Ancient Lake Alamosa and the Pliocene to Middle Pleistocene Evolution of the Rio Grande

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CHAPTER G

Abstract

From Pliocene to middle Pleistocene time, a large, high-altitude lake occupied most of the San Luis Valley of southern Colorado. This ancient lake accumulated sediments that Siebenthal (1910) designated as the Alamosa Formation, for which it is herein named.

The existence of this lake was first postulated in 1822 and proven in 1910 from well logs. It was one of the largest high-altitude lakes in North America, comparable only to historic Lake Texcoco in the Valley of Mexico. Lake Alamosa persisted for about 3 m.y., expanding and contracting and filling the valley with sediment until about 440 ka, when it overtopped a low sill on Oligocene volcanic rocks of the San Luis Hills. The resulting overflow cut a deep gorge, coursed southward, and flowed into the Rio Grande, entering at what is now the mouth of the Red River.

The key to this new interpretation is the discovery of still-extant shoreline deposits, including spits, barrier bars, and lagoons nestled among bays and in backwater positions on the northern margin of the San Luis Hills, southeast of Alamosa, Colo.

Alluvial and lacustrine sediment nearly filled the basin prior to lake overflow, which happened sometime around 440 ka as estimated from a ^{3}He surface-exposure age of about 439±6 ka on a boulder of reworked basalt and from strong calcic soils on barrier bars and spits at 2,330–2,340 m (7,645 ft–7,676 ft). Overtopping of the lake's hydrologic sill may have been stimulated by high lake levels during marine oxygen-isotope stage 12, which was one of the most extensive middle Pleistocene glacial episodes. This integration expanded the Rio Grande's drainage basin by nearly 18,000 km^2 to include the high-altitude, glaciated San Juan, Sawatch, and Sangre de Cristo Mountains.

Study Area

The San Luis Valley of southern Colorado and northern New Mexico is a windswept, high-altitude sedimentary basin within the northern part of the Rio Grande rift. The basin extends from the Taos Plateau on the south to Poncha Pass on the north (fig. G–1). The foothills of the San Juan Mountains bound it on the west and the Sangre de Cristo Mountains on the east. This somewhat desolate valley is the home to the oldest surviving town in Colorado (San Luis, established in 1851) and the newest national park (Great Sand Dunes). The nearly level floor of the valley belies its origin—that of an ancient lake basin which has been alluded to but poorly documented for nearly two centuries. The main objective of this paper is to demonstrate the extent and age of ancient Lake Alamosa and to describe how its demise led to the final evolutionary development in the Rio Grande drainage system.

Paleolakes preserve important evidence of past climates, geomorphic relations, and sedimentary processes. As such, the ancient lake in the San Luis basin provides a record of a high-altitude lacustrine environment rarely seen in North America. Additionally, this lake plays an important part in regional drainage evolution, a fact that is often overlooked or underappreciated in the literature.

The San Luis Basin is one of many linked structural basins that form the Rio Grande rift, which extends from central Colorado to northern Mexico. The western margin of the basin is largely passive, whereas the eastern margin is marked by the Sangre de Cristo fault system—the longest Quaternary fault within the rift (see discussion in chapter J, this volume; and U.S. Quaternary fault and fold database at http://earthquake.usgs.gov/regional/qfaults/). The San Luis Hills, about 20 km southeast of Alamosa (fig. G–1), is a horst block of Oligocene volcanic and volcaniclastic rocks that have San Juan volcanic field affinities but that were locally erupted within the rift. The San Luis Basin is mainly an east-tilted half graben with internal structural complexities, although few of these are preserved at the surface. New aeromagnetic

