New Mexico Geological Society Guidebook, 58th Field Conference, Geology of the Jemez Mountains Region II, 2007, p. 209-224. 

# SURFACE AND SUBSURFACE STRATIGRAPHY OF THE SANTA FE GROUP NEAR WHITE ROCK AND THE BUCKMAN AREAS OF THE ESPAÑOLA BASIN, NORTH-CENTRAL NEW MEXICO

DANIEL J. KONING[1], DAVID BROXTON[2], DAVID SAWYER[3], DAVID VANIMAN[2], AND JOHN SHOMAKER[4]
[1] New Mexico Bureau of Geology and Mineral Resources, 801 Leroy Place, Socorro, NM 87801, dkoning@nmt.edu
[2] Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
[3]U.S. Geological Survey, P.O. Box 25046, Federal Center, Mail Stop 913, Lakewood, CO 80225
[4] John Shomaker and Associates, 2703-B Broadbent Parkway, Albuquerque, NM 87107

Abstract — Numerous wells in addition to stratigraphic sections of surface exposures provide a robust data set to examine Santa Fe Group stratigraphic relations near the White Rock and Buckman areas of the Española Basin. Here, wells penetrate Santa Fe Group strata, ranging in age from ca. 13.5 to 8.5 Ma, that locally underlie Plio-Pleistocene strata. Surface exposures of Santa Fe group strata range in age from ca. 12 to 8.5 Ma. Santa Fe Group strata are characterized by fluvial deposits of sandy to gravelly channel-fills intercalated with floodplain deposits of clay, silt, very fine- to fine-grained sand, and silty sand. Most of the aquifer under the Buckman well field consists of ancestral Rio Grande fluvial deposits belonging to the Vallito Member of the Chamita Formation, which overlies finer-grained, basin-floor deposits of the Pojoaque Member of the Tesuque Formation. The Vallito Member is a very pale brown to pink to light gray unit dominated by subrounded (minor rounded and subangular), relatively clean, chert- and volcanic-bearing, quartz-dominated sand that is locally frosted. Vallito Member gravels consist of very fine to coarse pebbles. The Vallito Member interfingers westward with light gray volcaniclastic sediment of the Hernandez Member (Chamita Formation) west of Buckman, deposited by an ancestral Rio Chama derived from the northwest that flowed alongside and merged with the ancestral Rio Grande. A high degree of mixing occurs between the Vallito and Hernandez Members within 1-4 km of their interfingering zone, which extends about 7 km to the west of the Rio Grande at Buckman. The gravel fraction of the Hernandez Member in the study area includes very coarse pebbles and cobbles, and is dominated by subrounded to rounded, dark gray to greenish dacites-andesites with less than 15% quartzite. Locally, the Vallito Member overlies, and interfingers eastward with, fluvial deposits of the Cejita Member of the Tesuque Formation. However, it appears that the northeast-derived river associated with the Cejita Member merged with the ancestral Rio Grande north of Buckman. More commonly, the Vallito Member interfingers eastward with granite-bearing alluvial-slope deposits of the Cuarteles Member of the Chamita and Tesuque Formations. As is the case throughout the Española Basin, the Cuarteles Member here progressively prograded westward in the middle to late Miocene. A probable angular unconformity and a general down-section increase of dips indicate that the Santa Fe Group in the study area was deposited during active west-tilting of the Española Basin half-graben. We interpret a westward increase of stratal tilts as related to subsidence-related flexure on the eastern side of an intra-basin half-graben, marked by a pronounced low Bouguer gravity anomaly. The lack of significant playa or lacustrine deposits in these strata indicates that closed basin conditions did not exist during 8.5 to 13.5 Ma.

## INTRODUCTION

The aquifer underlying the Buckman area is penetrated by nine water supply wells that collectively provide 15-50% of the water used by the city of Santa Fe. Spread over an area of 6-7 km$^2$, the Buckman well field includes the location of the former town of Buckman (Fig. 1) and lies at the mouth of Cañada Ancha about 24 km northwest of downtown Santa Fe. The town of White Rock is located only 3 km southwest of Buckman, but is perched 210 m above it on the east edge of the Pajarito Plateau (Fig. 1).

Both Buckman and White Rock are in the south-central Española Basin, one of many basins near the Rio Grande in New Mexico formed by tectonism associated with the Rio Grande rift (Kelley, 1956; Spiegel and Baldwin, 1963; Chapin, 1971). Like these other basins, the Española Basin is filled by siliciclastic sediment (primarily sand, with lesser mud and gravel) and volcanic rocks of the Santa Fe Group of Spiegel and Baldwin (1963), which ranges in age from late Oligocene through late Miocene (Smith, 2004; Koning et al., 2004a). In our study area, Santa Fe Group strata may be as thick as 3000 m (Biehler et al., 1991). Two formations were included in the Santa Fe Group by Galusha and Blick (1971); the Chamita and underlying Tesuque Formations. The Chamita Formation was subdivided into five members by Koning and Aby (2005), four of which (Vallito, Hernandez, Cejita, and Cuarteles Members) are present in the study area. The Cejita and Cuarteles Members extend into both the Tesuque and Chamita Formations, as allowed by Article 25 of the North American Stratigraphic Code (NACSN, 2005), with those members in the Chamita Formation being restricted to west of the Rio Grande (Koning and Aby, 2005; Koning et al., 2005a). The Tesuque Formation was originally subdivided into the Chama-El Rito, Ojo Caliente Sandstone, Pojoaque, Skull Ridge, and Nambe Members (Galusha and Blick, 1971). Later workers have subdivided the Tesuque Formation based on provenance and paleocurrents. Applicable to our study are lithosomes A and B of Cavazza (1986) and the Cejita Member of Manley (1977, 1979). In the study area, the Santa Fe Group is unconformably overlain by coarse-grained sand and gravel of the Pliocene Puye Formation (Fig. 2) (Griggs, 1964; Bailey et al., 1969; Waresback, 1986; Turbeville et al., 1989; Waresback and Turbeville, 1990). Overlying the Puye Formation, and locally interbedded with it (Broxton and Vaniman, 2005), are basalt flows of the Cerros del Rio volcanic field (primarily 2.3-2.8 Ma; WoldeGabriel et al., 1996; Sawyer et al., 2002). The two ash-flow members of the Bandelier Tuff, having ages of about 1.2 and 1.6 Ma (Izett and Obradovich, 1994; Spell et al., 1996), cap the Pajarito Plateau and are present mostly

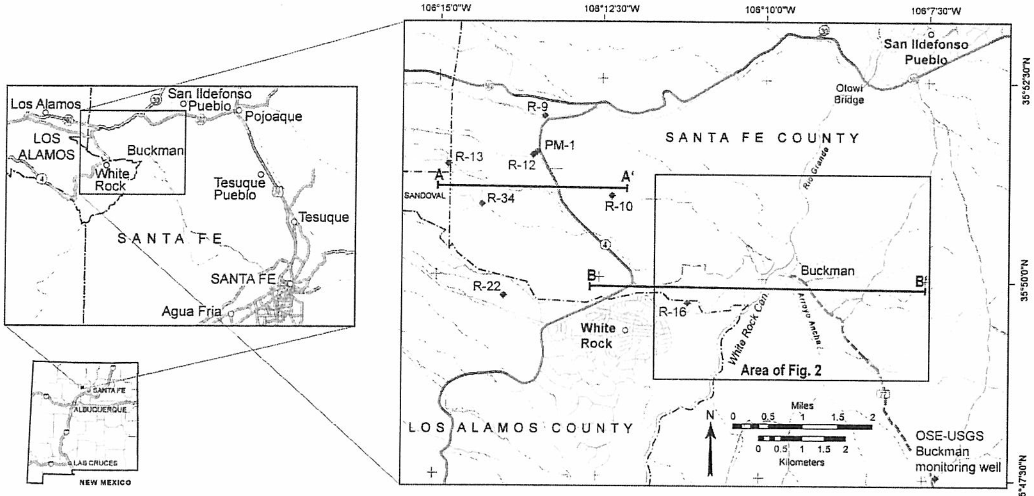


FIGURE 1. Location map of study area relative to the cities of Santa Fe and White Rock, New Mexico. Locations of the two cross-section lines (A-A' and B-B') together with relevant wells are also depicted.

west of the Rio Grande in the study area, with only minor remnants on the east side of the river along White Rock Canyon.

Although the stratigraphic relations of the Pliocene and Pleistocene units are generally obvious from surface exposures, those of the underlying Santa Fe Group cannot be understood without the aid of subsurface data. Understanding these relations is important for interpreting how groundwater flows in the aquifer – both in the cone of depression surrounding the Buckman well field and also beneath the Pajarito Plateau to the west, where movement of contaminants from Los Alamos National Laboratory pose a concern. Numerous site-specific studies at Buckman and White Rock document subsurface geology and hydrogeologic conditions at particular well sites. However, a comprehensive stratigraphic framework for the area has not been published previously. Furthermore, the existing geologic map of the White Rock Canyon quadrangle (Dethier, 1997) does not subdivide the Santa Fe Group. In this study, we examine the sedimentologic properties of various lithostratigraphic units in the Santa Fe Group for the area, and then correlate these to the stratigraphic nomenclature for the Santa Fe Group in the Española Basin established by Galusha and Blick (1971), Cavazza (1986), and Koning and Aby (2005). Also, we relate how the sedimentologic properties of these units result in certain patterns or signatures of down-hole geophysical data. Lastly, we discuss tectonic and hydrogeologic implications interpreted from our stratigraphic data.

## METHODS AND STRATIGRAPHIC FENCE DIAGRAMS

The lead author revised the White Rock quadrangle geologic map of Dethier (1997) by differentiating the Santa Fe Group into the lithostratigraphic units discussed in this paper (Figs. 2, 8; Dethier and Koning, 2007). He also measured and described strata in three stratigraphic sections illustrating the exposed lithologic units (Fig. 2; see also Dethier and Koning, 2007).

We then compiled subsurface data from the wells drilled at Buckman and White Rock (Figs. 1, 2). At Buckman, various well data are available for the Buckman-1 through -9 water supply wells, the old-Buckman-#6 well, the Skillet observation well, the OSE-USGS Buckman monitoring well, and the Nuclear Dynamic #34 exploratory borehole (ND-34). Under the Pajarito Plateau near White Rock, pertinent wells include R-9, R-10, R-12, R-13, R-16, R-22, R-34, and PM-1. This subsurface data set includes cuttings logs of various quality, borehole geophysical logs, and samples of cuttings from Buckman-9, R-10, and R-16.

Cuttings from R-10 and R-16 were collected at 5-ft intervals and examined with a hand lens and petrographic scope. Cuttings from Buckman-9 were collected at 10-ft intervals and examined with a hand lens. In addition, we examined detailed written descriptions of the cuttings from the Buckman-1 and -2 wells (courtesy of John Shomaker and Associates, Inc.), which were sampled at 5 ft-intervals. We cannot rely solely on cuttings for complete textural characterizations because of mixing and possible incomplete returns as cuttings are carried up the borehole by muddy drilling fluid. Rather, cuttings were utilized primarily for compositional characterizations and used together with standard geophysical logs to document relative changes in grain sizes with depth.

For the Buckman well field, geophysical logs include resistivity, spontaneous potential, and gamma measurements – with some wells having neutron and sonic data (e.g., Buckman-9 and the OSE-USGS Buckman monitoring well). Wells R-16 and R-10 near White Rock (Figs. 3, 4) contain these standard logs in addition to relatively recent innovations to borehole geophysical logging, such as the Formation Micro-Imager (electrical conductivity images and bedding orientations); Triple Detector Litho-Density (bulk density and photoelectric factor); Natural Gamma Spectroscopy (gross natural gamma and potassium, thorium, and uranium concentrations); Combinable Magnetic Resonance (porosity and pore-size distributions); and Elemental Capture Spectroscopy (neutron-induced gamma spectroscopy for eight rock-forming elements and hydrogen). Higher resistivity values typically indicate lower clay content, relatively clean sand, or cementation. Varying borehole diameters between wells may influence the data obtained from these logs, particularly the intensity or magnitude of a reading.

