BURIED EARLY PLEISTOCENE LANDSCAPES BENEATH THE PAJARITO PLATEAU, NORTHERN NEW MEXICO

DAVID E. BROXTON and STEVEN L. RENEAU
Geology and Geochemistry Group, MS D462, Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract—This paper describes the early Pleistocene landscapes of the northern and central Pajarito Plateau area prior to the eruption of the Otowi (1.61 Ma) and Tshirege (1.22 Ma) Members of the Bandelier Tuff, and the effects of these eruptions on the landscapes. Borehole and surface outcrop data were used to prepare preliminary pre-Otowi and pre-Tshirege structure contour and bedrock geologic maps, and isopach maps for the Otowi and Tshirege Members. The central part of this area was occupied by a broad SSW-trending valley prior to eruption of the Otowi Member. This early Pleistocene valley was flanked on the west by deeply dissected volcanic highlands of the Sierra de los Valles and on the east by a low north-trending basaltic ridge that stood approximately 500 ft higher than the valley floor. The basaltic ridge was a western extension of the Cerros del Rio volcanic field that was largely buried by the Bandelier Tuff. Gravity data and the lithology of the upper Santa Fe Group suggest that the early Pleistocene valley overlies a Tertiary graben on the western side of the Española basin, in turn suggesting an inherited structural control on valley location. Deposition of both the Otowi and the Tshirege Members significantly changed the landscape; subsequent drainage channels were commonly strongly oblique to prior channels and locally were superimposed on prior bedrock highs. Future monitoring wells evaluating the nature and extent of perched ground water systems beneath the Pajarito Plateau, and targeting specific geohydrologic horizons associated with these paleotopographic surfaces, should consider the flow paths controlled by these buried landscapes.

INTRODUCTION

This paper describes the early Pleistocene landscapes of the northern and central Pajarito Plateau prior to the eruption of the Otowi and Tshirege Members of the Bandelier Tuff, and the effects of these eruptions on the landscapes. Data presented were compiled to guide geohydrologic investigations examining the nature and extent of perched ground water systems beneath the Pajarito Plateau. The pre-Bandelier landscape is important to ongoing environmental restoration investigations at Los Alamos National Laboratory because ground water is perched above this buried land surface in some areas, within the Guaje Pumice Bed or in basal ignimbrites of the Otowi Member, and above soil horizons developed on top of the Plio-Pleistocene Puye Formation. In at least one location, a perched water body contains measurable concentrations of anthropogenic tritium, demonstrating recent recharge to a depth of at least 300 ft (Broxton et al., 1995). In addition, we suspect that tephras and volcaniclastic sediments of the Cerro Toledo interval (Broxton and Reneau, 1995), occurring between the Otowi and Tshirege Members, may also locally perch water. Because Cerro Toledo stratified beds would be the first significant perching layers encountered by infiltrating water beneath much of the Plateau, the paleogeography associated with this unit is also important in the evaluation of potential subsurface contaminant transport. Placement of future ground water characterization and monitoring wells will be guided in part by estimating the gradient and direction of ground water flow in potential perched zones associated with these buried landscapes.

Dransfield and Gardner (1985) originally prepared pre-Bandelier structure contour and bedrock geologic maps for the Pajarito Plateau, based on borehole data available at the time and the geologic map of Griggs (1964). Our maps revise their work and extend it to evaluate the pre-Tshirege landscape, incorporating more recent borehole data and extensive field checking of the base of the Otowi and Tshirege Members. Although our understanding of the buried early Pleistocene landscapes will improve as data from future core holes become available and following more detailed examination of outcrops, we believe that the available data reveal many of the significant features of these paleotopographic surfaces and should thus be useful in the siting of future ground water monitoring wells. In addition, this work allows an evaluation of how the landscape was affected by emplacement of Otowi and Tshirege ignimbrites and suggests some relationships between the early Pleistocene paleotopography and the structural evolution of the Pajarito Plateau area.

METHODS

The structure contour maps and pre-Bandelier geologic map were prepared using surface outcrop and borehole data, located as shown in Figs. 1, 2) of the area where the base of the Otowi and Tshirege Members are extensively exposed. Guided in part by available geologic maps (Griggs, 1964; Smith et al., 1970; Goff, 1995; Reneau et al., 1995; Dethier, in press), most sites (Figs. 1, 2) were field checked, and the altitude of the contact was determined using USGS or NAD83 topographic base maps, hand leveling, and/or an altimeter. A few control points were taken from Griggs (1964); these points were replotted on a NAD83 topographic base after confirming the location of the contact on high resolution orthophotographs. In some places where the base of the Tshirege Member is not exposed, the lowest exposures on canyon walls were used to provide maximum-limiting elevational control.

The elevation of the pre-Otowi and pre-Tshirege surfaces was assumed to correspond to the general present land surface in areas underlain by basalt near White Rock or by Tschicoma Formation dacite near Los Alamos, excluding narrow canyons (such as Pajarito Canyon through White Rock) which are likely post-Bandelier features. This assumption is reasonable because the lava flows underlying these areas are resistant to erosion and probably have been relatively little modified in the last 1.61 Ma. Furthermore, large parts of these areas were covered by the Tshirege Member of the Bandelier Tuff, which prevented erosion of these surfaces for much of the last 1.22 Ma.

Subsurface data were taken primarily from the comprehensive compilation of geologic logs of Los Alamos area boreholes by Purtymun (1995). Additional subsurface stratigraphic information was taken from Broxton et al. (1995) and Gardner et al. (1993), and from unpublished geologic logs of recent boreholes drilled for the Los Alamos National Laboratory Environmental Restoration Project.

Isopach maps of the Otowi and Tshirege Members were prepared from the same data sources as the structure contour maps. To minimize thickness variations resulting from post-Tshirege erosion, borehole or outcrop sites were eliminated from the Otowi isopach data set if the Tshirege Member was absent above the Otowi Member. Because the Otowi Member was exposed to erosion for 400 ka before the Tshirege Member was erupted, the Otowi isopach map represents the estimated thickness of the Otowi Member prior to eruption of the Tshirege Member rather than the original thickness. Isopachs for the Tshirege Member are based on measurements at mesa tops, thus minimizing the effects of erosion on estimated thicknesses. Nonetheless, the Tshirege Member has been exposed since its emplacement, and uppermost tuffs on mesa tops have been eroded to varying degrees over the last 1.22 Ma. Therefore, the original thicknesses of the Tshirege Member were certainly greater than shown.