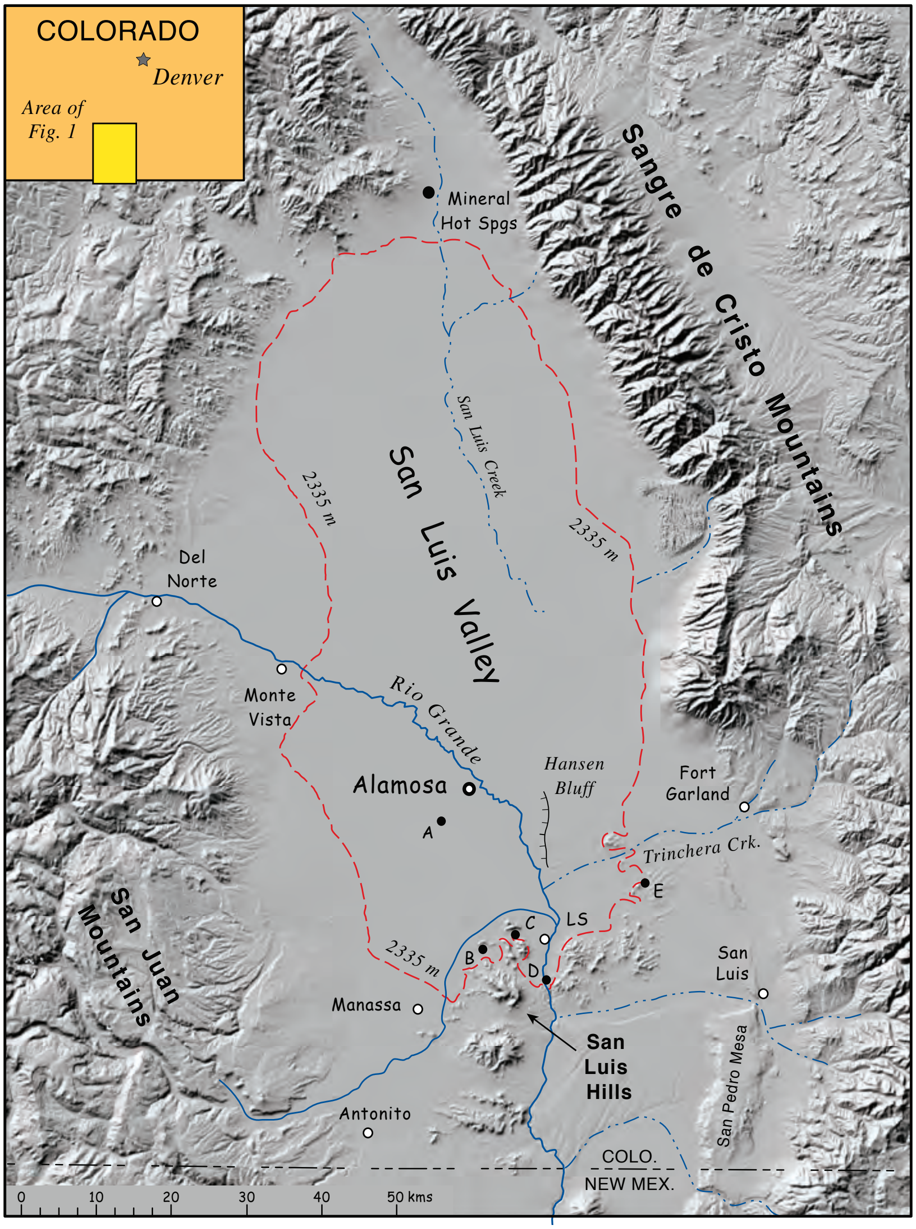

Figure G–1. Index map showing the San Luis Basin of southern Colorado and locations mentioned in the text. A-E are key localities for dating and reconstructing the lake's history.

data for the entire basin south of Alamosa (Bankey and others, 2005) show numerous intrarift faults that partition the basin into hydrologic compartments. Although the entire San Luis Basin now lies within the Rio Grande drainage basin, its geomorphology and surficial geology change markedly at the San Luis Hills (Thompson and Machette, 1989). To the north, the valley is nearly flat floored, rising gently from 2,285 m (7,500 ft) along the river to above 2,500 m (8,200 ft) at the mountain front. South of the San Luis Hills, the valley is largely covered by Pliocene basalts of the Servilleta Formation (hereafter referred to as the Servilleta Basalt; Lipman and Mehnert, 1979) and the Rio Grande flows in an ever-deepening gorge as it makes its way south into New Mexico and eventually to the Gulf of Mexico.

Previous Work

Lake Alamosa's discovery harkens back nearly two centuries. In 1821–22, three decades prior to settlement of the San Luis Valley, Jacob Fowler made his way up the Rio Grande on a hunting and trapping expedition. Fowler was a keen observer of topography, geography, and geology. His journals include this prescient passage that is particularly relevant to the lake:

> *"I Have no doubt but the River from the Head of those Rocks up for about one Hundred miles Has once been a lake of about from forty to fifty miles Wide and about two Hundred feet deep—and that the running and dashing of the Watter Has Woren a Way the Rocks So as to form the present Chanel."* (Cited in Siebenthal, 1910, p. 112–114.)

Jacob Fowler made this keen observation from the San Luis Hills (probably in the Fairy Hills, above the river's gorge), looking northward into the San Luis Valley. As we will show, Jacob Fowler accurately forecast the size, depth, and overflow of the lake—185 years ago.

In 1910, Claude Siebenthal proposed the existence of an unnamed Pliocene-Pleistocene lake in the San Luis Valley of southern Colorado. Siebenthal (1910) was studying the hydrology of this water-rich agricultural area and had examined hundreds of water-well drilling logs as part of his assessment. Of key interest to him was the presence of tight clays ("blue clays" in the logs) that form aquitards in the lower confined layer, whereas the upper unconfined layer was composed of more permeable alluvium (sand and gravel). At this time (early 20th Century) wells that penetrated blue clay in the lower confined layer were typically artesian. Siebenthal (1910) inferred that the blue clays were lacustrine, showed their extent in this ancient lake, and named its sedimentary deposits the "Alamosa Formation."

Siebenthal (1910) found the field evidence for his lake at Hansen Bluff, a 20-m-high exposure about 10 km southeast of Alamosa. In the 1980s, paleontologist Karel Rogers and colleagues conducted multidisciplinary studies of the Alamosa Formation at Hansen Bluff (Rogers and others, 1985, 1992) and documented that the exposed section of fluvial and lacustrine sediment was mainly early Pleistocene (Irvingtonion) in age (see stop B7, chapter B, this volume). These sediments contain abundant vertebrate fossils, two Pleistocene volcanic ashes, and a paleomagnetic record that spans the Brunhes-Matuyama polarity boundary at 780 ka. However, in the nearly 100 years since Siebenthal's work, no one had found surficial expression of this lake or documented its maximum altitude or lateral extent, mainly because the Quaternary deposits of the basin had not been mapped in detail.

New Evidence of the Lake

Machette's previous mapping in the Lake Bonneville Basin of Utah led him to suspect that shorelines and coarse-grained, near-shore deposits of this ancient lake might be preserved on bedrock. A likely area to look for such deposits was along the north side of the San Luis Hills, which had been mapped by Thompson and Machette (1989). During new mapping of the Alamosa ½° x 1° sheet (Machette and Thompson, 2005), we found several exposures of near-shore lacustrine and shoreline deposits. The first evidence came from the Bachus pit (fig. G–1, location A; stop B1, chapter B, this volume), which is located about 6 km southwest of Alamosa at an altitude of about 2,300 m (7,550 ft). This active sand pit exposes about 4 m of finely laminated silts and sands and sandy pebble gravels that we interpret as shallow, near-shore lacustrine deposits. Then we examined adjacent bedrock areas above 2,300 m and found unequivocal shoreline spits (stop B3, chapter B, this volume) perched on the back (south) side of Saddleback Mountain (fig. G–2), about 15 km to the southeast of the Bachus pit and at the southern end of Lake Alamosa, as we'll see later.

Key Locations

The shoreline features coincide with wave-eroded bedrock knobs and hills at altitudes around 2,330–2,335 m (7,645–7,660 ft) and suggest that the ancient lake reached the minimum overflow elevation of 2,335 m (7,660 ft) in the San Luis Hills. Other well-preserved bars, spits, and lagoons between bedrock-core hills were found at similar elevations, both west and east of the Rio Grande. Distinct spits at 2,330–2,335 m (7,645–7,660 ft, fig. G–2) wrap around the leeward, southern, side of Saddleback Mountain (fig. G–1, location B) and Sierro del Ojita (fig. G–1,