Using these geophysical borehole tools in conjunction with outcrop and cuttings lithologic data, we then constructed three

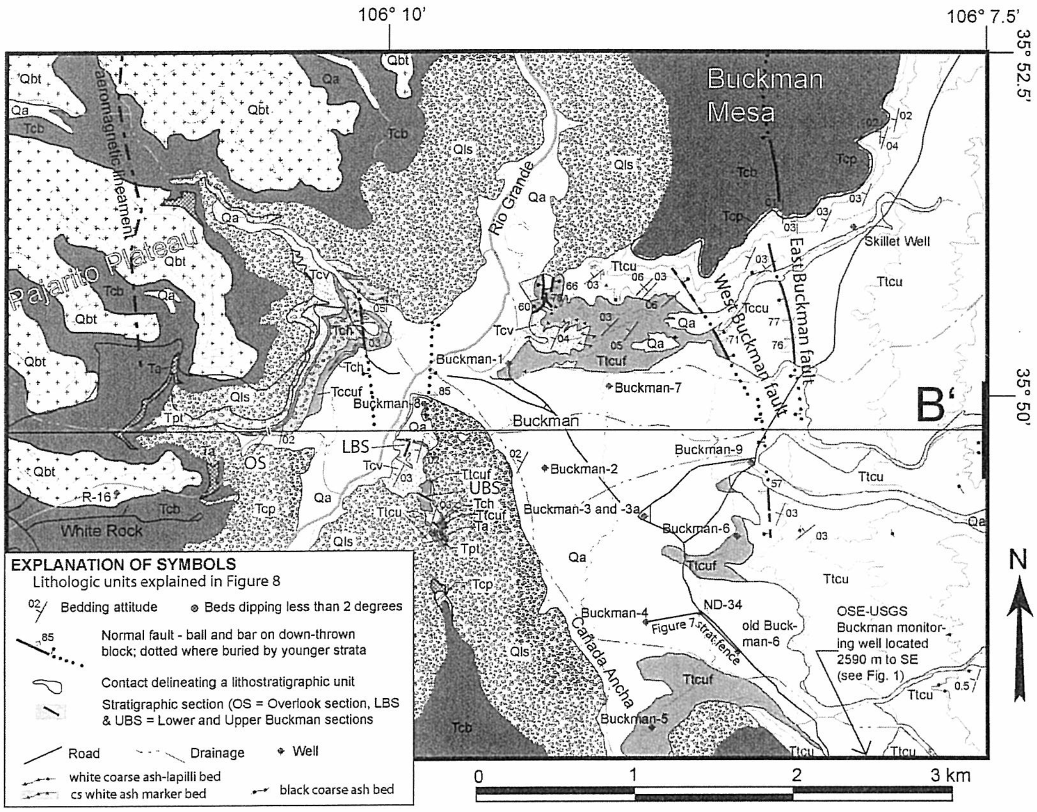


FIGURE 2. Geologic map of the Buckman and White Rock areas. The B-B' cross-section line and its east end are shown (at longitude 106° 7.5'), but the west end of the cross-section is located 1.53 km west of the western map boundary. The locations of the stratigraphic sections of Figure 5 are also depicted. Explanation for unit shading, patterns, and associated labels is given in Figure 8.

west-east stratigraphic fence diagrams through the study area. The first correlates the outcrop stratigraphic sections across the river and into well R-16 (Fig. 5). The second correlates subsurface strata between Buckman wells 1, 2, 3a, 7, 8, and 9-- most (1, 2, 3a, 9) of which have adequate cuttings descriptions (courtesy of John Shomaker and Associates; Fig. 6). The third west-east fence diagram depicts permeability-related stratigraphic relations between Buckman well 4, Nuclear Dynamic #34 exploratory borehole, and old Buckman #6 (Fig. 7). Stratigraphic relations in these diagrams were then compared with borehole geophysical and cuttings data from the other wells to produce a west-east cross-section (Fig. 8). We also scrutinized the borehole geophysical tool data to ascertain any patterns between the assorted geophysical data and the lithologic units.

## AGE CONTROL

The ages of Santa Fe Group strata in the study area appear to range from 13.5-8.5 Ma based on the following data. Direct age control is provided by a coarse white ash-lapilli bed in the western Buckman well field, denoted on the geologic map as the "coarse white ash marker bed" (Fig. 2). We interpret that it extends to the top of the lower Buckman section (Figs. 2, 3). $^{40}Ar/^{39}Ar$ analyses on biotite grains from this tephra bed yield an isochron age of 10.9 ± 0.2 Ma (W. McIntosh and S. Cather, unpubl. data for lab #6240).

A sharp gamma ray high at 1346-1348 ft in the Buckman-9 well is interpreted as an ash, located 13 ft below the Cejita Member-Pojoaque Member contact (Tesuque Formation). Near Española ashes at this stratigraphic position have been assigned to the Pojoaque white ash zone (e.g., unit 5a of the Cuarteles section in Koning and Manley, 2003, and Koning et al., 2005a), which is interpreted to have an age range of 14.0-13.2 Ma (Bargh-hoorn, 1981; Izett and Obradovich, 2001; Koning, 2002a; Koning et al., 2005a). Since this particular bed is likely at the top of the Pojoaque white ash zone, it probably has an age of ca. 13.2 Ma (based on interpretations of Koning et al., 2005a).

The basalt flow encountered at 586-671 ft in the R-10 well (Fig. 3) is interpreted to be 8.5-9.0 Ma because it lies at about the same stratigraphic level as basalt flows in the nearby R-9 well that were dated at 8.45-8.63 ± 0.24 Ma by $^{40}Ar/^{39}Ar$ methods (Broxton et al., 2001). This flow also appears to project to a basalt in the R-22 well that returned an $^{40}Ar/^{39}Ar$ age of 8.97 ± 0.11 Ma (WoldeGabriel, personal commun., 2003) (Figs. 1, 8).

## LITHOSTRATIGRAPHIC UNITS: STRATIGRAPHIC RELATIONS AND SEDIMENTOLOGIC AND GEOPHYSICAL PROPERTIES

The Santa Fe Group near Buckman and White Rock is composed of fluvial deposits associated with basin-floor and alluvial-slope (also known as piedmont slope) rivers and streams, with

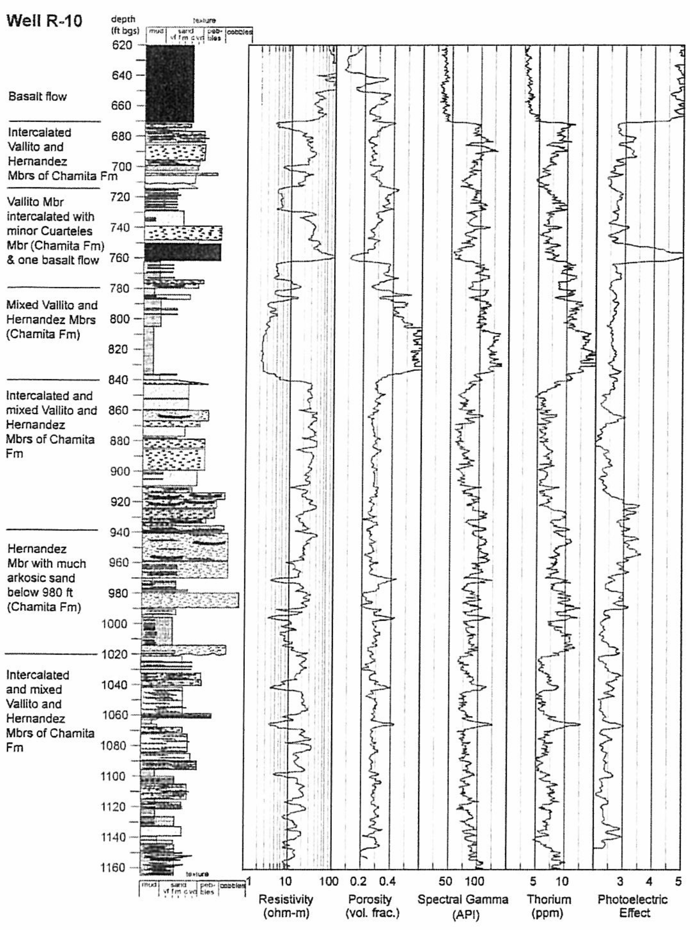


FIGURE 3. Interpreted textural and compositional log for the R-10 well (left), based on examination of cuttings and down-hole geophysical data. Data from various borehole geophysical logging tools that were useful for differentiating lithologic intervals within the well are shown to the right.

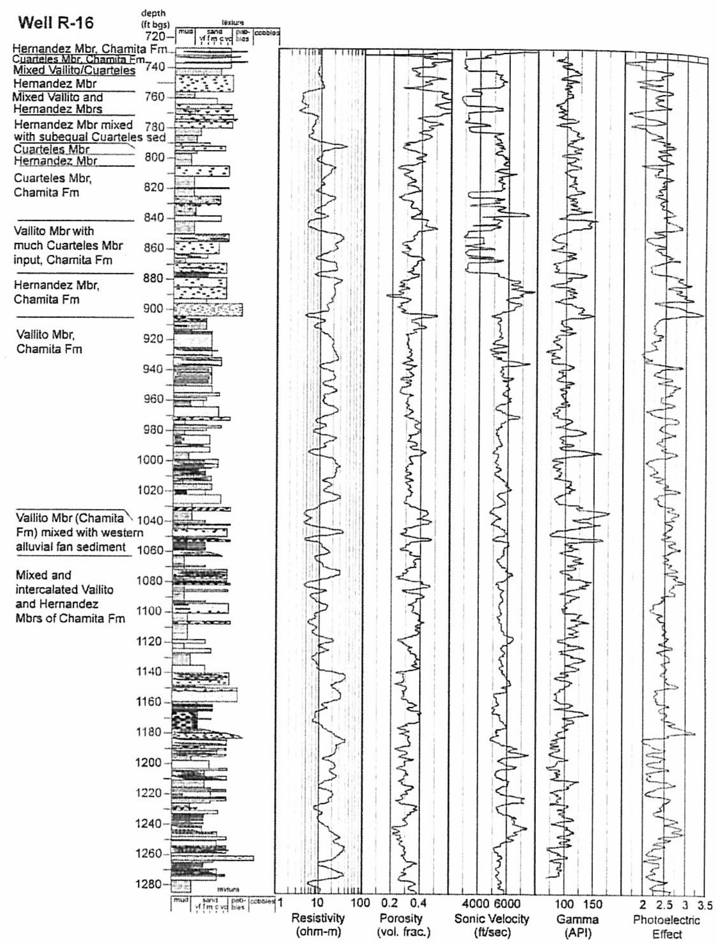


FIGURE 4. Interpreted textural and compositional log for the R-16 well (left), based on examination of cuttings and borehole geophysical data. Data from various borehole geophysical logging tools that were useful for differentiating lithologic intervals within the well are shown to the right.

minor (<10%) paludal clay-silt deposits and at least one small possible lacustrine deposit of clay at R-10 (805 to 836 ft depths). The fluvial deposits consist of sandy-gravelly channel-fills intercalated with floodplain deposits of clay, silt, very fine- to fine-grained sand, and silty fine sand. Among these channel-fill and floodplain deposits, we differentiate five lithostratigraphic units based on standard sedimentologic properties, particularly composition and texture but to a lesser extent bedding characteristics, color, and paleocurrent directions. Below, we treat the sedimentologic characteristics of these five units in detail, in addition to describing their stratigraphic relations with other units. We also discuss how these sedimentologic properties influence the data obtained with down-hole geophysical tools.