PRE-BANDELIER BEDROCK GEOLOGY

The pre-Bandelier bedrock geology of the Pajarito Plateau study area

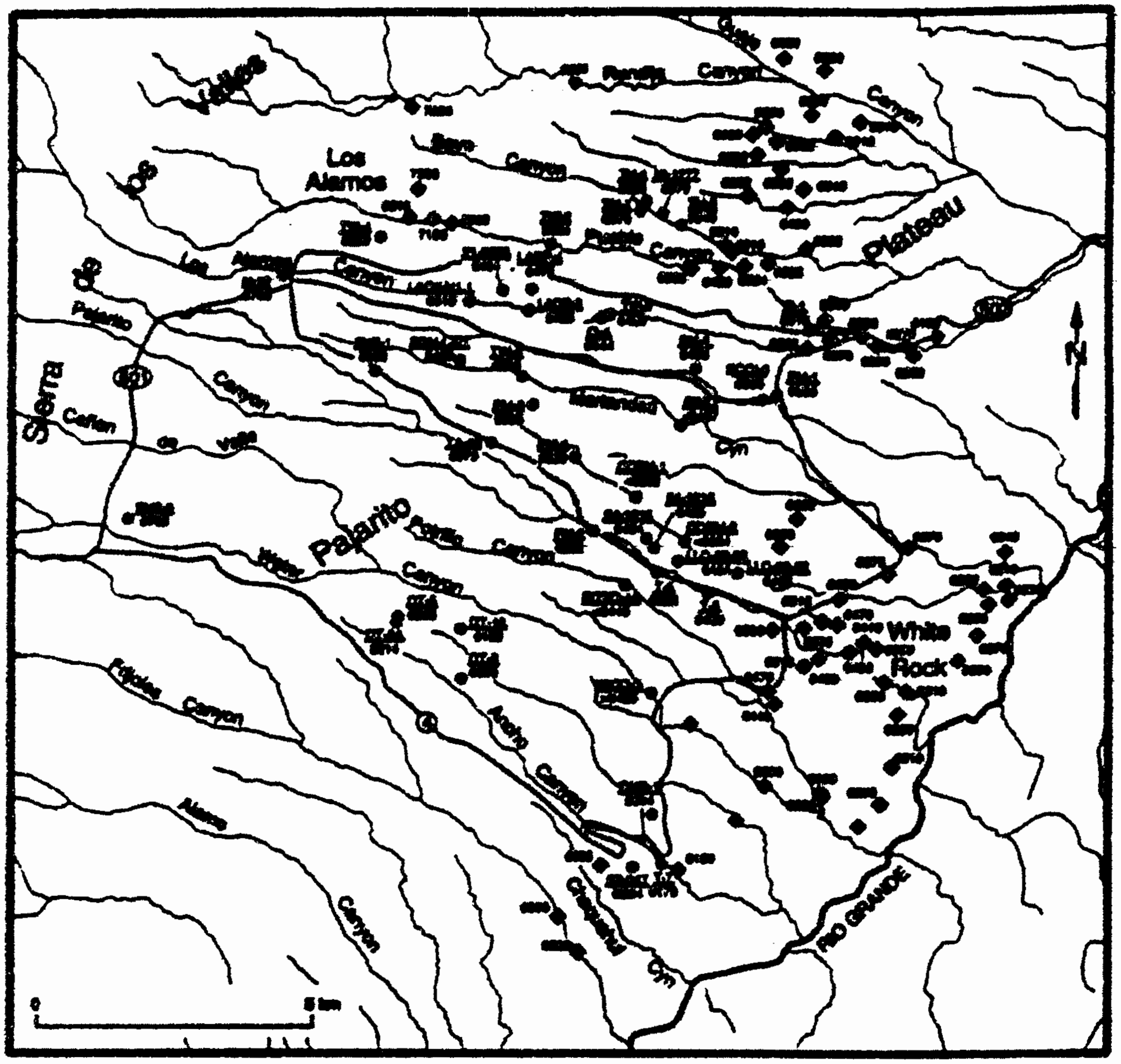

FIGURE 1. Location map of the Pajarito Plateau showing the data points used to construct the pre-Otowi structure contour map in Figure 4. Drill hole sites are indicated by solid black circles and outcrop sites are shown as shaded diamonds. The numbers next to the symbols indicate the elevation (in feet) of the pre-Bandelier surface at that site. Borehole names are underlined.

1978; Dransfield and Gardner, 1985). From west to east, they are the Tschicoma Formation, the Puye Formation, and basaltic rocks of Cerros del Rio. Southwest of the study area, the Santa Fe Group and Paliza Canyon Formation also formed pre-Bandelier bedrock exposures near St. Peters Dome.

The Tschicoma Formation consists of dacitic to rhyolitic lavas that were erupted from large overlapping dome complexes in the Sierra de los Valles approximately 3 to 7 Ma (Griggs, 1964; Doell et al, 1968; Gardner et al., 1986). Lava flows from the distal parts of these dome complexes extend under the western part of Los Alamos, where they are interbedded with the Puye Formation (Purtymun, 1995).

The Puye Formation (1.6-4 Ma; Turbeville et al., 1989; Spell et al., 1990) is a volcanogenic alluvial fan deposit shed eastward from the Tschicoma volcanic highlands. Prior to deposition of the Otowi Member, the Puye Formation was primarily exposed in a NE-trending belt of outcrops flanking the Sierra de los Valles (Fig. 3), although it also included narrow bands of alluvium along the pre-Otowi stream channels. It is a fanglomerate consisting of poorly sorted boulders, cobbles, and coarse sands made up of dacitic to rhyolitic debris, and contains numerous interbedded lapilli tuff beds and laharic deposits (Griggs, 1964; Waresback and Turbeville, 1990). In outcrops along the Rio Grande, the Puye Formation also contains basaltic debris derived from contemporaneous volcanism and erosion of the Cerros del Rio volcanic field.

The basalts of Cerros del Rio (2.3-2.8 Ma; Manley, 1976, 1979; Bachman and Mehnert, 1978; WoldeGabriel et al., 1995, and this volume) include Pliocene olivine tholeiites, basaltic andesites, basanites, alkali olivine basalts, and hawaiites erupted from vents east and west of the Rio Grande (Aubele, 1978, Baldridge, 1979; Dethier, in press). The main part of the volcanic field lies east of the Rio Grande, but outcrop and borehole data indicate that a major extension of the volcanic field is buried beneath the Bandelier Tuff on the Pajarito Plateau (Fig. 3). Cerros del Rio basalts formed surface outcrops as far west as borehole PM-5 (Fig. 1), and they were buried by Puye deposits even farther to the west (Fig. 3).

The west side of White Rock was a basaltic topographic high prior to eruption of the Otowi Member. West of White Rock, the uppermost basalt flows, including those buried by Puye Formation fanglomerates, systematically decrease in elevation from east to west. The uppermost basalts decrease in elevation from 6500 ft near White Rock to 6320 ft in borehole PM-4, beneath the north-central part of the Pajarito Plateau, and to 5977 ft in borehole DT-5A (Purtymun, 1995) in the south-central part of plateau. Basalts dip eastward from the crest of the basaltic high towards the Rio Grande in the eastern part of White Rock.

PRE-OTOWI LANDSCAPE

Structure contours for the base of the Bandelier Tuff show the paleotopography of the Pajarito Plateau area at about 1.61 Ma (ages of Bandelier Tuff from Izett and Obradovich, 1994), just prior to eruption of the Otowi Member, and reveal a landscape that was significantly different from that of today (Fig. 4). Whereas the modern Pajarito Plateau is a high E- and SE- dipping tableland dissected by numerous deep can-

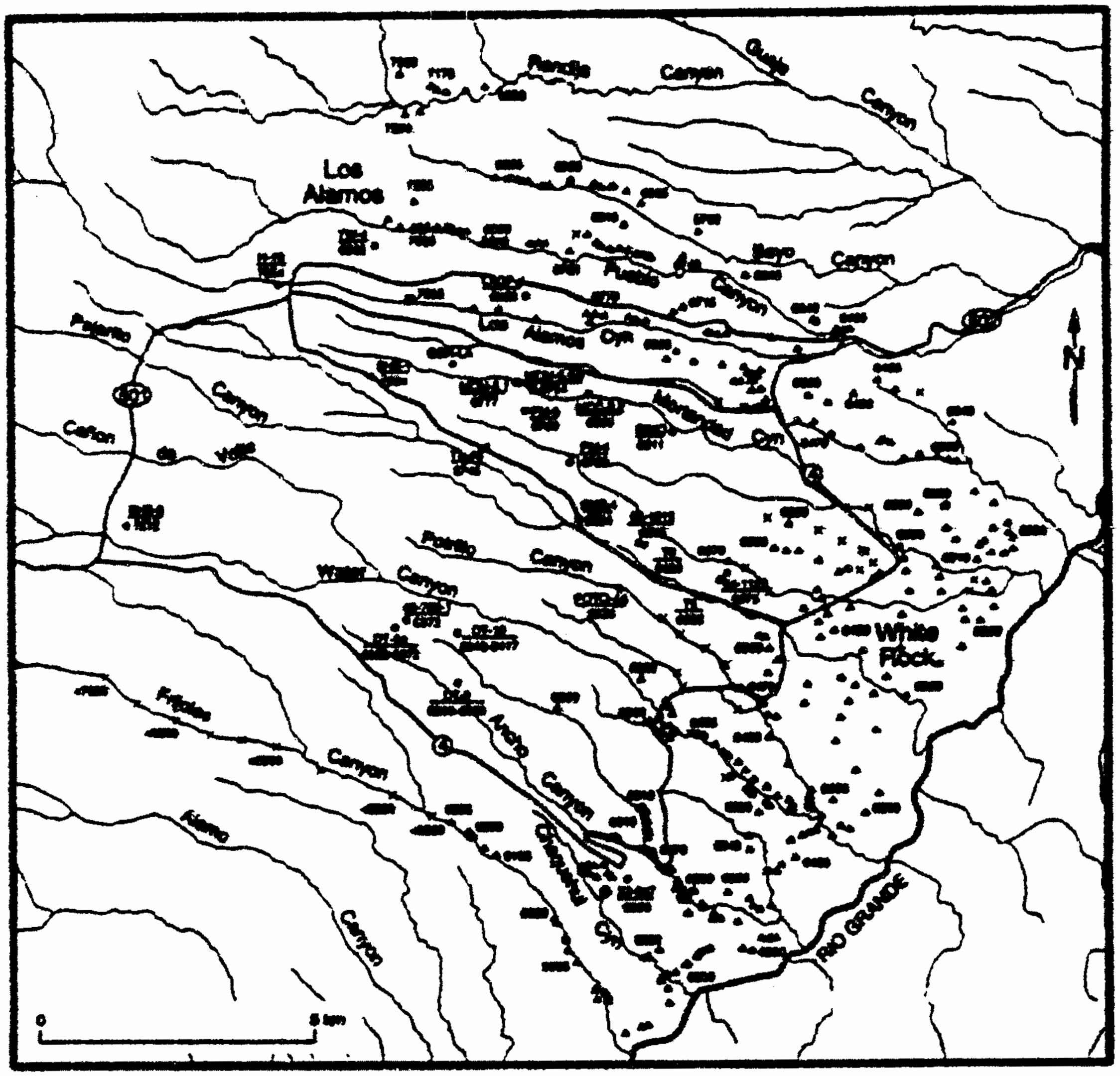

FIGURE 2. Location map of the Pajarito Plateau showing the data points used to construct the pre-Tshirege structure contour map in Figure 6. Drill hole sites are indicated by solid black circles and outcrop sites are shown as triangles. Sites used to constrain the maximum elevation of the Tshirege basal contact (where the base is not exposed) are marked by "x"s. The numbers next to some of the symbols indicate the elevation (in feet) of the pre-Tshirege surface at that site; only selected data are shown for areas with a high density of measurements. Borehole names are underlined.

yons, much of the same area was occupied by a broad SSW-draining valley prior to eruption of the Bandelier Tuff (Fig. 4). A roughly S-draining pre-Bandelier valley was also inferred by Dransfield and Gardner (1985) in this area. The valley was flanked on the west by the deeply dissected volcanic highlands of the Sierra de los Valles which rose ~4300 ft above the valley floor. The east side of the valley was separated from the ancestral Rio Grande by the basaltic highland west of White Rock that stood approximately 400 ft higher than the valley floor.