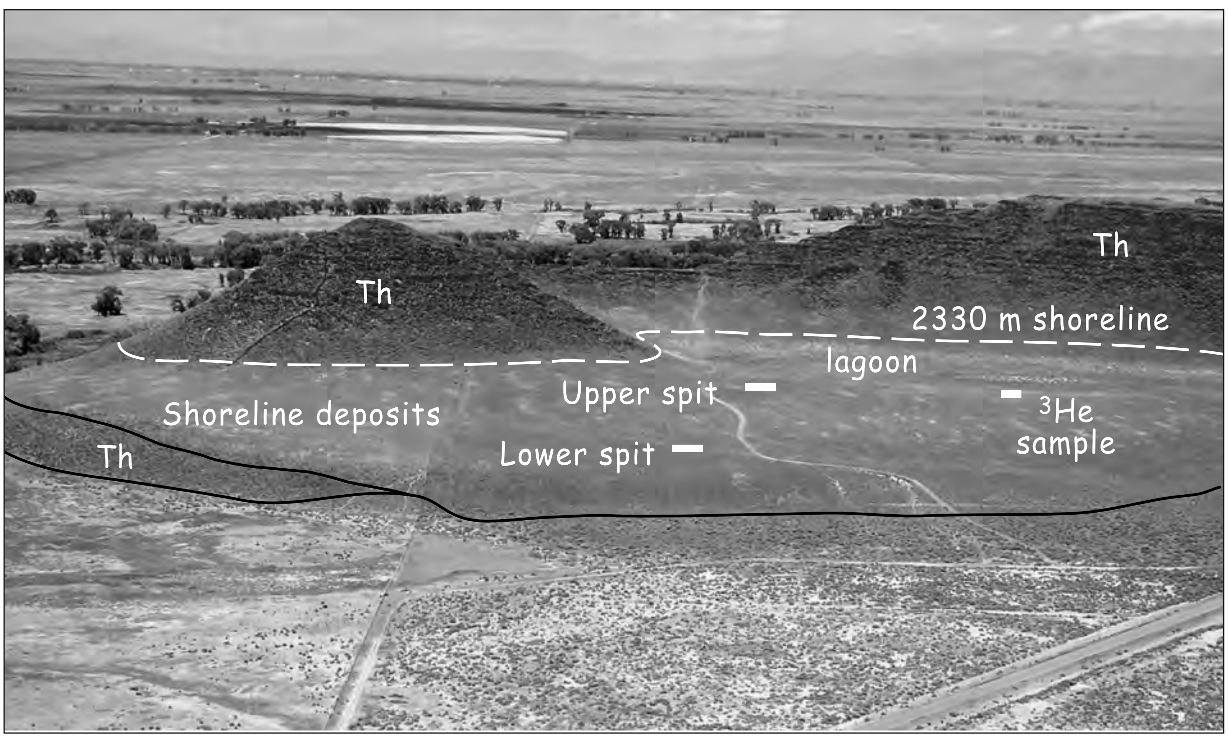

Figure G–2. Oblique aerial photograph of shoreline spits on Saddleback Mountain (location B, fig. G–1). The 2,300-m shoreline is cut across 26-Ma basalts of the Hinsdale Formation (Th); spits and a lagoon formed on the leeward (south) side of the mountain ridge. White boxes are locations of soil pits and basalt boulder sampled for ^{3}H surface-exposure dating.

location C), and a well-preserved, kilometer-long spit (stop B4, chapter B, this volume) lies on the eastern side of the Rio Grande (fig. G–1, location D), just above the basin's outlet near the small town of Lasauses, Colo. (see Machette and Thompson, 2005).

Barrier bay-mouth bars and back-bar lagoons of the ancient lake are still preserved in the southeastern part of the lake basin, both north and south of Trinchera Creek. These features span a narrow but slightly higher elevation range, primarily from 2,330 to 2,340 m (7,645–7,675 ft) (fig. G–3). At most locales, there is a single bar-lagoon complex, but pairs of these features are preserved at the Appleblossum Lane location (fig. G–1, location E; stop B5, chapter B, this volume).

The dozen large constructional lake features that we've found are not well exposed, so we excavated four pits to assess soil development as a relative-age tool. These pits exposed strongly developed, 0.75- to 1-m-thick calcic soils (stops B3.1 and B3.2, chapter B, this volume) that have stage III morphologies (see Birkeland, 1999). The amount of calcium carbonate in these soils is impressive in that they persist at high elevations, close to the pedocal-pedalfer soil boundary in the semiarid San Luis Valley (see discussion of soils at stop B3.2, chapter B, this volume). These soils probably persist owing to persistent relatively dry (semiarid) climate in the basin during the Quaternary. Conversely, soils above 2,500 m (8,200 ft) in the adjacent foothills rarely show significant accumulations of calcium carbonate owing to enhanced mobility of soil carbonate in colder temperatures and to leaching owing to increased precipitation, soil moisture, and lower vegetation zones (soil acidity) during glacial times.

Extent of Lake

Around 450,000 years ago, Lake Alamosa was forming shoreline features at its maximum elevation of about 2,335±5 m (7,660±15 ft). At this elevation, Lake Alamosa would have occupied most of the San Luis Valley north of the San Luis Hills (fig. G–1). This valley is a prime agricultural area for production of potatoes, barley, and hay. Thousands of wells have been drilled in the basin, and the majority of these are (or were) flowing as shown by Siebenthal (1910) and on USGS topographic maps. A quick tabulation of flowing versus standard wells shows that 95 percent of the artesian wells lie at or below the maximum paleoshoreline elevation. This is no coincidence because the aquitard (or aquitards) for pressuring the wells are lake bottom clays in the Alamosa Formation. Also, there are a variety of unusual geomorphic and hydrologic features at or slightly above the maximum paleoshoreline elevation, such as the abundant ponds and springs at Monte Vista Wildlife Refuge.

At its full extent, Lake Alamosa extended almost 105 km north-south and 48 km east-west (2335 m contour, fig. G–1). As such, it was one the largest high-altitude lakes in North America, comparable to historic Lake Texcoco in the Valley of Mexico. However large and long lived, since its overflow and draining at 440 ka, most of the geomorphic evidence of Lake Alamosa (such as shorelines on alluvial fans) has been eroded or buried by younger alluvium or eolian deposits.

