stringers, mudcracks, and pumice shards at the unit's top where beds become thinner and finer grained. Interbedded are shallow channels (4 cm deep, less than 5 m wide) and beds of pale-red, coarse, poorly sorted sandstone and conglomerate that are normally graded. Crossbedding in one well-exposed channel trace suggests waterflow from the southwest.

   Unit represents a short-term shift in source area, indicating a sudden influx of sheetwash storm sediment from the southwest onto the previously established playa or alluvial-flat surface 6

2. Interbedded granulestones and conglomerates, sandstones, siltstones and mudstones, and three tuffs. Unit generally fines upward and contains gypsum-infilled cracks, trails, burrows, mud chips, mudcracks, and raindrop imprints. Altered ash and pumice shards admixed into other lithologies cause poorer consolidation and grayer rocks than otherwise characteristic.

   Granulestones and conglomerates are light gray to greenish gray on fresh surfaces and yellowish gray on weathered surfaces. Ninety percent of the clasts are welded tuff; 10 percent are andesite. Beds may show low-angle crossbeds or may be laminated or featureless.

   The sandstones vary from salt-and-pepper, ash-rich, poorly consolidated and exposed beds; to pale- and grayish-red, lithic-rich, well-cemented sandstone in thin (2–3 cm) or massive (3–4 m) beds; to massive moderate- to dark-brown lenses. Most sandstones have calcareous cement, but others appear to be cemented by chert. Sandstones may grade into finer or coarser lithologies laterally or vertically. Stratification, induration, and weathering characteristics vary with compositional differences in proportions of quartz, feldspars, dark minerals, mica, lithic fragments, and tuff content.

   The moderate-reddish-orange fresh to grayish-orange-weathered siltstones to mudstones are poorly exposed and consolidated, massive to fissile, moderately calcareous, and may contain altered ash that gives a puffy smectitic weathering appearance to the outcrop. Their composition and calcareous cement and their thinly laminated (2 mm to 2 cm) beds make them the least resistant lithologies in the unit. When several resistant beds occur together, they may form cliffs; otherwise unit is moderately exposed in rolling hills and gullies.

   The three tuffs are white, grayish orange pink, and grayish pink. They vary from 120 to 130 cm thick in their featureless and entirely tuffaceous portion, and they pass upward to 3–4 m of overlying interlaminated tuff and detritus. The pure tuffs contain traces of lithic fragments, mica flakes, and mudchips; no residual glass-shard structure remains. The pure tuffs are cherty to zeolitic; the more detritus rich fraction contains increasing amounts of mud, silt, and sand and granules upward and has crossbedding, soft-sediment deformation, mudcracks, and a variety of lamination types. A few pumice balls appear in various lithologies throughout the unit.

   This unit is lithologically similar to unit 4 and represents the same environment of deposition on playa and alluvial-flat surfaces. Gypsum-filled cracks, raindrop imprints, mudchips, and mudcracks suggest deposition on or near an ephemeral playa lake 97

1. Interbedded conglomerate and sandstone that grade up into granulestone, sandstone, siltstone, and mudstone.

Popotosa Formation (part)—Continued Meters

Conglomeratic units are pale red to brownish gray. Clasts (½–20 cm) occur in beds and lenses 10–40 cm thick extending 10–15 m, feathering at edges to finer material; or discrete clasts may occur within sandstone. Conglomerate makes up more than 50 percent of unit but decreases upward. Clasts are poorly sorted, subangular to subrounded, 65 percent andesite, 30 percent welded tuff, and 5 percent other; feldspars are commonly weathered to a chalky material. Clasts float in, or are cemented together by, calcium carbonate, red-brown mudstone, sandstone, and lithic fragments. Conglomerate may show normal, inverse, or no grading within beds. Contacts between conglomerate packets are indistinct to erosional. Conglomerate breaks both across and between pebbles and cobbles.

Sandstone is pale red to grayish purple on fresh surface; pale brown to moderate yellowish brown on weathered surface. Grains vary from very coarse to very fine, are usually graded, and may be subangular to subrounded. Grains are quartz, feldspars, micas, and lithic fragments; feldspars are chalky. Sandstones are often in continuous gradational contact with underlying conglomerate; or they may form distinct beds about 1 m thick of laterally continuous over more than 10 m, internally graded, or low-angle crossbedded sandstone. Upper contacts of sandstone beds may be eroded by, or show loading from, overlying units. The sandstones and siltstones-to-mudstones show overall upward decrease in induration and exposure; they vary from 20 cm to 1 m thick and range from less than 20 to more than 50 m wide in broad, thin channels.

Unit grades up into granulestone, sandstone, and siltstone to mudstone at about 21 m. Conglomerates and granulestones contain more welded tuff (80 percent) and less andesite (10 percent) clasts upsection. Overall clast size decreases and channels show nested relationships to one another, but most grains and clasts still float in their matrix. Grains are poorly sorted to normally graded to cross-stratified with crossbed heights of 15–25 cm. Overall induration decreases upsection.

The siltstones to mudstones are pale red to grayish red on fresh surfaces and moderate reddish brown on weathered surfaces. They may show grading over 2 cm vertically, laminations of 1–2 cm, or may be massive to fissile depending on clay content.

The grain sizes and upward fining of the unit suggest that deposition occurred on the proximal to distal portions of alluvial fans. The upward fining and decrease in size and number of basaltic andesite clasts reflect the decrease

Popotosa Formation (part)—Continued Meters

in gradient produced by erosion of a nearby source of basaltic andesite 82

Total thickness of Popotosa Formation 1,447

La Jara Peak Basaltic Andesite in fault contact with Popotosa Formation.

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