The Vallito Member of the Chamita Formation extends east of the Rio Grande in the study area. We also extend the Vallito Member down-section south of Española to include sandy fluvial strata deposited concomitantly with eolian strata of the Ojo Caliente Sandstone Member (Tesuque Formation), as discussed below. Consistent with the nomenclature of Koning and Aby (2005), the Cejita and Cuarteles Members extend into both the Chamita Formation (west of the Rio Grande) and the Tesuque Formation (east of the Rio Grande). Some details of the sand descriptions may change with further work using thin sections and grain counts.

### Vallito Member of the Chamita Formation

In general, the Vallito Member represents an axial river system that was a precursor to the modern Rio Grande (Koning and Aby, 2005). The river depositing this unit extended northward into the San Luis Basin and drained the southern part of the Taos Range. Parts of this member include sandy tributary fluvial deposits derived from the Abiquiu embayment. The axial river system was dominated by a sandy bedload, and gravel becomes increasingly scarce downstream. Pebbles are almost absent where this member underlies southern Black Mesa (northwest of Española). However, the pebble content increases significantly near Española owing to input of small, southeast-flowing tributaries derived from the southern Tusas Mountains (Koning and Aby, 2005). Koning (2007) describes this member where it is found near Battleship Mountain, west of NM-30. The base of this member is coeval with the lower Cejita Member (see below), and thus is ca. 13.2 Ma. In R-10, this member extends up to the basalt flow that likely correlates to 8.5-9.0 Ma flows to the west (Fig. 3).

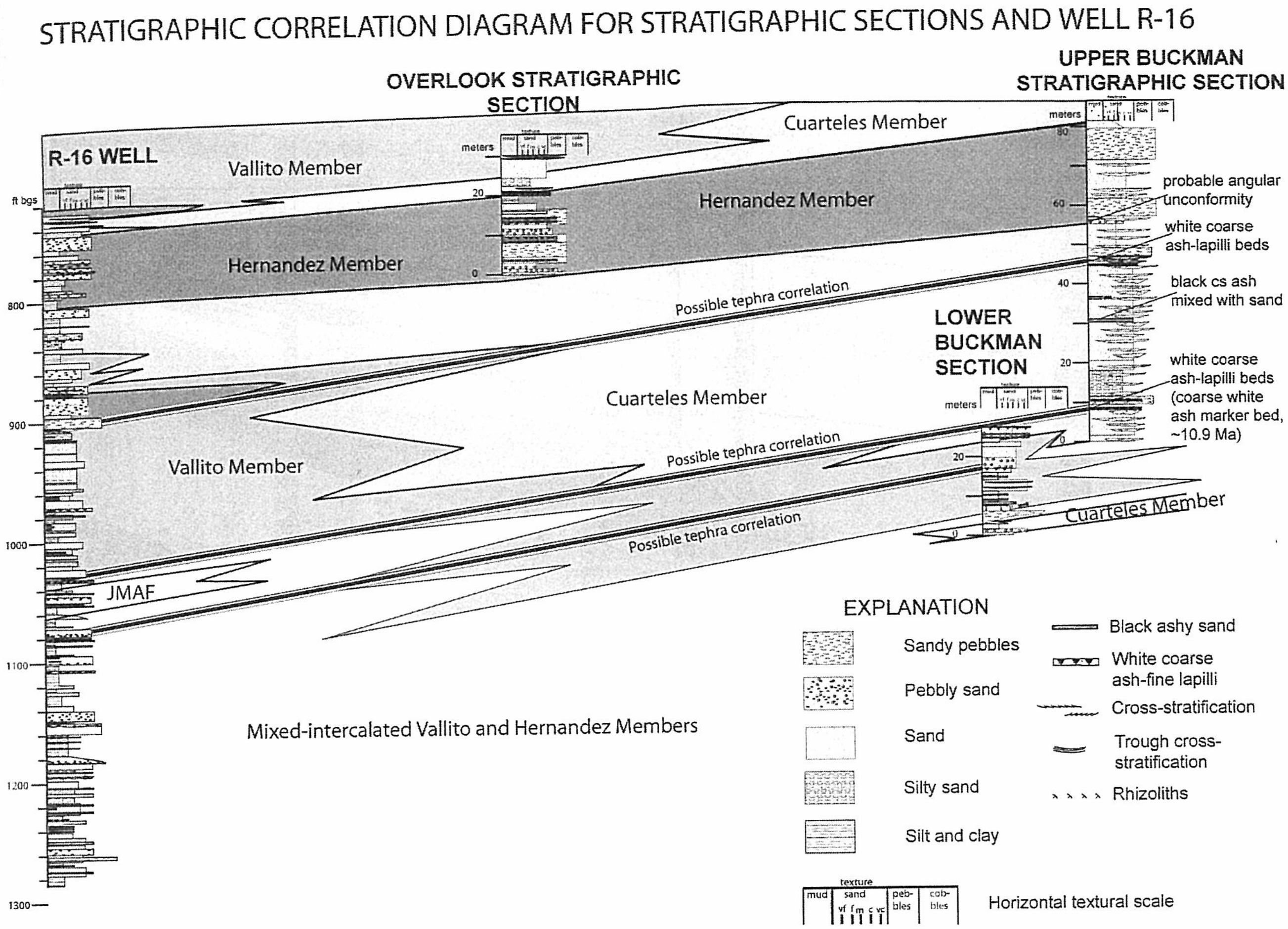


FIGURE 5. Stratigraphic fence diagram showing correlations between the R-16 well, Overlook section, lower Buckman section, and the upper Buckman section (left to right, west to east). Thick black lines are possible tie lines between tephra beds. Background shading illustrates inferred stratigraphic relations between the sections. JMAF = Jemez Mountains alluvial fan sediment. Listed members belong to the Chamita Formation; note that the Cuarteles Member extends from the Tesuque Formation (east of Rio Grande) into the Chamita Formation (west of Rio Grande). See Dethier and Koning (2007) for detailed descriptive data for these sections.

### Sedimentologic properties

The sand-dominated channel-fill sediments, together with the texture and composition of the sand fraction, are the diagnostic sedimentologic features of the Vallito Member. The broad channel-fills (typically >10s of meters wide) consist of sand-dominated sediment in horizontal to cross-stratified, laminated to very thin to medium beds (refer to Ingram, 1954, for bed thickness terminology). Units consisting of stacked channel-fills may be as much as 12 m thick. Most of the Vallito Member sand resembles the Ojo Caliente Sandstone Member of the Tesuque Formation – a consequence of fluvial reworking of the latter. The sand is very pale brown to pink to light gray in color, and consists of subrounded (with subordinate rounded and subangular), locally frosted quartz grains. There is typically trace to 3% red to brown, rounded chert or possible volcanic grains, 1-8% mafics, and 5-20% orange-stained quartz grains, together with minor potassium feldspar. Up to ~25% volcanic grains are also present, ranging from dacite (most common) to tuff, welded tuff, rhyolite, and basalt. Other lithic grains include <5% quartzite and Paleozoic sedimentary grains. Channel-fill sand generally ranges from fine to coarse grained. The pebble fraction rarely exceeds 40 mm in diameter; clasts are moderately sorted, subrounded, and consist largely of volcanic pebbles having similar composition as the volcanic sand grains (Table 1). Additionally, minor amounts of quartzite, granite, and Paleozoic sedimentary clasts (mostly sandstone, but also local limestone and siltstone) occur in the gravel fraction; these clasts were delivered to the axial river by eastern tributaries associated with the Cejita and Cuarteles Members upstream from Buckman. In available outcrops, pebbles are generally insufficient to produce clast-supported gravel beds. Basalt lithologic types occur in the Vallito Member only in its lower part east of the Rio Grande (Fig. 6), and are rare (<1%) in outcrops north of Otowi bridge. However, locally west of the Rio Grande and south of Otowi there may be significant amounts of basalt sand and pebbles (see sample WRC-79 in Table 1). Floodplain deposits consist of very fine- to fine-grained sand and silty sand, silt, and clay in various proportions. Locally, the Vallito Member contains intervals of extensively cross-stratified sand with ~20 cm-thick foresets; these are possibly eolian deposits, and suggest

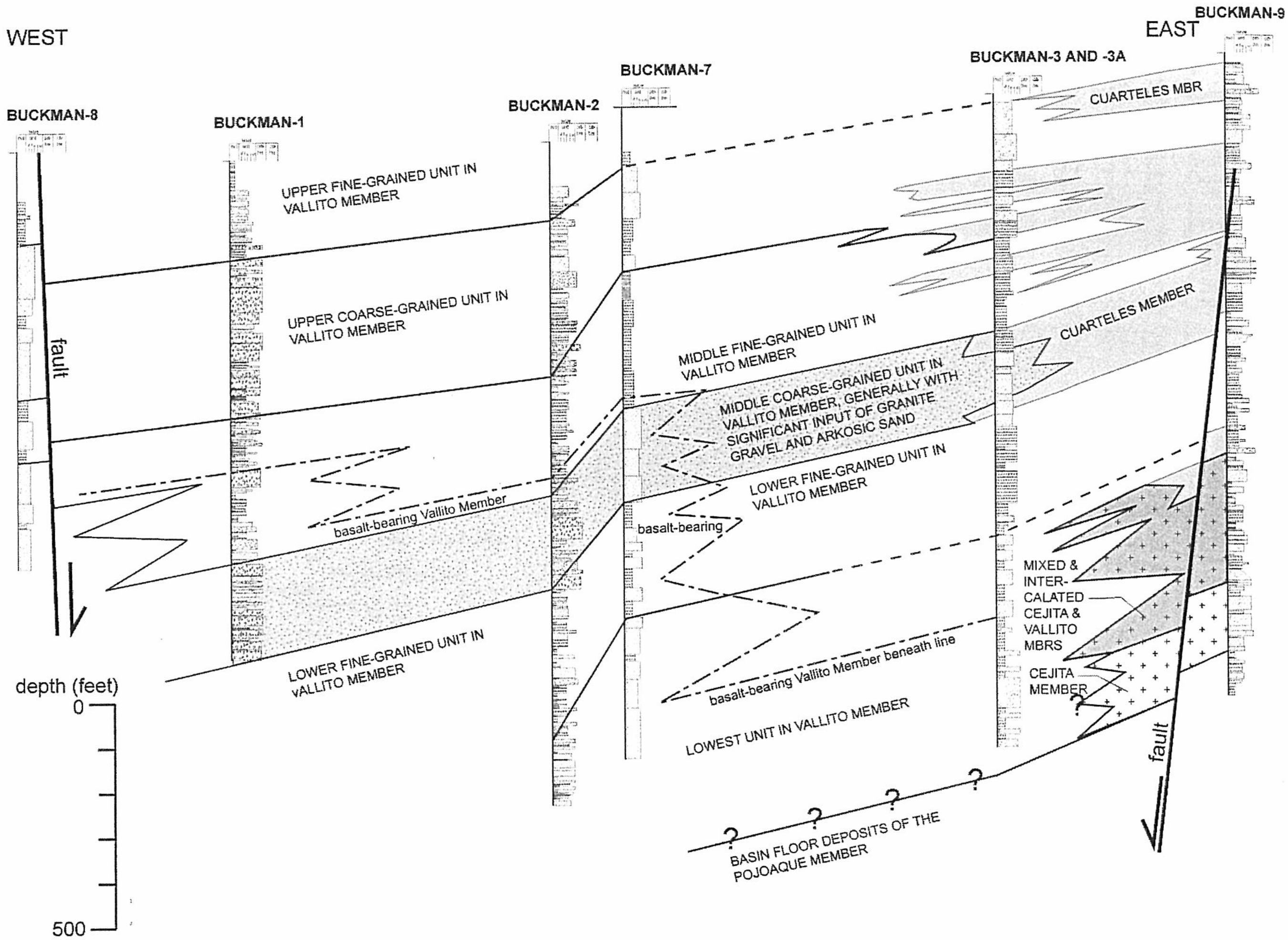


FIGURE 6. Stratigraphic fence diagram showing correlations between wells in the Buckman well field. Lithologic (textural) columns for Buckman-1, Buckman-2, Buckman-3a, and Buckman-9 constructed using cutting descriptions and available geophysical data. Lithologic (textural) columns for Buckman-7 and -8 constructed solely using geophysical data. The Vallito Member (Chamita Formation) is unshaded except for the middle coarse-grained interval containing input of granite gravel and arkosic sand. Correlation between wells relied heavily on the identification of the middle coarse-grained unit. Note that the Cejita and Cuarteles Members (Tesuque Formation) in the Buckman-9 well are interpreted to interfinger with and grade laterally westward into the Vallito Member (Chamita Formation), which for the Cejita Member is consistent with observations of outcrops along NM-502 to the north.