The age and extent of ancient Lake Alamosa have practical importance because during high stands of the lake (glacial

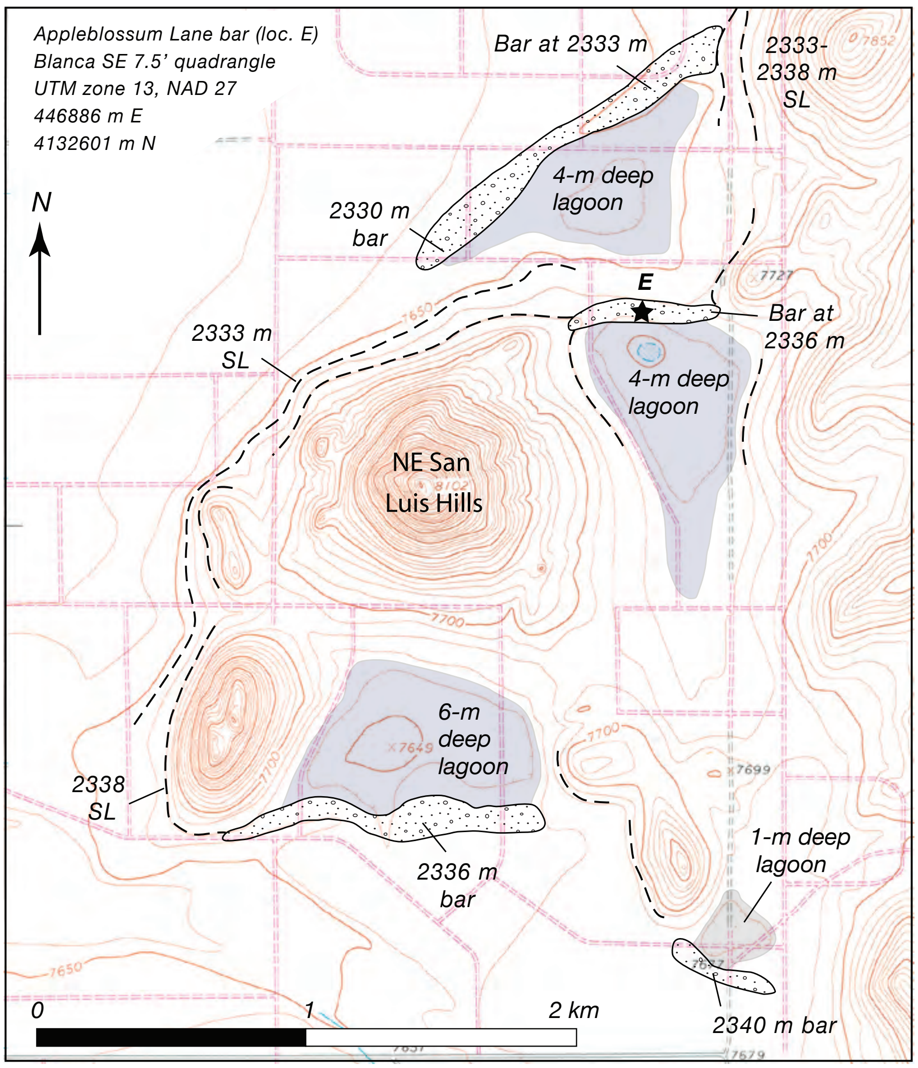

Figure G–3. Barrier bars and lagoons preserved along northeast margin of the San Luis Hills. Appleblossum Lane bar is labeled E, as on figure G–1.

times) silt and clay were deposited in the deeper parts of the basin. These fine-grained lacustrine sediments (the blue clay of drillers' logs) form the aquitards within the confined aquifer (the Alamosa Formation) in the basin and are the source of most agricultural waters.

As part of his work on the lake, Siebenthal (1910) plotted the locations of water wells in the Alamosa portion (subbasin) of the San Luis Basin. He noticed that most of the flowing (artesian) wells were concentrated in the central, lower parts of the basin (see area of flowing wells, plate 1, Siebenthal, 1910), whereas nonflowing wells were located at higher elevations (mountainward). After identifying the highest shoreline of Lake Alamosa at 7,760 ft (about 2,335 m), we plotted this contour against the locations of wells (artesian and nonartesian) and springs in the basin (fig. G–4). Roughly 95 percent of all artesian wells (as shown on USGS 1:100,000-scale topographic maps) in the basin lie within the 7660 ft contour. However, this contour is more restricted than that of the high shoreline owing to postlake deposition. For example, sedimentation by the Rio Grande has built a gigantic alluvial fan that spreads almost entirely across the Alamosa subbasin. Thus, the paleodatum of 7,660 ft (at which the shorelines formed) must lie buried beneath postlake alluvium and mountainward of the lake's extent as shown on figure G–4. Using this argument, we plotted the probable location of the buried shoreline level as a dashed line on figure G–4. As can be seen from the figure, virtually all of the artesian wells lie within this dashed line. Thus, the extent of artesian wells is virtually coincident with Lake Alamosa's highest shoreline. And it follows that the lake's shoreline restricted the deposition of tight, fine-grained deposits (blue clays) and, thus, aquitards in the Alamosa Formation. Recognizing the lake's maximum extent and its likely control by climatic conditions in the closed-basin's drainage area allows one to construct an improved geoclimatic sedimentation model for the Alamosa Formation. Currently, most groundwater assessments for the basin use a simple, multilayer model with little or no interfingering of lacustrine and alluvial materials and virtually no structural control on potential subsurface water flow paths.

Dating Lake Alamosa's Shoreline Deposits

Lake Alamosa persisted from the middle Pliocene to middle Pleistocene. Using sedimentation rates at Hansen Bluff, Rodgers and others (1985) suggested that this part of the section might be as young as 700,000 yr (see discussion for stop B7, chapter B, this volume). However, they did not recognize a significant lacuna at the top of the section where coarse-grained sandy fluvial gravels with stage III calcic soils are unconformable on sediment of the Alamosa Formation. From our study of the bluffs (see stop B7), it appears that the uppermost part of the Alamosa Formation (about <670 ka) has been locally removed by erosion and subsequent deposition of old alluvium (unit Qao, Machette and Thompson, 2005, 2007) that predates the overflow of the lake.