The overall shape and orientation of the Pleistocene valley is fairly well constrained by surface and subsurface data. The valley was about 4 mi wide, had a minimum length of 6.2 mi (Fig. 4), and extended from the present Los Alamos Canyon on the north at least to Frijoles Canyon on the south. An E- to SE-dipping surface of low relief bounds the north end of the valley. This surface is underlain by the Puye Formation, and probably represents the upper aggradational limit of an alluvial fan complex shed from Tschicoma Formation domes in the Sierra de los Valles (e.g., Waresback and Turbeville, 1990).

The southwest flank is poorly characterized compared to the rest of the valley. Few deep wells provide control in this area, and critical field relations are covered by the Tshirege Member. However, data from borehole SHB-3 (Gardner et al., 1993) and from the east slope of the Sierra de los Valles provide some constraints on the location of the west side of the valley and indicate that the valley axis must be near the location shown in Figure 4.

Early Pleistocene canyons of the Sierra de los Valles as far north as the headwaters of modern Rendija Canyon apparently drained eastward and southeastward into this pre-Bandelier valley (Fig. 4). Streams entering the valley probably merged into a master drainage that flowed south towards the Rio Grande. Undoubtedly, smaller west-flowing drainages emptied into the valley from the low N-trending basalt ridge to the east as well. However, this inferred finer-scale topography can not be resolved with available data.

The early Pleistocene topography of the east flank of the Sierra de los Valles highlands was probably little different from that of the middle and upper parts of the range today. Erosional remnants of Bandelier Tuff are found in many of the major canyons and on the lower slopes of the Sierra de los Valles, and the contact between the Bandelier Tuff and the dacitic lavas of the highlands preserves a record of the pre-Bandelier paleotopography. The distribution of these remnants on canyon floors and walls as well as on east-sloping surfaces indicate that the locations, sizes, and shapes of canyons at the time of the Otowi eruption were probably similar to those of today.

A north-trending structural high northwest of the valley is an eastern outlier of thick Tschicoma Formation lava flows exposed on the north wall of modern Pueblo Canyon (Fig. 4). These lava flows form a narrow ridge bounded by the Rendija Canyon and Guaje Mountain faults (Fig. 3), suggesting a tectonic influence on the paleotopography. Although the apparent relief of this buried ridge was enhanced by post-Otowi faulting,

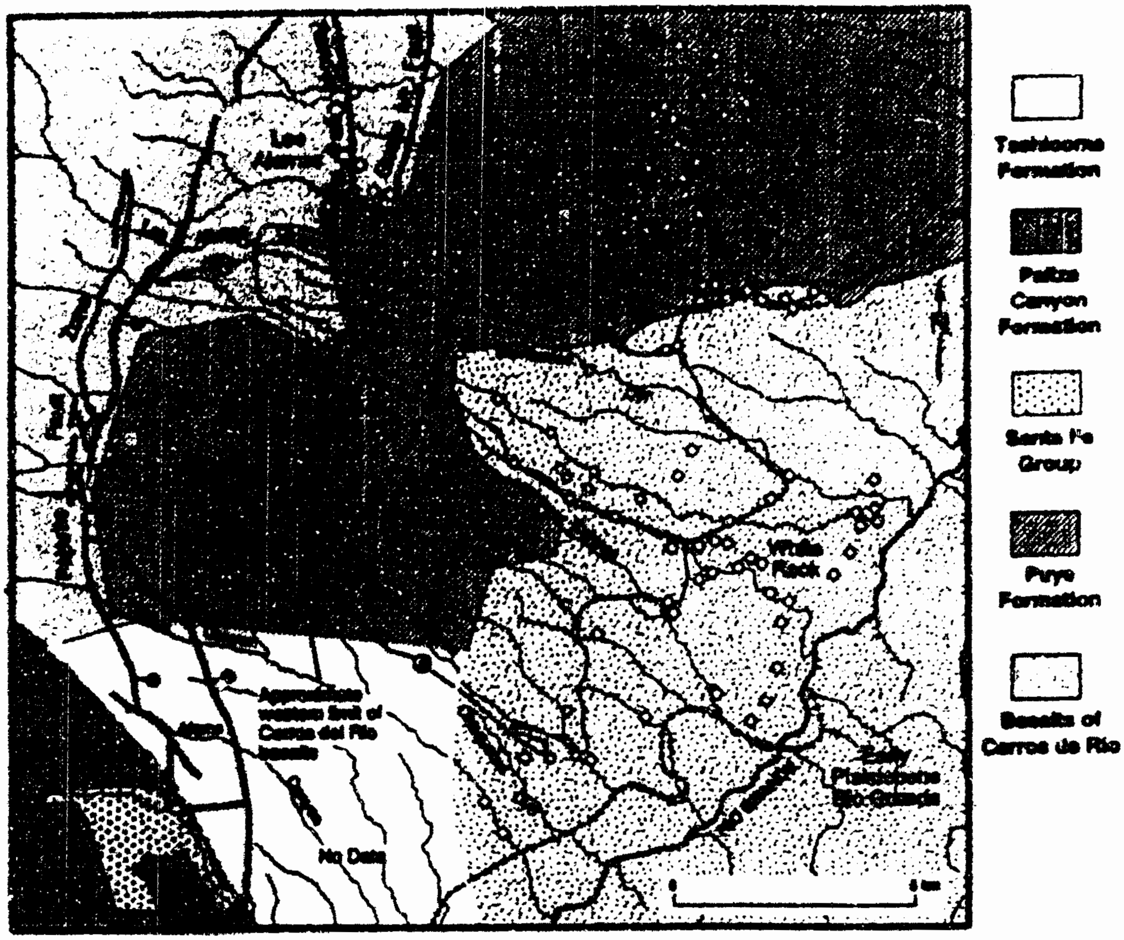

FIGURE 3. Generalized bedrock geologic map of the pre-Bandelier surface beneath the Pajarito Plateau. Control points are indicated by open circles for boreholes and open diamonds for outcrops. Geologic map unit distributions (Griggs, 1964; Smith et al, 1970) were also used to map the extent of bedrock units. The locations of major faults (thick black lines, modified from Gardner and House, 1987) are shown for comparison. The dashed black line shows the approximate western extent of Cerros del Rio basalts buried beneath Puye sediments on the Pajarito Plateau. Position of early Pleistocene Rio Grande (heavy dashed line) is from Reneau and Dethier (this volume).

its height relative to post-Tshirege faulting suggests that this area was a topographic high both before and after the Otowi eruption.

The basaltic highland above 6500 ft elevation near White Rock, which separated the early Pleistocene valley from the ancestral Rio Grande (Fig. 4), represents a western extension of the Pliocene Cerros del Rio volcanic field, most of which occurs east of the Rio Grande. This low N-trending ridge is probably a line of basaltic vents that extend from the west side of White Rock to the vicinity of Mortandad Canyon and perhaps farther north. Vent facies basaltic cinder and agglutinate deposits are exposed west of White Rock and were recently encountered in boreholes 54-1015 and 54-1016 (LANL Environmental Restoration Project, unpubl. data, 1995) (Fig. 1). Smith et al. (1970) showed a basaltic vent on trend with the ridge as far north as Bayo Canyon. The basaltic ridge was completely buried by the Tshirege Member, and it has no topographic expression today.

An isolated paleotopographic high southwest of White Rock, between Chaquehui and Ancho Canyons, is a Pliocene basaltic cinder cone (Fig. 4). The cinder cone, which stood about 500 ft above the valley to the northwest and 900 ft above the early Pleistocene Rio Grande to the southeast, was almost completely buried by the Tshirege Member of the Bandelier Tuff and has little surface expression today.

The early Pleistocene landscape was probably exposed for a long time prior to being covered by the Otowi Member, allowing the development of strong soil horizons in many locations. Immediately beneath the Otowi Member in Pueblo Canyon, near the junction with Los Alamos Canyon (Fig. 1), 20 cm of sandy soil overlies 3 cm of stage 4 laminar carbonates (soil carbonate terminology of Gile et al., 1966), and carbonate-coated clasts occur in the upper 1 m of the underlying Puye Formation. Clay-rich soils occur on top of the Puye Formation in Los Alamos Canyon in borehole LADP-3 (Broxton et al., 1995) and in outcrops in upper Rendija Canyon. Laminar carbonates are also common at the top of basalts in the White Rock area. Because of their apparent widespread occurrence and relatively impermeable nature, these buried soils may be be responsible for perching of ground water in the Guaje Pumice Bed where it overlies the Puye Formation in Los Alamos Canyon (Broxton et al., 1995) and in other areas.