a continuation of the sporadic eolian deposition that is more prevalent down-section (as exposed west of NM-30 near Battleship Mountain; see Koning, 2007). Strong cementation in outcrops is present but minor. At R-10 and R-16, cuttings of the Vallito Member commonly include a few sandstone clasts cemented by calcite. Borehole geophysical logs indicate sand-dominated intervals typically contain about 30% porosity (Figs. 3, 4), suggesting little cementation. X-ray diffraction data indicates that calcite is ubiquitous, but generally occurs at concentrations of only 0.1 to 5 wt % in drill cuttings and outcrop samples; more complete cementation (up to 32% calcite) occurs locally.

## Stratigraphic relations, thickness, and subunits

The Vallito Member (Chamita Formation) overlies the Ojo Caliente Sandstone Member (Tesuque Formation) north of Española in a gradational or unconformable manner, depending on location (Galusha and Blick, 1971; Dethier and Manley, 1985; Koning and Aby, 2005; Koning et al., 2005b). Between Buckman and Española, fluvially reworked sand compositionally similar to the Ojo Caliente Sandstone Member, which we correlate with the Vallito Member, both overlies and probably interfingers with the primarily eolian Ojo Caliente Sandstone Member. On San Ildefonso Pueblo land, Koning was not able to confidently map a contact from the top of the Ojo Caliente Sandstone proper southward into this fluvially reworked sand. What was called Ojo Caliente Sandstone Member by Galusha and Blick (1971) south of Santa Clara Canyon and west of the Rio Grande generally appears to be scattered eolian intervals within the predominately fluvially reworked sand. Consequently, we advocate extending the Vallito Member down-section to include fluvially reworked sand from the Ojo Caliente Sandstone Member that interfingers laterally north-

TABLE 1. Clast count data for Vallito and Hernandez Members, Chamita Formation

| Clast count site | UTM coordinates (zone 13, NAD 27) | Rhyolite | Rhyodacite | Lt gray to gray, relatively non-porphyritic dacite | Porphyritic dacite | Dacite to andesite that lack biotite | Basaltic andesite and basalt | Quartzite | Granite | Non-welded tuff | Welded tuff | Other |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| VALLITO MBR WRC-79 Count | 394455 E 3996855N | 3 | 1 | 2 | 1 | 0 | 50 basalt, 1 basaltic andesite | 2 | 19 | 0 | 1 | 1 quartz-porphyritic, gray hypabyssal intrusive, 1 vein quartz, 2 dark intermediate intrusive rocks, 1 un-i.d. mafic-rich rock, 1 green Pz sandstone, 3 granodiorite(?) clasts.. |
| % | | 3% | 1% | 2% | 1% | 0 | 57% | 2% | 21% | 0 | 1% | 10% |
| VALLITO MBR WRC-101 Count | 395670 E 3966300 N | 7 | 4 | 45 | 6 | 3 | 1 basaltic andesite | 0 | 5 | 29 (white, cs, and biotite- | 3 | 1 gray, weathered andesite; 3 volcaniclastic and Santa Fe Group sandstone. |
| % | | 7% | 4% | 42% | 6% | 3% | 1% | 0 | 5% | 27% | 3% | 4% |
| HNDZ MBR Lower Overlook section Count | 393865 E 3965680 N | 2 | 3 | 6 | 19 | 46 | 3 | 5 | 2 | 6 | | 1 muscovite-biotite-feld-qtz intrusive, 1 un-i.d., 3 whitish qtz-biotite-hbl hypabyssal intrusive, 1 orange chert, 2 meta-rhyolites (granite with minor bluish grains). 2 granodiorite(?) intrusives |
| % | | 2% | 3% | 6% | 19% | 45% | 3% | 5% | 2% | 6% | | 10% |
| HNDZ MBR Upper Buckman section, unit 2b Count | 394900E 3965090 N | 3 | 2 | 11 | 28 | 39 | 0 | 12 | 3 | 2 | 1 | 1 vein quartz, 1 granodiorite(?) intrusive, 2 reddish granitoid (meta-volcanic) |
| % | | 3% | 2% | 10% | 27% | 37% | 0 | 11% | 3% | 2% | 1% | 4% |

**Note:** HNDZ = Hernandez Member of the Chamita Formation.

wards with the primary eolian sands of the Ojo Caliente Sandstone Member. In the Buckman area, the lower contact of the Vallito Member is placed at the lowest occurrence of thick sand beds characterized by fine to coarse, subrounded to rounded, locally frosted quartz grains with minor rounded, red-brown chert or volcanic grains and orange-stained quartz. The underlying Pojoaque Member is mud-dominated, has a gray to pinkish gray to pale brown color, and has a different sand composition (see below).

The Vallito Member interfingers eastward with the Cuarteles Member, and locally with the Cejita Member. The Cejita Member generally is not present here because its sediment has been mixed with the axial river upstream of Buckman.

The middle to upper parts of the Vallito Member interfinger westward with the Hernandez Member in a broad zone (as much as 7 km wide) that includes much mixing between the two members (see fig. 1.4 of the 1st day road log and Fig. 8). In a formal sense, we group this broad mixing zone with the Vallito Member, but informally generally refer to this simply as a mixing zone. In exposures south of Buckman, near the mouth of Water Canyon, this mixing is relatively complete and the sediment there is preliminarily referred to as Vallito Member (these completely mixed strata may be designated as a new member in the future). The lower part of the Vallito Member may extend westward beneath the oldest Hernandez Member as far as the Pajarito fault. It is not known whether the lower Vallito Member is mixed with subordinate Hernandez Member west of the Rio Grande, or whether it interfingers westward with early Hernandez Member strata not exposed at the surface. East of the Rio Grande, the Cuarteles Member gradationally overlies the Vallito Member throughout its areal extent, whereas west of the Rio Grande the two are in an interfingering and mixed relation with no complete progradation except in the hills immediately northwest of Otowi Bridge. The Vallito Member is over 900 m thick, including where it is mixed with Hernandez Member detritus (Fig. 8).

Our stratigraphic fence diagrams and cross-sections (Figs. 6-8) indicate that the Vallito Member under Buckman can be subdivided into six successive units. With the exception of the middle coarse-grained unit, these units are correlated primarily using borehole geophysical data. The *lowest unit* consists of subequal fine- to coarse-grained sandy channel-fills and clay and silt. It may contain detritus from the coarse-grained, lower Cejita Member. The *lower fine-grained unit* is dominated by clay and muddy, very fine- to fine-grained sand, with subordinate very fine- to coarse-grained sand channel-fills. The *middle coarse-grained*

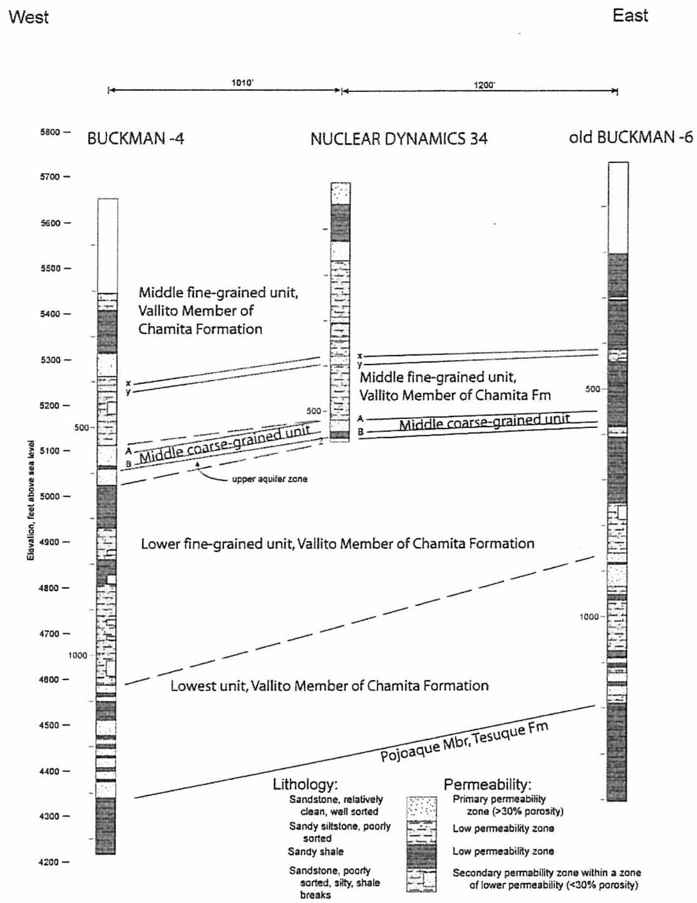


FIGURE 7. Stratigraphic correlations between Buckman wells 4, ND-34, and old Buckman-6 (west to east); lithologies and permeability zones are based on interpretations of borehole geophysical logs. No projections are involved in this fence diagram. Four tie lines are respectively labeled as X, Y, A, and B.

*unit* consists mostly of pebbly sand and sandy gravel channel-fills, with minor clay, silt, and muddy very fine- to fine-grained sand. A distinguishing feature of this unit is abundant potassium feldspar, angular to subangular quartz (and quartzite?), and fresh muscovite, indicating much input of arkosic sediment from the Cuarteles Member upstream (and probably input from the Cejita Member as well). The *middle fine-grained unit* consists of silty-muddy very fine- to medium-grained sand, together with clay and mud, (clay more abundant at Buckman-11) with subordinate very fine- to medium-grained sand channel-fills (which are locally gravelly, with clay is more abundant at Buckman-1). The *upper coarse-grained unit* is composed of coarse channel-fills (gravel, gravelly sand, medium- to very coarse-grained sand) with subordinate to subequal mud and muddy very fine-to fine-sand floodplain deposits. The *upper fine-grained unit* consists of subequal very fine- to medium-grained sand, muddy sand, and clayey mud; pebbly beds are very sparse. At the Buckman-1 well, the upper fine-grained unit includes 60-70 ft of clay. These six units are only local to the Buckman well field, and even within the well field may be difficult to correlate because of lateral gradations and natural heterogeneity associated with fluvial systems.

### Borehole geophysical properties

Most of the sandy channel-fills produce relatively low magnitude gamma-ray curves coupled with high-resistivity curves (Fig. 9). In the R-16, Buckman-9, and R-10 wells, the gamma magnitudes are 65-100, 60-90, and 65-90 API, respectively, and the resistivity magnitudes are 20-80, 15-35, and 10-30 ohm-m, respectively. Locally, high inputs of granitic and volcanic detritus may result in higher gamma-ray curves than typical, probably because of increased potassium feldspar or possible uranium concentrations.