In order to date the upper spit at Saddleback Mountain (fig. G–2), which is stop B3 on the Friends of Pleistocene trip (see chapter B, this volume), we sampled the largest intact (but

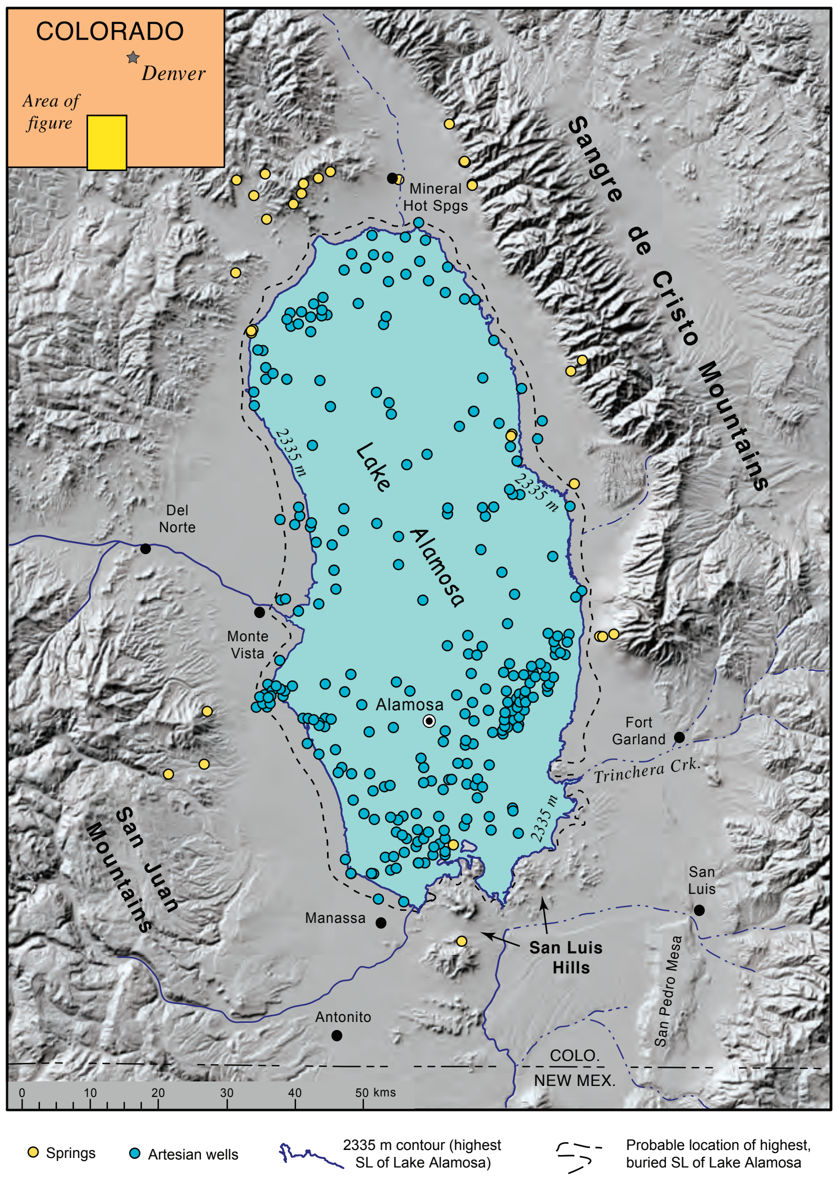

Figure G–4. San Luis Basin showing projected extent of Lake Alamosa, its buried shoreline (SL), and artesian wells and springs.

transported) boulder that showed minimal effects from erosion, such as spalling or eolian erosion (ventifacts are common at this site). The basalts of Saddleback Mountain are perfect for surface-exposure dating with ^{3}He isotopes because they contain phenocrysts of olivine and pyroxenes, two minerals that retain cosmogenic He isotopes. At this locality, the spits are composed almost entirely of reworked basalt boulders and lacustrine sand that has been transported southward around the leeward side of the bedrock hills. The larger basalt boulders are 1 m in diameter, of which 30–40 cm is exposed above ground surface.

The ^{3}He and ^{4}He concentrations were measured at the University of Utah Noble Gas Laboratory on a MAP-251 noble gas mass spectrometer. Gas was released using a modified Turner furnace heated to >1,400°C. SAES getters removed reactive gases; Ar and Ne were cryogenically separated from He. Air contamination was avoided by measuring He concentrations under ultrahigh vacuum (<10^{-8} torr) and using Ne concentrations as a check for possible leakage. The ^{3}He and ^{4}He amounts were standardized against Yellowstone Park gas (MM) at 16.5 R_A, where R_A is the $^{3}He/^{4}He$ ratio in air (1.39 x 10^{-6}). Furnace blanks were typically 0 to 3 x 10^{5} atoms for ^{3}He and near background values (1 x 10^{8} to 1 x 10^{9} atoms) for ^{4}He. The detection limit for ^{3}He in this system is about 50,000 atoms (table G–1).

Pyroxene separated from the surface layer of a large basalt boulder yielded a preliminary ^{3}He exposure age of 439±6 ka (table G–2). This age was determined using the total ^{3}He concentration and an absolute ^{3}He production rate of 116 atoms gram^{-1} year^{-1} (Licciardi and others, 1999) that was scaled to the samples altitude and latitude using Lal (1991) (table G–1). Pyroxenes from rocks with older (>1–2 Ma) crystallization ages can have significant noncosmogenic ^{3}He from nucleogenic reactions on ^{6}Li (^{6}Li (n, α) $^{3}H \rightarrow {}^{3}He$). Marchetti and Cerling (2005) and Marchetti and others (2005) used samples shielded from cosmic radiation to account for noncosmogenic ^{3}He in pyroxenes from intermediate volcanic rocks exposed on the western edge of the Colorado Plateau. These volcanic rocks are remarkably similar in crystallization age (~25 Ma) and petrology to the sample we dated in this study. Applying the $^{3}He/^{4}He$ shielded correction of Marchetti and others (2005) to the He data of the sample changes the exposure age slightly from 439 to 431±6 ka (table G–2). Using the ^{3}He surface-exposure age of 439 ka, we conclude that the spit was deposited at about 440 ka, towards the end of a major glacial episode (marine oxygen-isotope stage 12) that ended between 452 ka and 427 ka (see fig. G–5).

We recognize that our dating of the lake spits is based on only a single cosmogenic surface exposure age and assessments of relative soil development (see stop B3.2), so we are pursuing three additional dating techniques to help constrain the timing of lake's overflow:

1. Terrestrial cosmogenic nuclide (TCN) profile dating using ^{3}He isotopes. This technique uses small gravel clasts collected through a vertical profile at least 2–3 m deep, and it

Table G–1. Sampling data for ^{3}He surface-exposure dating of basalt.