EMPLACEMENT OF THE OTOWI MEMBER

Emplacement of the Otowi ignimbrite sheet largely reshaped the early Pleistocene landscape of the Pajarito Plateau. Ignimbrites from the Jemez Mountains to the west, moving under the influence of gravity, travelled down the slopes and canyons of the Sierra de los Valles before merging at the mountain front and spreading across the adjacent lowland areas. The ignimbrites largely filled in topographic lows such as the pre-Otowi early Pleistocene valley and smoothed out the land surface, forming a broad ignimbrite sheet that dipped gently to the east, southeast, and locally south.

The isopach map (Fig. 5) shows the distribution and thickness of Otowi deposits prior to emplacement of the Tshirege Member. The map may reflect the original thickness of the Otowi Member in some areas. However, because of its poorly indurated nature and its exposure at the face for about 400 ka, the Otowi Member was probably extensively eroded before its burial by the Tshirege Member, and its original thickness cannot be estimated.

Thick Otowi deposits are found in the northern half of the SSW-draining pre-Bandelier valley. These deposits are up to 465 ft thick in borehole EGH-LA-1 (Fig. 5), and may represent topographically controlled ponding of the ignimbrites near the mouth of the early Pleistocene Lo

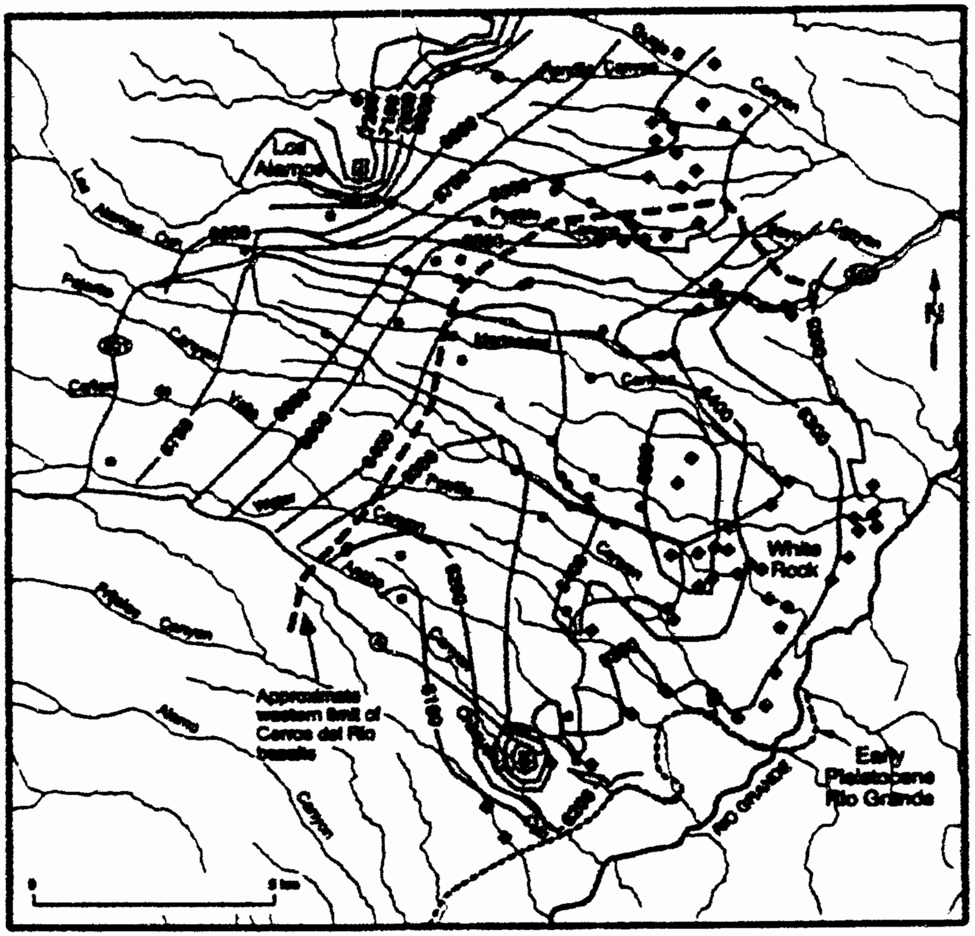

FIGURE 4. Structure contour map (contour interval 100 ft) for the pre-Otowi surface beneath the Pajarito Plateau. Control points are shown for boreholes (solid black circles) and outcrop sites (diamonds).

Alamos Canyon. Thick deposits (415 ft) of Otowi ignimbrites were also penetrated in borehole SHB-3 on the southwest flank of the valley. The SHB-3 deposits are adjacent to the area where Cañon de Valle exits the Sierra de los Valles, and they may represent an apron of Otowi ignimbrites piled up at the mouth of this early Pleistocene canyon. Los Alamos Canyon and Cañon de Valle were major drainages that headed in broad passes between the dacitic domes of the Tschicoma Formation prior to the Otowi eruption, and may have acted as funnels during passage of ignimbrites from the caldera source to the west.

The Otowi ignimbrites thin eastwards against the basaltic ridge, and they are absent in the area around White Rock (Fig. 5). These ignimbrites may have overtopped the basaltic ridge near White Rock, but, if so, the resulting deposits were relatively thin and were eroded before deposition of the Tshirege Member. Ignimbrites skirted the basaltic ridge to north, resulting in thicker deposits of the Otowi Member in that area.

PRE-TSHIREGE LANDSCAPE

Structure contours for the base of the Tshirege Member show the estimated paleotopography of the Pajarito Plateau area at about 1.22 Ma (age from Izett and Obradovich, 1994), and indicate significant differences from both the pre-Otowi and the modern landscape (Fig. 6). Although some of the major pre-Otowi features remained, such as the basaltic high near White Rock and the SSW-trending valley in the southern part of the map area, their relief had decreased substantially and the northern part of the early Pleistocene valley had been completely buried.

The pre-Tshirege landscape included outcrops of Tschicoma Formation dacite to the west and Cerros del Rio basalts to the east, with extensive areas of relatively low relief where drainages had eroded into the Otowi Member. Widespread areas were apparently occupied by stream terraces that formed between 1.61 and 1.22 Ma, indicated by alluvial deposits that are typically overlain by pumice beds associated with the Cerro Toledo Rhyolite (Heiken et al., 1986) and intervening buried soils In other areas, inferred to be paleotopographic drainage divides o hillslopes, pre-Tshirege alluvial deposits are absent and the Otowi Mem ber is overlain either by a sequence of Cerro Toledo pumice beds an buried soils or by thin colluvial deposits. Local relief was apparentl much less than today, and, where well exposed to the north, the pre Tshirege stream valleys were typically about 50-100 ft deep in areas wher modern canyons locally exceed 300 ft in depth (Fig. 6). Notably, be cause the Otowi Member is entirely nonwelded in this area, the pre Tshirege landscape lacked the sharp mesa-canyon topography that is s prominent today.

The approximate locations of four major pre-Tshirege drainages hav been identified based both on the structure contour map (Fig. 6) and o the presence of pre-Tshirege alluvial deposits that contain cobbles an boulders of Tschicoma Formation dacite derived from the Sierra de lo Valles. One large drainage basin headed in the Tschicoma highlands nort and northwest of Los Alamos and included the headwaters of the mod ern Rendija Canyon basin. The axial channel of this large drainage trende southeast across what are now Bayo, Pueblo, Los Alamos, and Sandi Canyons before emptying into the ancestral Rio Grande north of the Whi Rock basalt high. Another stream, whose headwaters apparently include the modern Los Alamos Canyon headwaters, trended southeast acros Pajarito, Potrillo, and Fence Canyons; alluvial deposits from this strea are exposed along lower Water Canyon on the southwest side of the Whi Rock basalt topographic high. Pre-Tshirege alluvial deposits along low Ancho Canyon record an additional drainage northeast of the Plioce cinder cone, and the active stream channel at the time of the initial Tshire eruptions was exposed at one location, shown by fluvial erosion of th basal Tsankawi pumice bed and basal Tshirege ignimbrite prior to em placement of the main Tshirege ignimbrites. The course of this strea beneath the Plateau is poorly defined due to the scarcity of subsurfac