## Hernandez Member of the Chamita Formation

Near Española, the Hernandez Member represents an ancestral Rio Chama based on southerly to southeasterly paleocurrent directions and a clast composition of dacite-andesite volcanic rocks and subordinate granite, basalt, and quartzite (Koning and Aby, 2005). One andesite clast returned an $^{40}Ar/^{39}Ar$ age of 29.08 ± 0.13 Ma (Kempter et al., 2004) and probably has a San Juan Mountain provenance. The presence of this member so far south indicates that upon reaching the axis of the Española Basin (i.e., between the modern Rio Grande and the Pajarito fault system), this river flowed alongside and west of the river associated with the Vallito Member until the two rivers merged near our study area. A high degree of mixing and interfingering occurs in a zone as much as 7 km wide near the confluence of the two rivers. Formally, we group this mixed zone with the Vallito Member. In exposures south of Buckman near the mouth of Water Canyon, this mixing is relatively complete. We do not know how far down-section the Hernandez Member extends west of the Rio Grande because of partial well penetration. Deposits of rounded axial river gravels described as "older river deposits" by Broxton and Vaniman (2005) beneath the central Pajarito Plateau are probably equivalent to the Hernandez Member. These older river deposits occur as far west as well R-33, located 10.5 km WNW of the Rio Grande at Buckman, and they are overlain by volcanic sands and gravels that contain primary pumice falls that yielded $^{40}Ar/^{39}Ar$ ages of 7.00 ± 0.63 to 7.50 ± 0.30 Ma (WoldeGabriel, personal commun., 2003). The Hernandez Member extends up to the 8.5-9.0 Ma basalt flows in well R-10 (Fig. 3).

### Sedimentologic properties

Away from where it is mixed and intercalated with the Vallito Member, the Hernandez Member is characterized by its light gray color and relatively abundant gravelly channel-fills with very coarse pebbles and cobbles. Units consisting of stacked channel-fills may be as much as 18 m thick. Gravels are subrounded to rounded, very poorly sorted, and commonly clast supported. Lithologic types include a high amount of gray to dark gray to greenish gray to brown dacites to andesites, with minor amounts of rhyolite, welded tuff, and less than 15% quartzite in our study area (Table 1). Above strata of ~8.5 Ma age near Española, the proportion of quartzite increases up-section from 10 to 26% (Koning and Aby, 2005, table 6). Locally, there is less than 10% Paleozoic

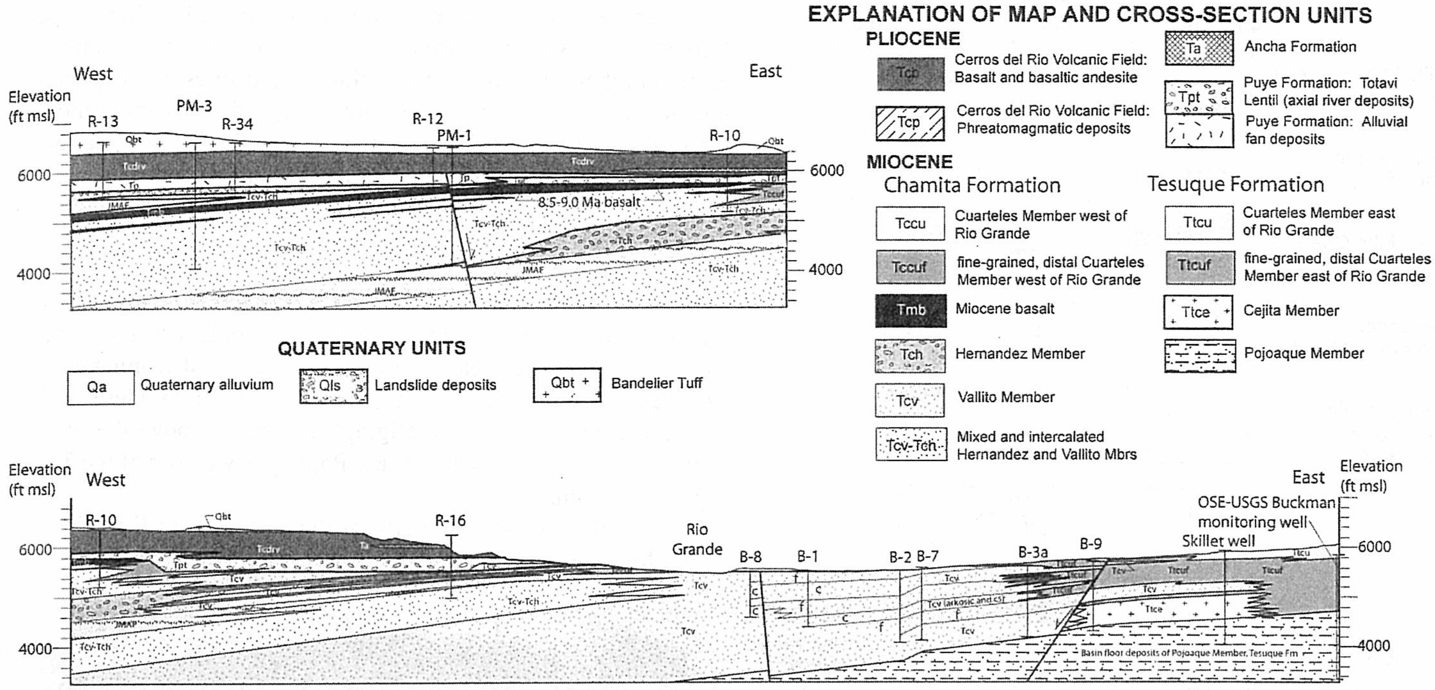


FIGURE 8. Two west-east cross-sections, A-A' to the north and B-B' to the south (see Figs. 1 and 2 for locations of cross-section lines). Subdivisions of the Vallito Member at Buckman are shown by the following abbreviations: C=grossly coarse-grained Vallito Member under the Buckman field, and F=grossly fine-grained Vallito Member under the Buckman field. JMAF = Jemez Mountains alluvial fan sediment from west.

sedimentary clasts and minor granitic detritus. The coarse-grained channel-fills are marked by a variety of bed forms, ranging from planar to lenticular to cross-stratified. These channel-fills locally fine upwards into horizontal-bedded floodplain deposits of clay, silt, and clayey-silty very fine- to fine-grained sand. In outcrops, the floodplain deposits are minor to very minor compared to the coarse channel-fills, but locally floodplain deposits are abundant in wells R-10 and R-16. The sand fraction has low amounts of the frosted quartz and rounded, red-brown chert and volcanic(?) sand grains observed in the Vallito Member (generally less than 15% of the sand fraction). The sand mostly contains subangular to subrounded, relatively clear quartz and plagioclase, with less than 15% orange-stained quartz + potassium feldspar, 1-15% mafics, <2% chert, <5% green quartz grains, and 3-50% volcanic grains similar in composition to the gravel fraction

## Stratigraphic relations and thickness

The Hernandez Member interfingers eastward with the Vallito Member (fig. 1.4 of 1st day road log), and probably overlies the lower Vallito Member, although we cannot demonstrate that with available data. Locally, such as at the base of the west slope of White Rock Canyon directly across from the Buckman well field, the Hernandez Member directly interfingers eastward with the Cuarteles Member. The Hernandez Member is 27 m thick in the upper Buckman stratigraphic section (Fig. 5), and attains unknown, but probably much higher, thicknesses to the west.

## Borehole geophysical properties

Channel-fills of the Hernandez Member have a relatively high gamma signature (80-115 API) coupled with high resistivity values (60-100 ohm-m; Fig. 9). In R-10 and R-16, the volcanic sands of the Hernandez Member have lower silica contents, higher iron and titanium contents, and a higher photoelectric factor than the quartz-dominated sands of the Vallito Member.

## Cejita Member of the Chamita and Tesuque Formations

To the north, the Cejita Member is associated with a river system having its source in the Sangre de Cristo Mountains east of the Peñasco embayment (Manley, 1977, 1979; Koning and Aby, 2005; Koning et al., 2005a). It is best identified by its clast composition, which is dominated by Paleozoic sedimentary clasts of limestone, sandstone, and siltstone, together with subordinate quartzite and lesser amounts of felsic-intermediate volcanic clasts (to the west) and granite clasts (to the east). Paleoflow data indicate westward flow in the Peñasco embayment (Manley, 1977; Koning and Aby, 2003). However, to the south-southwest, these data indicate a southwesterly direction as the river associated with the Cejita Member enters the south-sloping basin-floor (Koning and Manley, 2003; Koning and Aby, 2005).

The Cejita Member is uncommon in our study area. At Buckman, the Cejita Member is only interpreted in the Skillet well (which does not have a detailed cuttings lithologic log) and in

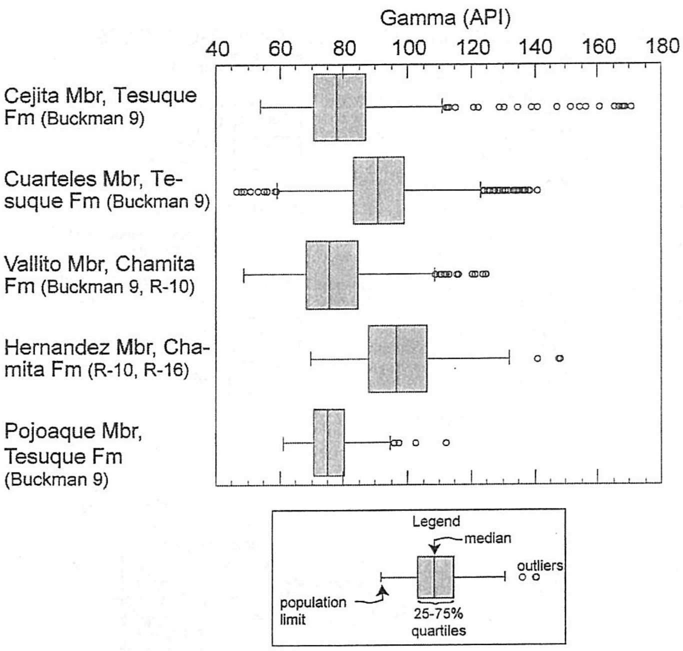


FIGURE 9. Box and whisker plots statistically comparing gamma values (API) of sand and gravel fraction obtained from wells penetrating the Cejita, Cuarteles, Vallito, Hernandez, and Pojoaque Members of the Chamita and Tesuque Formations in the study area.

Buckman-9. Deposits similar to this unit are exposed in NM-502 roadcuts north of the study area (at and generally between the following UTM coordinates: 398530 m E, 3970783 m N, and 400117 m E, 3971589 m N; NAD27, zone 13). The lower Cejita Member observed at 1180-1333 ft depth in the Buckman-9 well overlies an ash bed by 13 ft. As discussed above, we correlate this ash to the top of the Pojoaque white ash zone. Consequently, the lower Cejita Member observed in Buckman-9 is probably 13.0-13.2 Ma in age.

## Sedimentologic properties

The Cejita Member in the 1180-1333 ft depth range of the Buckman-9 well is not noticably mixed with sediment associated with other members, and consists primarily of upper-fine to upper-medium sand in stacked channel-fill intervals as thick as 4 m. The sand is moderately sorted, subangular to subrounded, and composed of quartz, 10% probable potassium feldspar, and 10-20% lithic grains that include 1-5% quartzite, 1-2% green-brown quartz grains (probably representing eroded Paleozoic sedimentary rocks), 5% mafics, and trace-1% felsic volcanic grains. The minor floodplain deposits present here consist of silt and silty-clayey very fine- to fine-grained sand.