Sample number	Latitude (°N)	Longitude (°W)	Altitude (m)	Topo shielding factor	Self shielding factor	Total shielding factor	^{3}He production rate (atoms g^{-1} yr^{-1})*
PS–MM05–72c	37.262416	105.842416	2,324	0.999	0.942	0.941	598

*Determined using an absolute ^{3}He production rate of 116 atoms g^{-1}yr^{-1} (Licciardi and others, 1999) that was scaled using Lal (1991).

No corrections for potential snow shielding applied to production rate. Topo, topographic.

Table G–2. He isotope data for cosmogenic surface-exposure dating of basalt.

Sample number	$^{4}He_{total}$ (10^{12} atoms g^{-1})	$^{3}He_{total}$ (10^{6} atoms g^{-1})	$^{3}He/^{4}He$ fusion	$^{3}He_c$ (10^{6} atoms g^{-1})	$^{3}He_c$ (percent)	Exposure age (ka)±2σ
PS–MM05–72c	22.92±0.06	262.5±3.5	1.15 x 10^{-5}	262.5±3.5	100	439±6
PS–MM05–72c*	22.92±0.06	262.5±3.5	1.15 x 10^{-5}	257.7±3.5	98.2	431±6

*Sample corrected using an estimated $^{3}He/^{4}He$ correction. The $^{3}He_c$ (cosmogenic) component was determined using the following relationship: $^{3}He_c = {}^{3}He_{total} - ({}^{4}He_{total}$ x $^{3}He/^{4}He$ shielded), where $^{3}He/^{4}He$ shielded ratio is 2.08x10^{-6} (Marchetti and others, 2005).

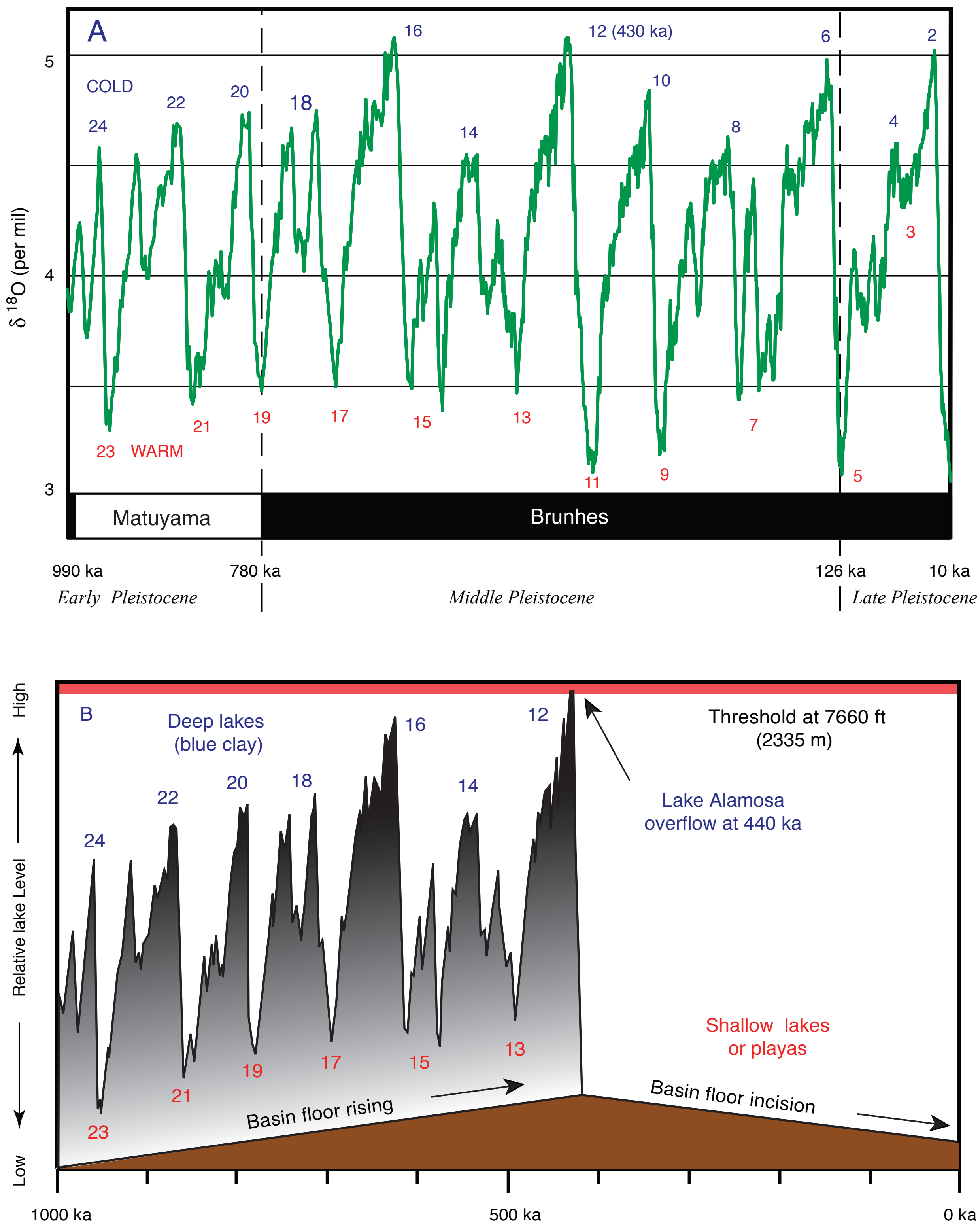

Figure G–5. Marine oxygen-isotope curve and its relation to Lake Alamosa. *A*, OIS curve from Lisiecki and Raymo (2005) showing changes in oxygen-18 isotope concentrations in benthic fauna and related glacial and interglacial stages. *B*, OIS curve from part *A* superposed on an aggrading basin floor. The basin floor was incised after overflow of Lake Alamosa.

can date deposits as old as 1 Ma if they contain olivine or pyroxene.

2. Terrestrial cosmogenic nuclide profile dating using ^{36}Cl isotopes. These analyses are being performed by the PRIME Lab at Purdue University (Lafayette, Indiana), and the modeling work is being done in cooperation with Fred Phillips of New Mexico Institute of Mining and Technology (Socorro). This technique uses small gravel clasts collected through a vertical profile at least 2–3 m deep, and it can date deposits as old as 300 k.y.