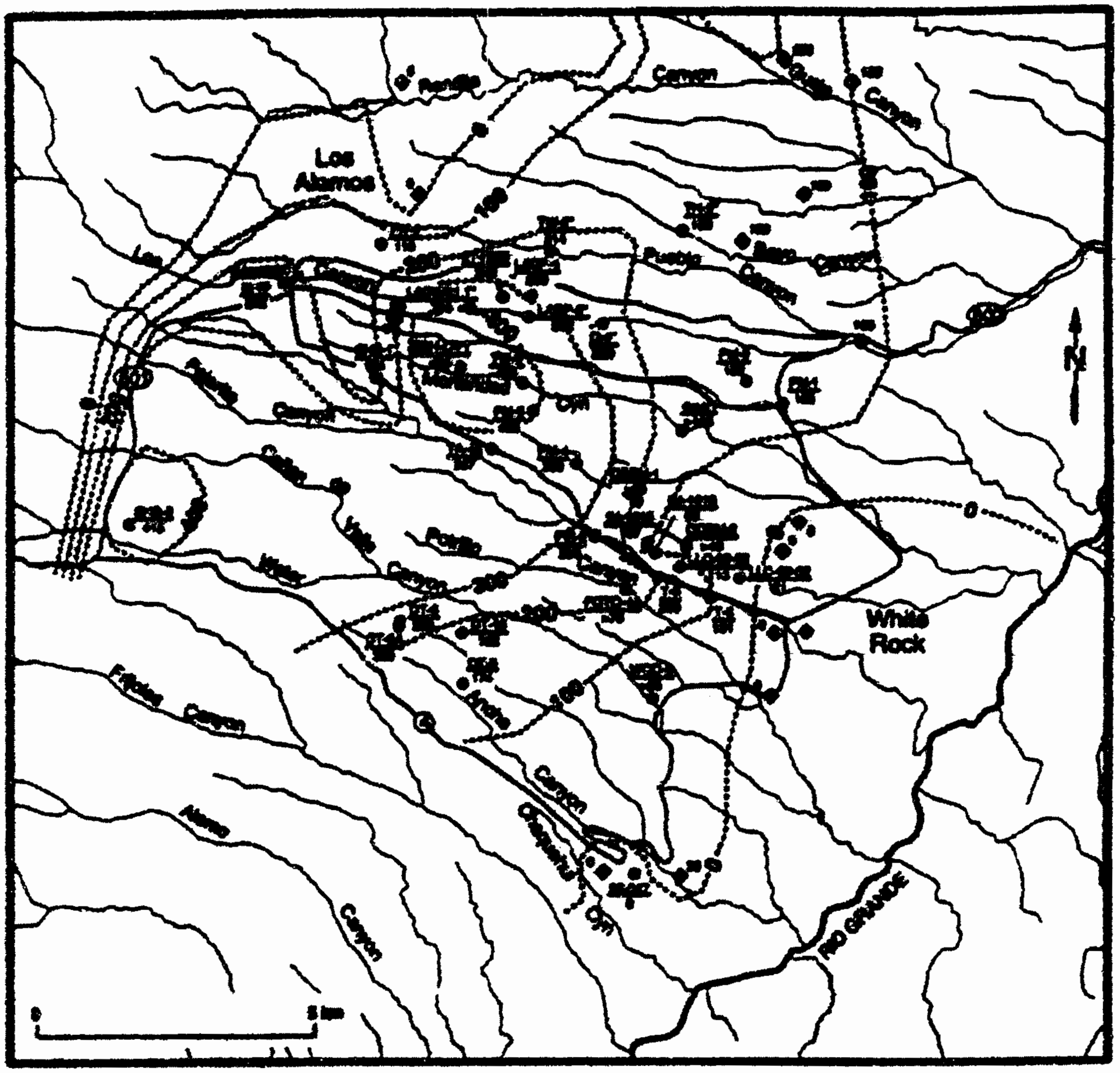

FIGURE 5. Isopach map showing the approximate thickness of the Otowi Member of the Bandelier Tuff just prior to emplacement of the Tshirege Member. Control points are shown for boreholes (solid black circles) and outcrop sites (diamonds). The numbers next to the symbols indicate the thickness (in feet) of the Otowi Member, including the Guaje Pumice Bed. Borehole names are underlined. A small asterisk next to a borehole name indicates the thickness was determined from the bottom of the unit in the borehole and the top of the unit in nearby outcrops.

data, but the structure contour map (Fig. 6) suggests its headwaters included the modern upper Pajarito Canyon basin. A SSW-draining basin, inferred largely from subsurface data, is a subdued version of the major pre-Otowi valley; its headwaters apparently included the modern Cañon de Valle and Water Canyon watersheds. Although the southern extent of this drainage is not certain, dacite-rich pre-Tshirege alluvium exposed in Alamo Canyon may be associated with this stream.

EMPLACEMENT OF THE TSHIREGE MEMBER

The thickness of the Tshirege Member varies greatly across the Pajarito Plateau (Fig. 7). These thickness variations are controlled at least in part by the paleotopography developed on top of the Otowi Member prior to Tshirege deposition. Deposition of the Tshirege ignimbrites largely erased the former topography and provided a new surface for the development of the post-Tshirege drainages. The Tshirege Member exceeds 650 ft in thickness in the south part of the study area, and the SSW-draining valley inherited from pre-Otowi time was completely buried, being replaced by an ESE-trending post-Tshirege drainage system. About 750 ft of tuff was emplaced in the area of lower Chupaderos and Frijoles Canyons, where the early Pleistocene Rio Grande paleocanyon was also completely buried (Reneau and Dethier, this volume), and the tuff is at least 850 ft thick in upper Frijoles Canyon (west of the main study area). In contrast, the tuff thinned to virtually nothing over the Pliocene cinder cone, whose top forms a very low hill above the modern mesa. The Tshirege Member also did not completely bury many outcrops of Tschicoma Formation dacite to the west and north.

Over most of the central and northern Pajarito Plateau, the Tshirege Member reached a thickness of between 100 and 400 ft (Fig. 7), and it is typically thicker than what is preserved of the Otowi Member. Thicknesses greater than 400 ft are confined to the southwest part of the study area and the Rio Grande paleocanyon; thicknesses of less than 100 ft are confined to the area of the White Rock basalt high, the Pliocene cinder cone, and the Tschicoma highlands. Notably, there is a general decrease in the thickness of the Tshirege Member along strike to the north, and the top of the ignimbrite sheet has a more easterly slope than the pre-Tshirege landscape. As a result, a post-Tshirege drainage network was established that is generally oblique to the earlier channels, and the locations of the modern canyons on the Plateau apparently have little or no relation to the pre-eruption channels. Locally, the post-Tshirege channels were superimposed on pre-Tshirege paleotopographic highs, such as Pajarito Canyon at White Rock.

The north-to-south thickness variations are likely related in part to topographic funnelling of the Tshirege ignimbrites down paleocanyons in the Sierra de los Valles. The area of relatively thin tuff to the north appears to be a "shadow zone" behind high Tschicoma domes, whereas the area of thicker tuff to the south would have been fed by ignimbrites