In outcrops a few kilometers to the north, the Cejita Member consists of sandy and gravelly channel-fills that are extensively very thinly to thinly cross-stratified (up to ~ 1m-thick foresets) within 1-2 m-thick channel-fills of pebbly very fine- to very coarse-grained sand and sandy pebble-cobble conglomerate (Fig. 10). Clast lithologic types are dominated by Paleozoic sandstone, limestone, and siltstone with an estimated 10-50% granite and 5-8% quartzite. Locally, granites are the dominant lithologic type (probably owing to input from alluvial-slope tributaries from the east), and there may be 10-90% pink-gray dacites and rhyolites together with light gray dacites-andesites(?) that resemble those seen in the Chama-El Rito Member of the Tesuque Formation. Clast imbrication is approximately due south (+/- 25°).

## Stratigraphic relations and thickness

The overall coarse texture of the Cejita Member here is similar to that of the lower part of the Cejita Member to the north, illustrated in the Cuarteles stratigraphic section of Koning et al. (2005a). Assigning these strata to the lower Cejita Member is also consistent with their stratigraphic position above the finer-grained, basin-floor deposits of the Pojoaque Member of the Tesuque Formation.

A few kilometers to the north of the Buckman well field, the Cejita Member grades upward into fine-grained, distal Cuarteles

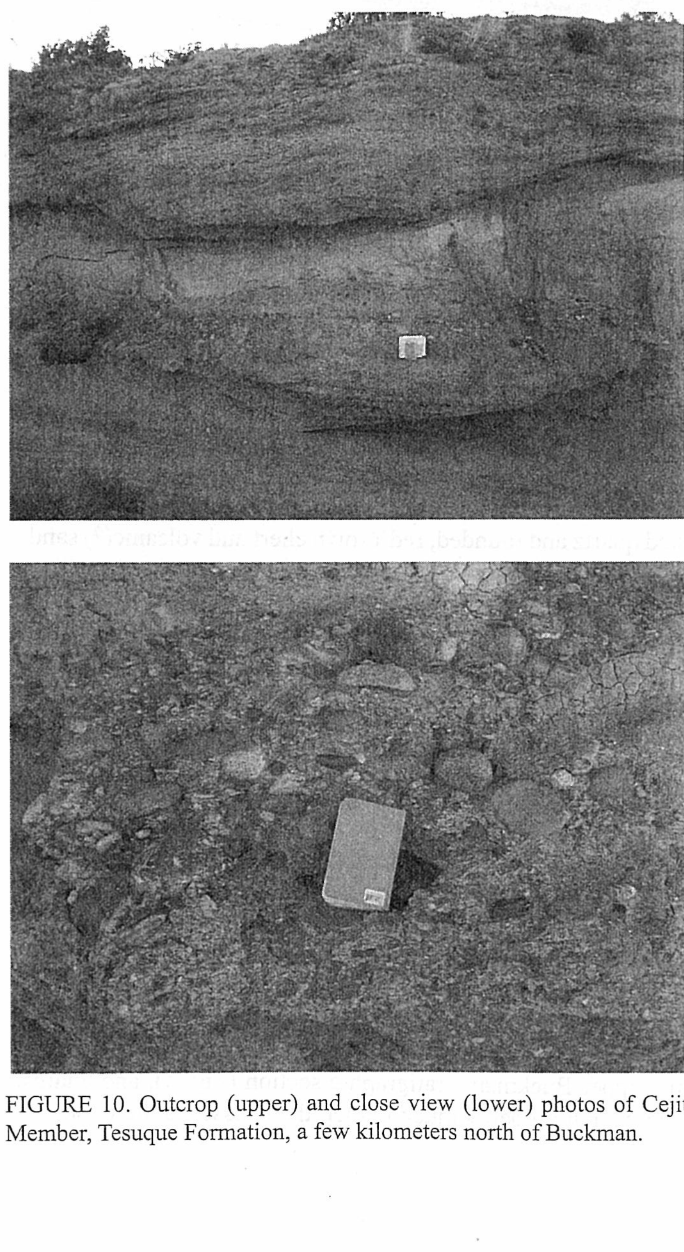

FIGURE 10. Outcrop (upper) and close view (lower) photos of Cejita Member, Tesuque Formation, a few kilometers north of Buckman.

Member strata; the latter are particularly interesting in that they lack the white coarse ash-lapilli beds observed in this same stratigraphic interval near Española (i.e., the lower coarse white ash zone; see Koning et al., 2007). In the Española quadrangle to the northeast, the base of the Cejita Member overlies relatively coarse-grained granitic and arkosic sediment correlative to the Cuarteles Member (Koning, 2002a). The aforementioned volcanic-dominated pebble beds are found to the west within the Cejita Member, and probably represent interfingering and mixing with Vallito Member sediment.

Given the southerly paleoflow directions and the coarse gravel size (i.e., cobbles) in outcrops a few kilometers to the north, the stream depositing this unit could have extended to the latitude of the Buckman-9 well. However, the Cejita Member in the eastern Buckman well field seems to lack pebbles and cobbles. This observation indicates that the lower Cejita Member, for the most part, has merged with the Vallito Member axial river before reaching the Buckman area. An alternative possibility is that the coarse-grained part of the lower Cejita Member is located to the east of Buckman-9, but if so it did not extend as far southeast as the OSE-USGS Buckman monitoring well. Up-section in the Vallito Member, detritus of the Cejita Member is even more diluted by typical Vallito Member sand -- suggesting a confluence farther upstream to the north, consistent with observations west of Española (Koning and Aby, 2005, fig. 9). The Cejita Member is 125-135 m-thick in the Cejita and Skillet wells (Figs. 6, 8).

### Borehole geophysical properties

Unsurprisingly, the coarse channel-fills of the Cejita Member commonly have moderate to high resistivity values. In the Buckman-9 well, channel-fills of the Cejita Member have slightly higher ranges in gamma values (60-90 API) than those in the underlying basin-floor deposits of the Pojoaque Member of the Tesuque Formation (60-75 API) (Fig. 9). The gamma ray values of the Cejita and Vallito Members are similar, whereas those of the Cuarteles Member are slightly higher (generally 75-125 API).

## Cuarteles Member of the Chamita and Tesuque Formations

The Cuarteles Member represents alluvial-slope deposits (also called piedmont slope deposits) shed from the granite-cored Sangre de Cristo Mountains to the east. Paleocurrent data to the north (Koning, 2002a; Koning and Aby, 2005) and here (Dethier and Koning, 2007) indicate that the plethora of streams depositing arkosic sediment on the piedmont flowed northwest to west to southwest. These streams were smaller than the rivers depositing the Hernandez, Vallito, and Cejita Members. A thin finger of Cuarteles Member strata is interbedded in basal Cejita Member strata at Buckman-9 based on inspection of cuttings. Minor interfingering of Cuarteles Member for 120 ft below the Miocene basalt in R-10 indicates that the Cuarteles Member persisted to 8.5-9.0 Ma.

### Sedimentologic properties

Most of the Cuarteles Member consists of slightly silty-clayey, poorly sorted, very fine to very coarse sand intercalated with 25-50% channel-fills of pebbly sand and sandy gravel. However, relatively fine-grained, distal alluvial-slope deposits of the Cuarteles Member (units Tccuf and Ttcuf on the geologic map, Fig. 2), near where this member interfingers westward into basin-floor deposits (commonly the Vallito Member), tend to be composed of silty very fine- to medium-grained sand with approximately 5-25% channel-fills of fine- to very coarse-grained sand and pebbly sand. The silty-clayey sand beds are typically thin to thick and tabular to broadly lenticular. The coarse channel-fills are commonly in medium to thick beds that are lenticular to ribbon-shaped. Cuarteles Member sand is angular to subrounded (mostly subangular), commonly moderately to poorly sorted, and has an arkosic composition. Gravels of the Cuarteles Member are poorly sorted, subangular to subrounded, and consist of granite with 1-3% quartzite and 1-3% amphibolite and gneiss clasts.

### Stratigraphic relations and thickness

The Cuarteles Member interfingers westward with the Vallito and Cejita Members on the basin floor. At the base of the slope on the west side of the Rio Grande across from Buckman, the Hernandez and Cuarteles Members interfinger. The Cuarteles Member progressively prograded over the Vallito Member after the deposition of the lower Cejita Member. This progradation is illustrated by the fact that almost all of the outcrops exposed in the Buckman area consist of Cuarteles Member strata, but the wells generally penetrate the Vallito Member at depth. The Cuarteles Member extended across the present-day location of the Rio Grande after deposition of the 10.9 Ma coarse white ash marker bed. But strata penetrated by the R-10 well (8.5-10.5(?) Ma) combined with outcrops along the west slope of White Rock Canyon indicate that the main body of this prograded Cuarteles Member body was between this well and the present Rio Grande, with only few, relatively thin fingers of the Cuarteles Member reaching the R-10 well. The Cuarteles Member is as much as 400 m thick (Fig. 8).

### Borehole geophysical properties

The gamma ray signature of Cuarteles Member strata may be the most useful parameter for its recognition. Commonly, gamma ray values are relatively high (75-125 API) and produce curves marked by low amplitude, low wavelength fluctuations. The upper 1100 ft of the OSE-USGS Buckman monitoring well nicely characterizes the gamma ray signature of the Cuarteles Member (Figs. 9, 11). The high gamma values are a result of the high potassium and possible uranium content of the arkosic and granitic sediment. Additionally, field inspection of the sediment indicates low amounts of clay and calcite cement in the matrix in the sand and even in much of the pebbly channel-fill sediment (Sigda et al., 2004). The silty-clayey fine sand of the distal Cuarteles may pro-

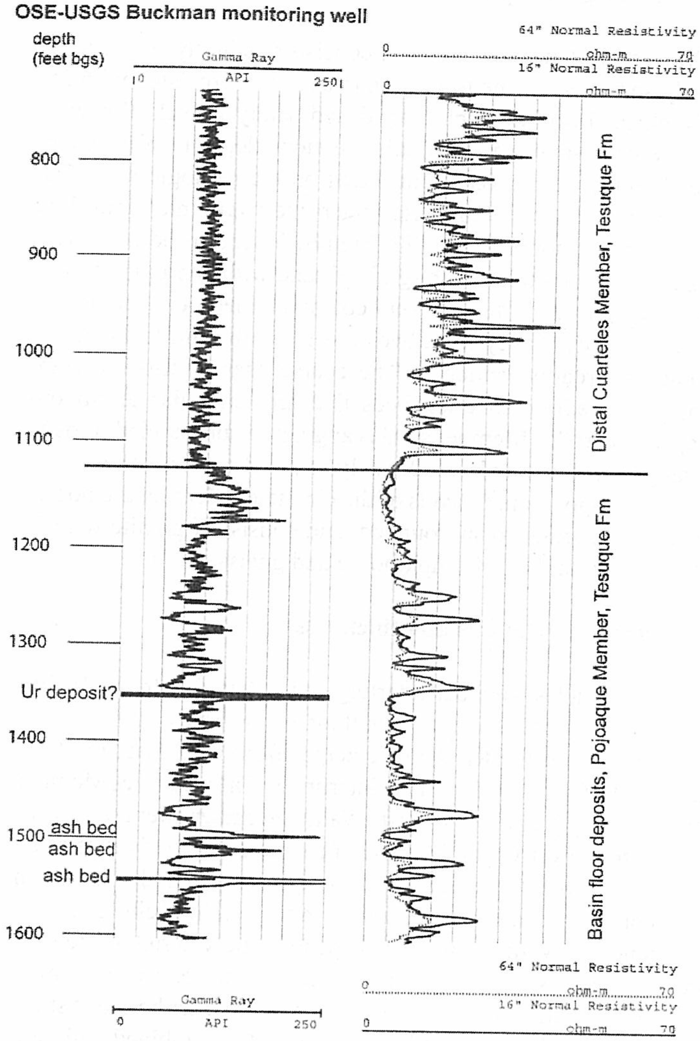


FIGURE 11. Gamma ray and resistivity data from the middle part of the OSE-USGS Buckman monitoring well, showing interpreted depths of the Cuarteles and the Pojoaque Members of the Tesuque Formation. The resistivity values are higher in the Cuarteles Member relative to the underlying basin-floor deposits of the Pojoaque Member. Also, the gamma ray curve in the Cuarteles Member has a higher frequency, lower amplitude signal compared to that of the underlying basin-floor deposits of the Pojoaque Member.

duce resistivity values as low as 8-10 ohm-m, whereas the coarser channel-fills give resistivity values as high as 25-30 ohm-m.