3. Experimental U/Th dating using laser-ablation mass-spectrometer techniques. These analyses are being done as part of a cooperative project with Warren Sharp at the University of California Berkeley Geoscience Center. This technique uses calcium-carbonate rinds on the base of large clasts. The best rinds are typically in the Bk horizon of a thick calcic soil. The technique can date deposits as old as 750 ka if they have small amounts of detrital thorium and if the carbonate is a closed system (no leaching and reprecipitation).

Climate Changes and Lake Alamosa

Lake Alamosa formed in the high (>2,300 m) altitude San Luis basin, surrounded by mountainous terrain that commonly exceeds 4,000 m (about 13,000 ft) in elevation. Presently, the central low-lying parts of the basin have a cool, semiarid climate. Modern climatic conditions in Alamosa are cool (41°F or 5°C, mean annual temperature (MAT)) and relatively dry (about 7 in. or 180 mm, mean annual precipitation) on average for the year (see http://www.wrcc.dri.edu). However, during full glacial conditions (that is, at 15 ka), the climate was probably much colder than now (that is, <0°C MAT), and it may have been drier according to some studies (see for example, Leonard, 1989; Fall, 1997). Nevertheless, meltwater from the abundant glaciated basins in the San Juan, Sawatch, and Sangre de Cristo Mountains must have supplied adequate water to fill the lake.

Assuming that the lake's level rose and fell synchronously with changing climates, we can use the marine oxygen-isotope record as a proxy for lake level. Lisiecki and Raymo's (2005) summary of marine benthic oxygen-18 records shows regular cyclic oscillations in sea temperature that is directly linked to glacial and interglacial stages. On figure G–5A, we have reproduced their oxygen-isotope stage (OIS) record for the period between 990 ka and 10 ka, which includes the late-early Pleistocene, middle Pleistocene, and late Pleistocene. From the work on Hansen Bluff by Rogers and others (1992) (fig. G–1), we know that the upper part of the Alamosa Formation includes sediment deposited between about 900 ka and 670 ka (see discussion of stop B8, chapter B, this volume), so this section relates directly to climatic conditions and depositional environments during OIS 22-18.

Because Lake Alamosa formed within a closed basin, sedimentation caused the basin floor to aggrade with time. Downdropping along the Sangre de Cristo fault zone may have created additional space for sediments, but this space was restricted to the eastern margin of the San Luis Basin. Thus in the Pleistocene, Lake Alamosa rose from increasing base levels with the passage of time. Maximum shoreline elevations of Lake Alamosa would have increased through time, until the lake could reach the lowest hydrologic threshold in the basin, which is in the San Luis Hills (fig. G–4).

To illustrate the point of increasing base level and overflow, we simply modified Lisiecki and Raymo's (2005) oxygen-18 record (fig. G–5*A*) so that the maximum shoreline levels (at late-glacial maxima) climb though time. Under this scenario, the lake reached the hydrologic sill at the close of OIS 12, which terminated at about 430 ka. Although figure G–5*B* is model driven, we believe that it is no coincidence that our dating of the highest spit of Lake Alamosa (440 ka) is virtually identical to the close of OIS 12, which was one of the most extensive glacial stages in the northern hemisphere in the Quaternary (see fig. G–5*A*). Presumably, meltwater inputs to the lake during the decline of OIS 12 led to high water levels and overflow.

Implications of Overflow

Understanding the temporal and spatial history of Lake Alamosa has important implications for the San Luis Valley and the Rio Grande, which has the largest drainage system in the southern Rocky Mountains. It provides a geologic framework for interpreting the Alamosa Formation, one in which the lake history is characterized by expansions and contractions in response to changing climates during the Quaternary (the past 1.6–1.8 m.y.). Dating the overflow of the lake limits the time of integration of the Rio Grande to the middle Pleistocene (>440 ka). Overflow of the lake and incision of its sill in the Fairy Hills increased the drainage area of the Rio Grande by about 22,000 km^2 (Wells and others, 1987). Prior to 440 ka, the Rio Grande had its most northerly headwaters in the Red River drainage of the Sangre de Cristo Mountains, north of Taos, N. Mex. (fig. G–6).

To illustrate these points, we have reconstructed the Pliocene to middle Pleistocene history of the upper Rio Grande drainage basin as shown in figure G–6. These scenarios are based on our mapping of the Taos Plateau and San Luis Basin and on earlier reconstructions of the Rio Grande's evolution by Wells and others (1987). Between 5 and 4 Ma, massive flood basalts (Servilleta) erupted on the Taos Plateau, completely burying former drainage channels (including any ancestral Rio Grande). By 3.5 Ma, these basalts flowed northward into Colorado, around the western and eastern margins of the San Luis Hills that partially subdivided the San Luis Basin from the Taos Plateau. These flows extended north of Antonito and Fort Garland, possibly closing off any southward drainage