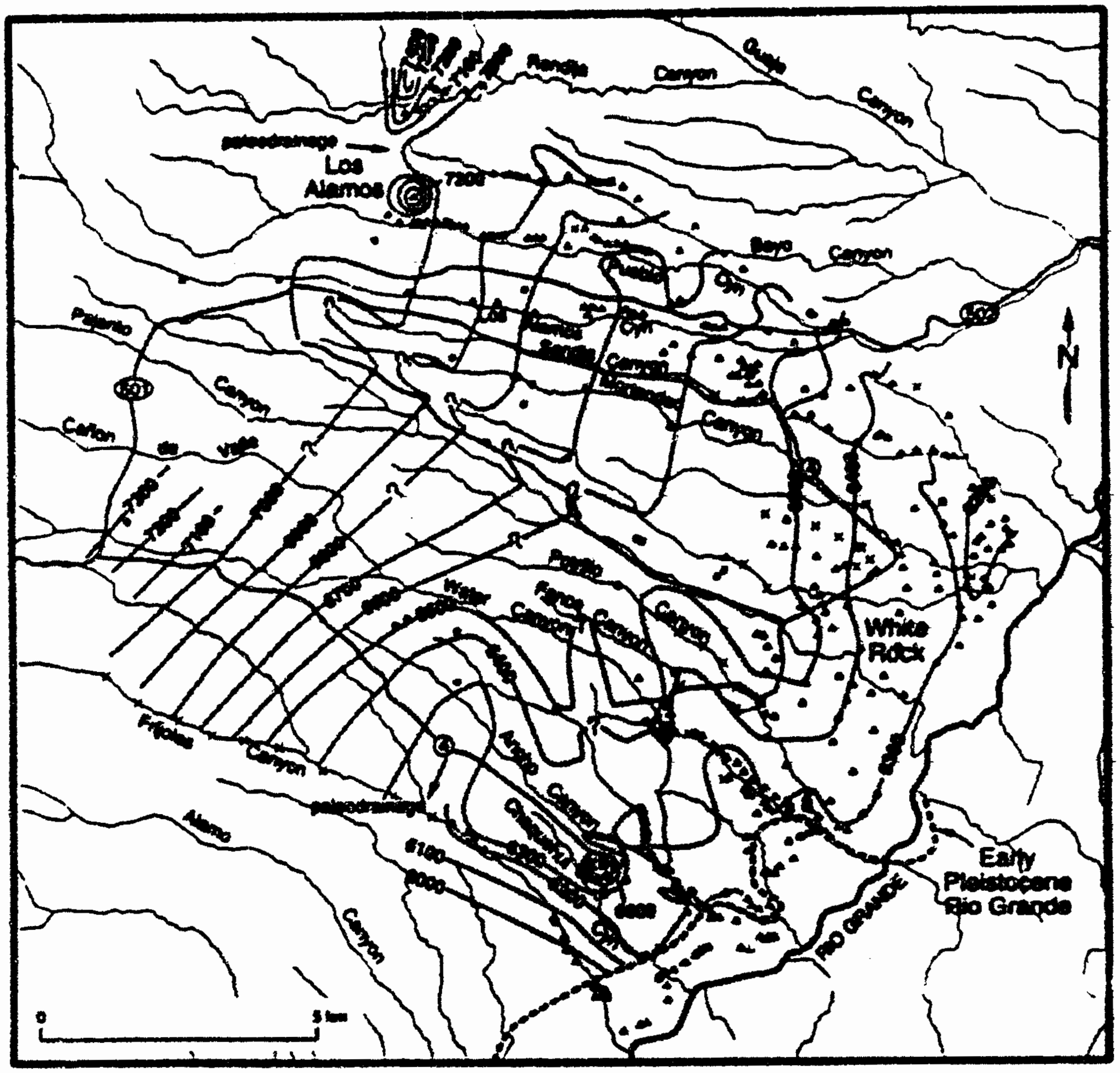

FIGURE 6. Structure contour map (contour interval 100 ft) for the pre-Tshirege surface beneath the Pajarito Plateau. Control points are shown for boreholes (solid black circles) and outcrop sites (triangles). Sites used to constrain the maximum elevation of the Tshirege basal contact (where the base is not exposed) are marked by "x"s. Note that local paleotopographic relief and location of buried drainages is known with greatest confidence in areas where the base of the Tshirege Member is exposed in outcrop (generally to the east and north), and that under much of the Plateau, data are insufficient to delineate drainages. In these areas (generally to the west and south), the paleotopography is undoubtedly more dissected than depicted.

passing through low areas on the caldera rim and travelling down the pre-Tshirege Los Alamos Canyon and Cañon de Valle.

IMPLICATIONS FOR STRUCTURAL EVOLUTION OF THE PAJARITO PLATEAU AREA

Gravity data and the lithology of the upper Santa Fe Group suggest that the SSW-trending pre-Otowi valley of the Pajarito Plateau is at least in part a structurally controlled basin, as opposed to simply an erosional valley that formed between two constructional volcanic highlands. A series of en echelon gravity lows occur on the west side of the Pajarito Plateau (Budding, 1978; Cordell, 1979; Ferguson et al., 1995). These gravity lows have amplitudes of over 4 mgals and are defined by N- and NNE-trending anomalies. One of these gravity lows occurs in the vicinity of Los Alamos. It has a dumbbell shape with the larger, southern part overlapping the western flank of the early Pleistocene valley (Fig. 8). The west side of the anomaly coincides with the Pajarito fault zone, and the east side appears to coincide with the west flank of the Cerros del Rio volcanic field (Fig. 8). Ferguson et al. (1995) interpreted the gravity lows as thick sequences of low-density sedimentary deposits that accumulated in narrow grabens on the western side of the Española basin of the Rio Grande rift.

It seems likely that the location of the early Pleistocene valley was at least partly controlled by subsidence of this graben. The Pajarito fault zone has been active from at least 16 Ma to the present (Gardner and Goff, 1984; Gardner and House, 1987) and sediments of Santa Fe and Puye age may have accumulated in this graben during much of this time. The axis of the valley lies east of the axis of the gravity low (Fig. 8), suggesting that prograding alluvial fans of the Puye Formation infilled the graben from the west, forcing the depositional axis to migrate to the east side of the graben.

The lithology of the upper Santa Fe Group supports the interpretation of a graben under the Pajarito Plateau. Purtymun (1995) described a trough of coarse-grained sediments at the top of the Santa Fe Group ("Chaquehui Formation") that would allow the development of high-yield, low-draw-down water supply wells. The trough is late Miocene in age (based on ca. 9 Ma basalt flows interlayered with the sediments in well Otowi-4; $^{40}Ar/^{39}Ar$ ages (A. W. Laughlin, unpubl. report for Los Alamos National Laboratory, 1993); and its location coincides with the early Pleistocene valley described in this paper (Fig. 8). This Miocene trough is about 2.5 mi wide and extends at least 7.5 mi from the northeast to the southwest, although subsurface data are not available to determine its full length. It is filled with up to 1500 ft of coarse gravelly sediments, including volcanic, metamorphic, and sedimentary clasts possibly derived from highlands to the north, east, and west. The apparent persistence of this depositional basin from the Miocene into the early Pleistocene suggests that the graben beneath the western part of the Pajarito Plateau was a long-

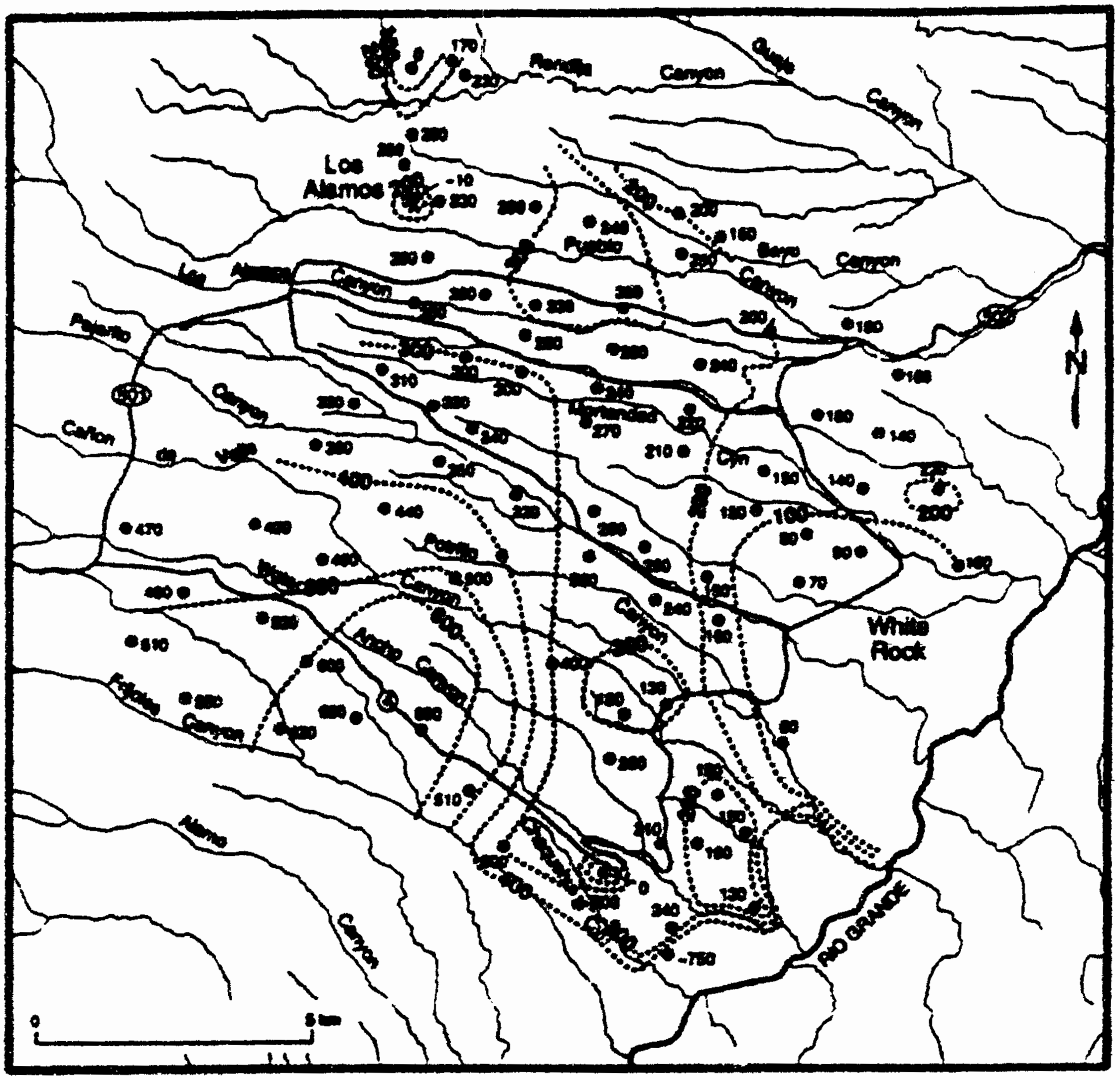

FIGURE 7. Isopach map showing the approximate original thickness of the Tshirege Member, Bandelier Tuff. Control points (solid black circles, with adjacent numbers indicating estimated thickness in feet) are based on difference between mesa top elevation and the estimated pre-Tshirege structure contours, based on Fig. 6. No attempt was made to estimate the thickness of tuff eroded from the mesa tops, and the actual original thickness may generally be greater.

lived feature, although the evidence is not available to indicate when it was initiated or if it remained active into the Pleistocene.