### Basin-floor deposits of the Pojoaque Member, Tesuque Formation

The basin-floor deposits of the Pojoaque Member generally lie below the depths of the wells in this study, with the exception of the eastern Skillet, Buckman-9, and OSE-USGS Buckman monitoring wells. These deposits correlate northwards with lithosome B of the Pojoaque Member. At this latitude, however, there has been sufficient input by the arkosic alluvial-slope tributaries that these basin-floor deposits themselves locally are arkosic. Consequently, we refer to the Pojoaque Member deposits here simply as "basin-floor deposits of the Pojoaque Member." The minimum age for these deposits is constrained by the Pojoaque white ash zone discussed above (13.2-14.0 Ma; Koning, 2002a; Koning et al., 2005a).

#### Sedimentologic properties

The basin-floor strata of the Pojoaque Member consist mostly of floodplain deposits of silt, very fine- to fine-grained sand, silty very fine- to fine-grained sand, and clay, based on well data for the OSE-USGS Buckman monitoring well and inspection of outcrops south of NM-502 near Pojoaque Pueblo (Koning and Maldonaldo, 2001; Koning, 2002a). Subordinate, intercalated channel-fills composed of fine- to coarse-grained sand are up to 4.6 m thick. Beds are very thin to thick, broadly lenticular (10-30 m lateral length) to tabular (Koning, 2002a). The sediment is pinkish gray to light gray to light brown to pale brown. In general, this sediment has a noticeable darker or grayer hue than that of the Vallito and Cejita Members up-section. The sand possesses 0 to 5% green-colored quartz grains together with very minor Paleozoic detritus (usually trace to 3%, locally as much as 15%). Most of the sand, however, consists of quartz with 5-20% feldspar. Near the top, there may be as much as 10-15% quartzite, as seen in Buckman-9. In some arkosic intervals (e.g., 2000-2090 ft in the OSE-USGS Buckman monitoring well), the feldspar percentage may be as high as 60%.

#### Stratigraphic relations and thickness

Although only encountered in the eastern wells, the basin-floor strata of the Pojoaque Member very likely extend beneath the entire study area. To the west of Buckman, the sediment probably contains more volcanic grains because of input from the Chama-El Rito Member alluvial-slope streams that drain the Abiquiu embayment. This unit is the lateral equivalent of lithosome B of the Pojoaque Member to the north, as mentioned above. At the OSE-USGS Buckman monitoring well, these basin-floor deposits seem to grade gradually upwards into sandy arkosic sediment of the Cuarteles Member (at 1115-1120 ft depth) (Fig. 11). Since this unit is only partially penetrated by wells, its total thickness is unknown in the study area.

#### Borehole geophysical properties

The gamma-ray values of channel-fills in the Pojoaque Member basin-floor deposits are remarkably lower than those of the overlying Cuarteles Member (50-75 API, typically 50-65 API; Figs. 9, 11). Resistivity values as low as 1-5 ohm-m are common in the mudstone floodplain deposits of this unit, with a range of 1-8 ohm-m. Channel-fills attain resistivity values as high as 35 ohm-m, but are mostly 10-25 ohm-m.

## DISCUSSION

### Tectonic inferences

Observations of dip-meter data in the R-16 well (Fig. 12) and the general downward steepening of dips in the cross-section and

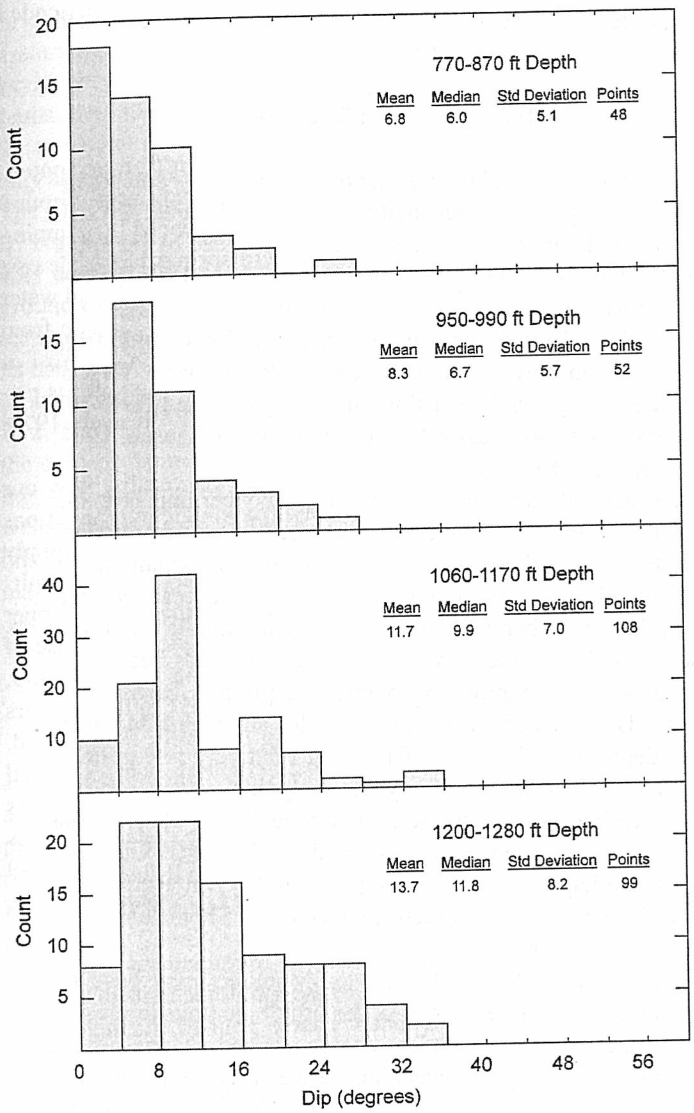


FIGURE 12. Histograms comparing FMI-derived dip data from well R-16. These indicate a higher abundance of steeper dips with depth.

fence diagrams (Figs. 5-8) indicate active westward tilting of the Española Basin half-graben following deposition of the Pojoaque Member. Two interwell correlations illustrate this downward steepening trend (note that these are apparent dips): 1) between Buckman wells 7 and 3a, the top of the lowest unit dips 6° west and the top of the middle coarse-grained unit dips 5° west; 2) between Buckman wells 1 and 2, the base of the middle coarse-grained unit dips 4° west, and the base of the upper fine-grained unit dips 2° west. Strata between wells 2 and 7 also progressively dip more steeply down-section, with the notable exception of the middle fine-grained unit. We do not have sufficient data to determine if there is also a down-section dip increase in Pojoaque Member strata of the Tesuque Formation.

Consistent with syndepositional tilting is the presence of a probable angular unconformity at the sharp contact between the Hernandez and Cuarteles Members in the upper Buckman stratigraphic section (at 55.3 m; Fig. 5). Below this contact, strata dip 3° west, but above it strata dip less than 2°. Elsewhere in the stratigraphic sections, contacts between units are gradational in that the lower unit fines upward towards the contact and commonly gradation in composition occurs on either side of the contact as well. In the Overlook section, the Hernandez Member fines upward into floodplain-dominated strata just below the progradation of the Cuarteles Member (Fig. 5). A similar fining upward is found in the Vallito Member below its contact with the Cuarteles Member in the upper part of the lower Buckman section, and the Vallito Member contains progressively more granite clasts and arkosic sand as one moves upward towards this contact (see units 14 through 17 (17-24.6 m) of the lower Buckman section in Dethier and Koning, 2007). In contrast, no such mixing or fining trends occur at the sharp contact between the Hernandez and Cuarteles Members in the upper Buckman stratigraphic section.

In addition to showing an increase in dip magnitudes with depth, comparison of FMI-derived mean dips at R-16 with our correlated strata to the east indicates that a given stratigraphic interval appears to progressively steepen towards the west (particularly west of the Rio Grande; Fig. 8). Westward steepening also is seen elsewhere in the Española Basin at this approximate longitude. West and south of Well R-22, Vallito Member strata that crop out on the southeast side of the Rio Grande at the mouth of Frijoles Canyon have apparent westward dips of greater than 30°, probably owing to extension-related flexure or block rotation; these strata lie above a 9.3 ± 0.2 Ma basalt flow located at the mouth of Ancho Canyon (WoldeGabriel et al., 1996, 2006). In contrast, older uppermost Pojoaque Member strata east of the Rio Grande and west of the Huerfano fault generally dip 2-5° west in the area north of San Ildefonso Pueblo (Galusha and Blick, 1971; Kelley, 1978; Koning 2002a). Near Española, 3-6° west dips are common in the uppermost Pojoaque Member (Tesuque Fm), but westward of the Rio Grande, towards the Santa Clara fault, dips increase to 6-12° west in higher strata of the Chamita Formation (Koning and Manley, 2003; Koning et al., 2005b). However, equivalent Chamita Formation strata near the confluence of Guaje and Los Alamos Canyons and south of Santa Clara Canyon either dip <6° west or <4° east.

Interestingly, the westward steepening both here and near Española coincides with the eastern boundaries of low Bouguer anomaly values associated with the Santa Clara and Los Alamos inner half-grabens (see Ferguson et al., 1995, and Koning et al., 2004, for maps showing the locations of these gravity lows). The area of lower-magnitude, west- and east-directed dips between Los Alamos and Santa Clara Canyons corresponds to a gravity saddle between the Santa Clara and Los Alamos inner half-grabens and an apparent structural high, based on a significant southward apparent dip of late Miocene basalts along its south flank (WoldeGabriel et al., 2006). Consequently, we interpret the westward increase in dip directions as related to the development of these inner half-grabens. North of the Los Alamos inner half-graben (i.e., on the structural high between lower Los Alamos-Guaje and Santa Clara Canyons), evidence of westward increase in dip direction is lacking.

It is worth noting that no thick, definitive playa or lacustrine deposits were encountered in the wells of our study. Such deposits would be expected if the Española Basin was a closed basin (i.e., if the ancestral Rio Grande was not able to exit the basin). Closed basins may result from extreme differences in throw magnitudes on the master faults of the half-graben, perhaps due to fault segmentation or rift accommodation zones, as well as from emplacement of thick lava flows. The fact that we do not see closed basin conditions in our studied strata suggests that the Española Basin was effectively continuous with the Santa Domingo basin from 13.5-8.5 Ma, and perhaps this was previously the case as well.

Numerous, relatively small, north-trending normal faults occur in the study area (Fig. 2). Of these, the two largest faults are the east-down West Buckman fault and the west-down East Buckman fault. We interpret that two faults offset strata along the cross-section line based on our mapping and inter-well correlations, but there may possibly be more faults not shown on the cross-section. To the east is a west-down fault located en echelon to the southern tip of the East Buckman fault. This fault appears to have a throw magnitude of 20-25 m at the cross-section line. To the west is an east-down fault having an apparent throw magnitude of ~30 m. Interestingly, the East Buckman fault does not appear to displace strata in the upper part of the Cuarteles Member on the south slope of Buckman Mesa. Consequently, offset along the East Buckman fault appears to have slowed and then effectively stopped sometime after the emplacement of the coarse white ash marker bed (10.9 Ma) but before deposition of the upper part of the Cuarteles Member (probably 9-10.5 Ma). This fault appears to align with a west-down fault inferred in the northern part of the White Rock quadrangle (Dethier and Koning, 2007).