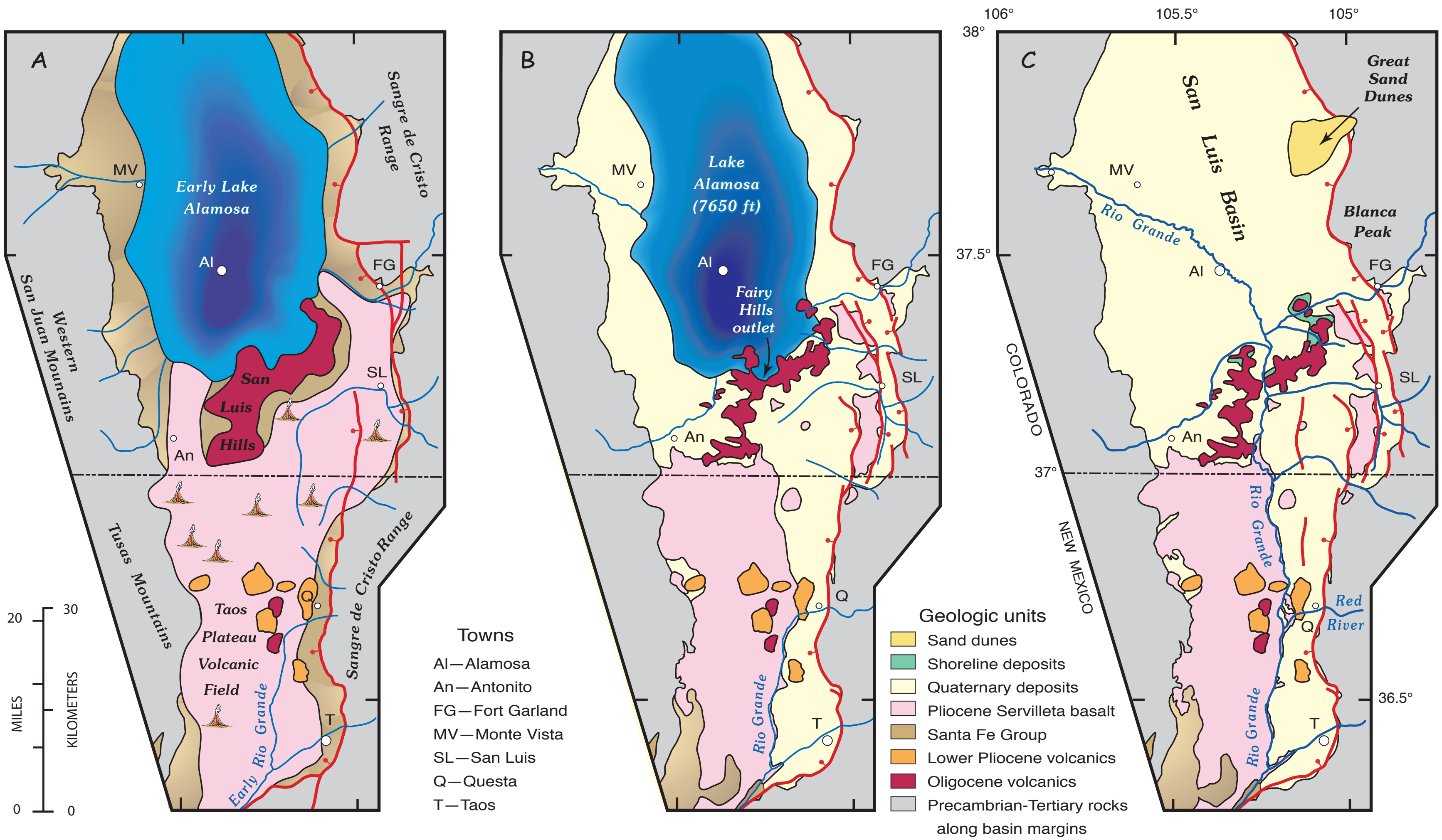

Figure G–6. Simplified geologic map of the San Luis Basin showing generalized geology and drainage patterns for the time intervals of *A*, 3.5–3 Ma; *B*, 440 ka; and *C*, the present.

from the basin (fig. G–6*A*). By 3.5–3 Ma, the basin was filling with sediment of the Alamosa Formation, and Lake Alamosa became a persistent yet variable part of the sedimentologic environment, expanding and contracting in response to the alternating glacial and interglacial climates in the Pleistocene. As a result, the Alamosa Formation has thick impermeable clays in the deep parts of the basin near Alamosa and along the eastern margin of the valley, whereas thinner clay beds interspersed with silt, sand, and gravel were deposited in shallower environments (fig. G–6*B*), such as at Hansen Bluff along the eastern margin of ancient Lake Alamosa.

Around 440 ka (middle Pleistocene), Lake Alamosa reached its highest elevation and had built a series of shorelines, spits, barrier bars, and lagoons (fig. G–6*B*) coincident with the 2,335-m topographic sill in the Fairy Hills (fig. G–1, location D; stop B4, chapter B, this volume). Overflow of the sill led to deep incision through fault-softened and dike-intruded Tertiary volcanic rocks in the Fairy Hills (see mapping of Thompson and Machette, 1989). Lake Alamosa waters flowed southward across the Servilleta Basalt and entered the Rio Grande west of Questa (fig. G–6*B*), which had already incised a modest canyon along the present course of the Red River (former headwater of the Rio Grande). Since integration of the Rio Grande (fig. G–6*C*), the river's 135-m-high knick point has retreated about 8 km north of the Red River to a point east of Brushy Mountain. The Rio Grande gorge is about 165 m deep at the Gorge Bridge (west of Taos, N. Mex.), where it exposes 4.8 to 3.0 Ma basalts interbedded with sediment (Appelt, 1998, table 1). Above the nick point, the Rio Grande has downcut <35 m into the Servilleta Basalt since 440 ka. Wells and others' (1987) careful analysis of the Rio Grande's Quaternary history in New Mexico suggested that integration of the Rio Grande was the result of headward stream erosion and drainage capture by causes that were "unclear and enigmatic" (Wells and others, 1987, p. 63). They considered two possible causes:

1. Overflow of a lake (Sunshine Lake of Winograd, 1959) or restricted drainage areas just north of a paleodrainage divide between Cerro Chieflo and Guadalupe Mountain (Wells and others, 1987, fig. 4a)

2. Regional uplift, which led to increased stream incision and enhanced stream sapping.

However, as a result of our mapping and surface-exposure dating of Lake Alamosa deposits in Colorado, we now believe that integration was a direct result of overflow of Lake Alamosa at 440 ka and not headward capture. Lake water that exited the basin through the Fairy Hills must have flowed along the lowest course out of the San Luis Hills, along the western, distal end of the Costilla Plain and southward along the juncture between west-dipping sediments of the Sunshine Valley and east-dipping flows of Servilleta Basalt (Pliocene, ca. 3.7–4.8 Ma) (see discussion of Rio Grande in chapter C, this volume).

Since 440 ka, Rio Grande has built a large alluvial fan at Monte Vista that effectively further subdivides the San Luis Valley (Alamosa Basin) into northern and southern subbasins. Streams graded to the Rio Grande on the southeast side of the San Luis Basin have cut a series of terraces in response to further river downcutting through the San Luis Hills. The modern Rio Grande is mainly eroding Quaternary deposits west of the river and south of Alamosa, but little of the underlying basin fill of the Alamosa Formation has been removed.

This new history of Lake Alamosa and the Rio Grande has important hydrologic and geologic implications for the San Luis Basin. On a broader basis, it shows that large paleolakes can have a profound influence on the evolution of large river drainage basins and it illustrates the importance and rapidity of overflow events in the Quaternary record.

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