CONCLUSIONS

The pre-Bandelier landscape beneath the Pajarito Plateau was significantly different from that of today. Much of the area was apparently dominated by a SSW-draining valley flanked by dacitic highlands of the Sierra de los Valles on the west and by a low N-trending basaltic ridge on the east. Paleocanyons of the Sierra de los Valles drained eastward to this valley where the mountain streams probably merged with a master drainage that flowed south towards the Rio Grande. Dacite-rich gravels of the Puye Formation occur within this valley and also underlie a broad alluvial fan to the north. Outcrop and borehole data indicate that a major extension of the Cerros del Rio volcanic field lies buried beneath the Bandelier Tuff on the Pajarito Plateau. Cerros del Rio basalts formed surface outcrops as far west as the floor of the early Pleistocene valley and extended even farther to the west beneath the Puye Formation.

Eruption of the Otowi Member reshaped much of the early Pleistocene landscape, partially filling in the SSW-draining valley. The true thickness of the Otowi Member after emplacement can not be reconstructed with certainty because of its erosion prior to burial by the Tshirege Member. However, the Otowi ignimbrites ponded to a thickness of at least 465 ft in the north part of the early Pleistocene valley and thinned eastwards against the basaltic ridge.

A smaller SSW-draining post-Otowi drainage was reestablished over the southern part of the early Pleistocene valley, but a SE-trending drainage network was established over the northern part and over the buried fan to the north. Where exposed in outcrop, the pre-Tshirege landscape that developed on top of the Otowi ignimbrites had relatively little relief, with drainage channels incised about 50-100 feet below drainage divides, and flanked by extensive early Pleistocene stream terraces that were mantled with Cerro Toledo pumice deposits.

Eruption of the Tshirege Member further altered the landscape by completely burying the relict SSW-trending valley and basaltic highs to the east. The Tshirege Member generally thinned to the north, but the upper constructional surface sloped towards the east. The modern drainage systems developed on this new land surface have little relation to the pre-Tshirege drainages.

Gravity data suggest that the early Pleistocene pre-Bandelier valley is at least in part a tectonic feature. The presence of a significant gravity low in this area supports the interpretation that the valley was the surface expression of a graben on the western side of the Española basin. The Pliocene-Pleistocene depositional axis lies east of the axis of the gravity low, possibly because prograding alluvial fans of the Puye Formation infilled the graben from the west and forced the topographic axis of the valley to migrate eastward. The existence of a buried graben in this area is also supported by the presence of a SSW-trending trough of coarse-grained late Miocene sediments at the top of the Santa Fe Group.

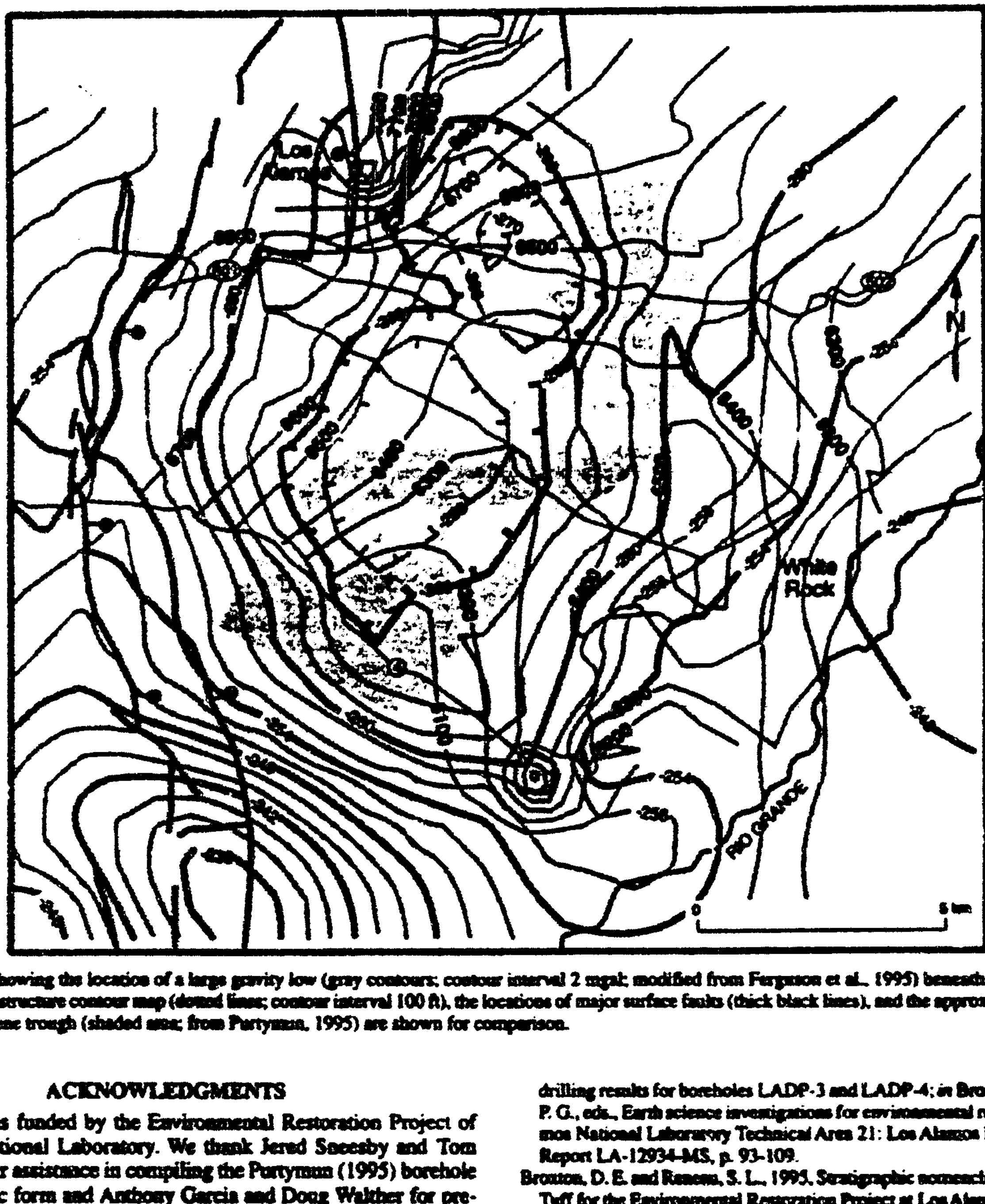

FIGURE 8. Map showing the location of a large gravity low (gray contours: contour interval 2 mgal; modified from Ferguson et al., 1995) beneath the Pajarito Plateau. The pre-Bandelier structure contour map (dotted lines; contour interval 100 ft), the locations of major surface faults (thick black lines), and the approximate position of the inferred late Miocene trough (shaded area; from Purtymun, 1995) are shown for comparison.

ACKNOWLEDGMENTS

This work was funded by the Environmental Restoration Project of Los Alamos National Laboratory. We thank Jered Sneesby and Tom McVittie for their assistance in compiling the Purtymun (1995) borehole data in electronic form and Anthony Garcia and Doug Walther for preparing the final maps. The ideas in this paper benefited from discussions with many people, including Scott Baldridge, David Dethier, Jamie Gardner, David Vaniman and Giday WoldeGabriel. John Ferguson and the Summer of Applied Geophysical Experience (SAGE) program kindly provided electronic copies of the gravity used in Figure 8. David Sawyer, James Stimac and David Vaniman provided critical reviews of this paper.

REFERENCES

Aubele, J. C., 1978, Geology of the Cerros del Rio volcanic field, Santa Fe, Sandoval, and Los Alamos counties, New Mexico [MS Thesis]: Albuquerque, University of New Mexico, 136 p.

Bachman, G. O. and Mehnert, H. H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America Bulletin, v. 89, p. 283-292.

Baldridge, W. S., 1979, Petrology and petrogenesis of Plio-Pleistocene basaltic rocks from the central Rio Grande rift, New Mexico, and their relation to rift structure; *in* Riecker, R. E. ed., Rio Grande rift, tectonics and magmatism: American Geophysical Union Monograph, p. 323-353.

Broxton, D. E., Longmire, P. A., Eller, P. G. and Flores, D., 1995, Preliminary drilling results for boreholes LADP-3 and LADP-4; *in* Broxton, D. E. and Eller, P. G., eds., Earth science investigations for environmental restoration—Los Alamos National Laboratory Technical Area 21: Los Alamos National Laboratory, Report LA-12934-MS, p. 93-109.

Broxton, D. E. and Reneau, S. L., 1995, Stratigraphic nomenclature of the Bandelier Tuff for the Environmental Restoration Project at Los Alamos National Laboratory: Los Alamos National Laboratory, Report LA-13010-MS, 21 p.

Budding, A. J., 1978, Gravity survey of the Pajarito Plateau, Los Alamos and Santa Fe Counties, New Mexico: Los Alamos National Laboratory, Report LA-7419-MS, 15 p.

Cordell, L., 1979, Gravimetric expression of graben faulting in Santa Fe County and the Española basin: New Mexico Geological Society, Guidebook 30, p. 59-64.

Dethier, D. P., in press, Geologic map of the White Rock quadrangle: New Mexico Bureau of Mines and Mineral Resources.

Doell, R. R., Dalrymple, G. B., Smith, R. L. and Bailey, R. A., 1968, Paleomagnetism, potassium-argon ages, and geology of rhyolites and associated rocks of the Valles caldera, New Mexico: Geological Society of America, Memoir 116, p. 211-248.

Dransfield, B. J. and Gardner, J. N., 1985, Subsurface geology of the Pajarito Plateau, Española basin, New Mexico: Los Alamos National Laboratory, Report LA-10455-MS, 15 p.

Ferguson, J. F., Baldridge, W. S., Braile, L. W., Biehler, S., Gilpin, B. and Jiracek, G. R., 1995, Structure of the Española basin, Rio Grande rift, New Mexico, from seismic and gravity data: New Mexico Geological Society, Guidebook 46, p. 105-110.

Gardner, J. N. and Goff, F., 1984, Potassium-argon dates from the Jemez volcanic fault implications for tectonic activity in the north-central Rio Grande rift: New Mexico Geological Society, Guidebook 35, p. 75-81.

Gardner, J. N., Goff, F., Garcia, S. and Hagan, R. C., 1986, Stratigraphic relations and lithologic variations in the Jemez volcanic field, New Mexico: Journal of Geophysical Research, v. 91, no. B2, p. 1763-1778.

Gardner, J. N. and House, L., 1987, Seismic hazards investigations at Los Alamos National Laboratory, 1984 to 1985: Los Alamos National Laboratory, Report, LA-11072-MS, 76 p.

Gardner, J. N., Kolbe, T. and Chang, S., 1993, Geology, drilling, and some hydrologic aspects of Seismic Hazards Program core holes, Los Alamos National Laboratory, New Mexico: Los Alamos National Laboratory, Report LA-12460-MS, 19 p.

Gile, L., Peterson, F. F. and Grossman, R. B., 1966, Morphologic and genetic sequences of carbonate accumulation in desert soils: Soil Science, v. 101, p. 347-360.

Goff, F., 1995, Geologic map of Technical Area 21; in Broxton, D. E. and Eller, P. G., eds., Earth science investigations for environmental restoration—Los Alamos National Laboratory Technical Area 21: Los Alamos National Laboratory, Report LA-12934-MS, p. 33-64.

Griggs, R. L., 1964, Geology and ground-water resources of the Los Alamos area, New Mexico: U.S. Geological Survey Water-Supply Paper 1753, 107 p.

Heiken, G., Goff, F., Stix, J., Tamanyu, S., Shafiqullah, M., Garcia, S. and Hagan, R. C., 1986, Intracaldera volcanic activity, Toledo caldera and embayment, Jemez Mountains, New Mexico: Journal of Geophysical Research, v. 91, p. 1799-1815.

Izett, G. A. and Obradovich, J. D., 1994, $^{40}Ar/^{39}Ar$ age constraints for the Jaramillo Normal Subchron and the Matuyama-Brunhes geomagnetic boundary: Journal of Geophysical Research, v. 99, p. 2925-2934.

Manley, K., 1976, K-Ar age determinations on Pliocene basalts from the Española basin, Rio Grande rift, New Mexico: Isochron West, no. 16, p. 29-30.

Manley, K., 1979, Stratigraphy and structure of the Española basin, Rio Grande rift, New Mexico; in Riecker, R. E., ed., Rio Grande rift, tectonics and magmatism: American Geophysical Union Monograph, p. 71-87.

Purtymun, W. D., 1995, Geologic and hydrologic records of observation wells, test holes, test wells, supply wells, springs, and surface water in the Los Alamos area: Los Alamos National Laboratory, Report LA-12883-MS, 339 p.

Reneau, S. L. and Dethier, D. P., 1996, Pliocene and Quaternary history of the Rio Grande, White Rock Canyon and vicinity, New Mexico: New Mexico Geological Society, Guidebook 47.

Reneau, S. L., Dethier, D. P. and Carney, J. S., 1995, Landslides and other mass movements near Technical Area 33, Los Alamos National Laboratory: Los Alamos National Laboratory, Report LA-12955-MS, 48 p.

Smith, R. L., Bailey, R. A. and Ross, C. S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geological Survey, Miscellaneous Geologic Investigations Map I-571, scale 1:125,000.

Spell, T. L., Harrison, T. M. and Wolff, J. A., 1990, $^{40}Ar/^{39}Ar$ dating of the Bandelier Tuff and San Diego Canyon ignimbrites, Jemez Mountains, New Mexico: temporal constraints on magmatic evolution: Journal of Volcanology and Geothermal Research, v. 43, p. 175-193.

Turbeville, B. N., Waresback, D. B. and Self, S., 1989, Lava-dome growth and explosive volcanism in the Jemez Mountains, New Mexico: evidence from the Plio-Pleistocene Puye alluvial fan: Journal of Volcanology and Geothermal Research, v. 36, p. 267-291.

Waresback, D. B. and Turbeville, B. N., 1990, Evolution of a Plio-Pleistocene volcanogenic alluvial fan: the Puye Formation, Jemez Mountains, New Mexico: Geological Society of America Bulletin, v. 102, p. 298-314.

WoldeGabriel, G., Laughlin, A. W., Dethier, D. P., and Broxton, D. E., 1995, Episodic volcanism and geochemistry in the Pajarito Plateau, Jemez volcanic field, New Mexico: Geological Society of America, Abstracts with Programs, v. 27, no. 6, p. A-419.

WoldeGabriel, G., Laughlin, A. W., Dethier, D. P. and Heizler, M., 1996 Temporal and geochemical trends of lavas in White Rock Canyon and the Pajarito Plateau, Jemez volcanic field, New Mexico, U.S.A.: New Mexico Geological Society, Guidebook 47.

12

55429

THE JEMEZ MOUNTAINS REGION

Broxton and Reneau, 1996

A-38

76.95

Editors

FRASER GOFF
BARRY S. KUES
MARGARET ANNE ROGERS
LES D. McFADDEN
JAMIE N. GARDNER

New Mexico Geological Society
Forty-Seventh Annual Field Conference
September 25–28, 1996

1996
FIELD CONFERENCE SCHEDULE

Wednesday, September 25—Registration Day

4:00–8:00 p.m.	Registration at Sheraton Uptown Hotel, northeast corner of Menaul and Louisiana, Albuquerque
5:00–8:00 p.m.	Icebreaker and snacks, Sheraton Uptown

Thursday, September 26—First Day

7:00 a.m.	Assemble at First Day starting point, north side of Bernalillo
12:00 noon	Lunch provided
6:00 p.m.	Arrive in Los Alamos
6:30 p.m.	Banquet buffet at Fuller Lodge, Los Alamos; tours of nearby Los Alamos Historical Museum and Los Alamos Lab Museum
8:30 p.m.	Speaker: Hal K. Rothman, Historian, "The Pajarito Plateau Before the Bomb."

Friday, September 27—Second Day

6:00 a.m.	Breakfast at Sullivan Field, Diamond Drive, Los Alamos
7:00 a.m.	Depart from Sullivan Field in 15-passenger vans
12:00 noon	Lunch provided
5:30 p.m.	Return to Los Alamos
6:00 p.m.	Barbecue dinner at North Mesa picnic grounds, Los Alamos

Saturday, September 28—Third Day

6:00 a.m.	Breakfast at Sullivan Field, Los Alamos
7:00 a.m.	Depart from Sullivan Field
12:00 noon	Lunch provided
5:30 p.m.	Field Conference ends at Tent Rocks, near Cochiti Pueblo

CREDITS

Front Cover: Generalized map of the Jemez Mountains region, Fraser Goff, Los Alamos National Laboratory.

Front End Sheets: Satellite photo of the Jemez Mountains region, courtesy of Los Alamos National Laboratory.

Logistical Assistance: Los Alamos Chamber of Commerce; Tom Merson, Los Alamos Geological Society; Capt. Ken Horton, Los Alamos Police Department; Santa Fe National Forest; John Corbin, Sulphur Springs; Los Alamos First United Methodist Women.

Extraordinary Assistance: General thanks to Los Alamos National Laboratory, EES and CST Divisions, for financial support, logistical assistance, and access to some LANL areas.

Photography and Figures: Filler photos and captions provided by Los Alamos National Laboratory; figure preparation, Anthony Garcia of EES-1 (LANL), and Kathryn Glesener, N.M. Bureau of Mines and Mineral Resources.

Word Processing and Computer Publishing: Lynne Hemenway and Terry Tellis, N.M. Bureau of Mines and Mineral Resources.

Printing and Graphic Design: University of New Mexico Printing & Quick Copy Services.