### Temporal changes in paleogeography and depositional environments

The Buckman and White Rock areas occupied a basin-floor to distal alluvial slope environment during the middle to late Miocene. During the latter stages of Pojoaque Member deposition (ca. 13.5-13.2 Ma), the southward-flowing streams on the basin floor were characterized by subordinate, sandy-floored channels within extensive floodplains underlain by clay, silt, and very fine- to fine-grained sand. The Cejita Member heralded a more vigorous fluvial system from the north-northeast that left more abundant channel-fill deposits of sand and gravel. Likewise, reworking of Ojo Caliente Member eolian sand into the axial river resulted in more abundant sandy bedload deposits (Vallito Member) compared to prior to ~13.2 Ma. This post-13.2 Ma, relatively coarse-grained deposition generally continued through the remainder of the Miocene, with some grossly finer-grained intervals preserved under the Buckman well field. During and after the waning of eolian deposition to the north (~11-12.8 Ma; Dethier et al., 1986; Aldrich and Dethier, 1990; Koning et al., 2005a, b), an ancestral Rio Chama became established (Hernandez Member) and flowed south-southeast onto the floor of the Espanola Basin from the northwest, where it then flowed parallel alongside of the ancestral Rio Grande (Vallito and/or Cejita Member) before merging in the Buckman-White Rock study area. Westward-flowing alluvial-slope deposits (Cuarteles Member) progressively extended westwards during the late Miocene.

### Hydrogeologic inferences

There is much societal interest in ground water flow and potential impacts to ground water quality in our study area. Ground water flow in the Buckman area has been influenced by pumping in the well field. Based on the presence of springs along the east side of the Rio Grande, it is reasonable to infer that ground water originally flowed west-southwest towards the Rio Grande from the east, with an upward gradient near the Rio Grande. West of the Rio Grande, groundwater flow in the regional aquifer is primarily easterly to southeasterly (Purtymun and Johansen, 1974; Purtymun, 1995; Keating et al., 2005).

A few general statements can be made concerning how our stratigraphic framework will affect hydrogeologic interpretations for the Buckman-White Rock area. First, the Buckman supply wells generally pump from two or more of the six localized units of the Vallito Member. Of these six units, the middle and upper coarse-grained units may produce the highest yields because of their coarse gross textures. A notable exception is Buckman-9, which is also screened across the Cuarteles and Cejita Members (screen depth of 300 to 1340 ft). Being relatively fine-grained, Buckman-9 did not encounter any relatively thick, coarse-grained Vallito Member strata in the saturated zone. These observations and the greater presence of silty sand in the distal Cuarteles Member (perhaps creating lower permeability) in Buckman-9 may partly explain its relatively low yield (J. Shomaker, 2002, unpubl. consultant report).

Second, the Vallito and Hernandez Members may have the highest hydraulic conductivities of the lithologic units in the area owing to the relatively abundant coarse-grained channel-fills in these strata, assuming a correlation between hydraulic conductivity and increasing grain size. The basin-floor deposits of the Pojoaque Member, dominated by fine-grained floodplain deposits, likely have the lowest gross hydraulic conductivity values. If so, then there is little reason to drill water supply wells beyond the Vallito Member in the Buckman area, especially in light of the general coarsening-upward trend observed in middle Miocene strata to the north (Koning et al., 2005a; Koning, 2002a, b, 2003). Our cross-section indicates that the Chamita Formation increasingly thickens westward towards White Rock and beyond (Fig. 8). West of the Rio Grande, the Chamita Formation generally consists of the Vallito and Hernandez Members, which overall are relatively sandy and likely have relatively high conductivity values. Thus, the same aquifer exploited by the Buckman field continues west of White Rock and thickens in that direction, where it and stratigraphically higher rock units are tapped by the highly productive Pajarito and Guaje well fields (Purtymun, 1995).

Third, the Vallito Member as a whole, together with most of its associated channel-fill deposits, trends approximately north-south, parallel to the flow of the Rio Grande (in the middle-late Miocene and today). If the Vallito Member does have the highest gross permeabilities in the Buckman well field, then the cone of depression produced by the Buckman well field also likely assumes an asymmetric, north-south elongation. This north-south asymmetry will be enhanced by the West and East Buckman faults, the latter of which possibly continues northward towards the north boundary of the San Ildefonso Pueblo (although probably as a series of segments rather than one continuous fault line). The East Buckman fault underwent ~20 cm of dilation and 20-25 cm of west-down vertical slip between 2000 and 2002, probably because of sediment compaction accompanying decreasing groundwater levels in the well field at that time. If this fault was able to separate strata undergoing dewatering and compaction on its hanging wall from less dewatered and compacted strata on its footwall, then it may be functioning as a barrier to groundwater flow. Having this fault act as a groundwater barrier may allow the cone of depression to proceed farther northward in its hanging wall as opposed to its footwall. Consequently, monitoring wells such as the Skillet well, which is located on the footwall of this fault and has experienced lowering of ground water levels, may not adequately delineate the northward extent of the cone of depression on the hanging wall of the East Buckman fault.

## ACKNOWLEDGMENTS

We thank our reviewers Jack Frost and Giday WoldeGabriel. Jack Frost provided borehole geophysical data for Buckman-9 and the SEO-USGS Buckman monitoring well. Funding for this project was provided by the AQUIFERMAP and STATEMAP programs as well as the Office of the New Mexico State Engineer. Descriptions for the OSE-USGS Buckman monitoring well were provided by Scott Aby.

## REFERENCES

Aldrich, M.J., and Dethier, D.P., 1990, Stratigraphic and tectonic evolution of the northern Española Basin, Rio Grande rift, New Mexico: Geological Society of America Bulletin, v. 102, p. 1695-1705.

Bailey, R.A., Smith, R.L., and Ross, C.S., 1969, Stratigraphic nomenclature of volcanic rocks in the Jemez Mountains, New Mexico: U.S. Geological Survey, Bulletin 1274-P., 19 p.

Barghoorn, S., 1981, Magnetic-polarity stratigraphy of the Miocene type Tesuque Formation, Santa Fe Group, in the Española Valley, New Mexico: Geological Society of America Bulletin, v. 92, p. 1027-1041.

Biehler, S., Ferguson, J., Baldridge, W.S., Jiracek, G.R., Aldern, J.L., Martinez, M., Fernandez, R., Romo, J., Gilpin, B., Braile, L.W., Hersey, D.R., Luyendyk, B.P., and Aiken, C.L., 1991, A geophysical model of the Española Basin, Rio Grande rift, New Mexico: Geophysics, v. 56, p. 340-353.

Broxton, D., and Vaniman D., 2005, Geologic framework of a groundwater system on the margin of a rift basin, Pajarito Plateau, north-central New Mexico: Vadose Zone Journal, v. 4, p. 522-550.

Broxton D., Gilkeson, R., Longmire, P., Marin, J., Warren, R., Vaniman, D., Crowder, A., Newman, B., Lowry, B., Rogers, D., Stone, W., McLin, S., WoldeGabriel, G., Daymon, D., and Wycoff, D., 2001, Characterization well R-9 completion report: Los Alamos National Laboratory, Report LA-13742-MS, 85 p.

Cavazza, W., 1986, Miocene sediment dispersal in the central Española Basin, Rio Grande rift, New Mexico, USA: Sedimentary Geology, v. 51, p. 119-135.

Chapin, C.E., 1971, The Rio Grande rift; Part 1, modifications and additions: New Mexico Geological Society, 22nd Field Conference, Guidebook, p. 191-201.

Dethier, D.P., 1997, Geology of the White Rock quadrangle, Los Alamos and Santa Fe Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 73, scale 1:24,000.

Dethier, D.P., and Koning, D.J., 2007, Geology of the White Rock quadrangle, Los Alamos and Santa Fe Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report GM-134, scale 1:24,000.

Dethier, D.P., and Manley, K., 1985, Geologic map of the Chili quadrangle, Rio Arriba County, New Mexico: U.S. Geological Survey, Miscellaneous Field Studies Map MF-1814, scale 1:24,000.

Dethier, D.P., Aldrich, M.J. Jr., and Shafiqullah, M., 1986, New K-Ar ages for Miocene volcanic rocks from the northeastern Jemez Mountains and Tejana Mesa, New Mexico: Isochron/West, no. 47, p. 12-14.

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

Galusha, T., and Blick, J.C., 1971, Stratigraphy of the Santa Fe Group, New Mexico: Bulletin of the American Museum of Natural History, v. 144, 127 p.

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.

Ingram, R.L., 1954, Terminology for the thickness of stratification and parting units in sedimentary rocks: Geological Society of America Bulletin, v. 65, p. 937-938.

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.

Izett, G.A., and Obradovich, J.D., 2001, $^{40}Ar/^{39}Ar$ ages of Miocene tuffs in basin-fill deposits (Santa Fe Group, New Mexico, and Troublesome Formation, Colorado) of the Rio Grande rift system: The Mountain Geologist, v. 38, p. 77-86.

Keating, E., Robinson, B., and Vesselinov, V., 2005, Development and application of numerical models to estimate fluxes through the regional aquifer beneath the Pajarito Plateau: Vadose Zone Journal, v. 4, p. 653-671.

Kelley, V.C., 1956, The Rio Grande depression from Taos to Santa Fe: New Mexico Geological Society, 7th field conference, Guidebook, p. 109-114.

Kelley, V.C., 1978, Geology of the Española Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 48, scale 1:125,000.

Kempter, K.A., Kelley, S., Goff, F., and Rampey, M., 2004, Preliminary geologic map of the Polvadera Peak 7.5-minute quadrangle, Rio Arriba County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 96, scale 1:24,000.

Koning, D.J., 2002a, revised July-2005, Geologic map of the Española 7.5-minute quadrangle, Rio Arriba and Santa Fe Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 54, scale 1:24,000.

Koning, D.J., 2002b, Depositional trends of the upper Tesuque Formation, Española Basin, N.M., and inferred tectonic and climatic influences on aggradation (abs.): Geological Society of America, Abstracts with Programs, v. 34, no. 6, p. 281.

Koning, D.J., 2003, revised 2005, Geologic map of the Chimayo 7.5-minute quadrangle, Rio Arriba and Santa Fe Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM-71, scale 1:24,000.

Koning, D.J., 2007, Stratigraphic notes on Santa Fe Group exposures west of the Rio Grande between Otowi and Española:New Mexico Geological Society, 58th Field Conference, Guidebook, p. 41-43.

Koning, D.J., and Aby, S.B., 2005, Proposed members of the Chamita Formation, north-central New Mexico: New Mexico Geological Society, 56th Field Conference, Guidebook, p. 258-278.

Koning, D.J., and Maldonado, F., 2001, Geologic map of the Horcado Ranch quadrangle, Santa Fe County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Geologic Map OF-GM-54, scale 1:24,000.

Koning, D.J., and Manley, K., 2003, revised 2005, Geologic map of the San Juan Pueblo 7.5-minute quadrangle, Rio Arriba and Santa Fe Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM-70, scale 1:24,000.

Koning, D.J., Aby, S.B., and Dunbar, N., 2004, Middle-upper Miocene stratigraphy of the Velarde graben, north-central New Mexico: tectonic and paleogeographic implications: New Mexico Geological Society, 55th Field Conference, Guidebook, p. 359-373.

Koning, D.J., Connell, S.D., Morgan, G.S., Peters, L., and McIntosh, W.C., 2005a, Stratigraphy and depositional trends in the Santa Fe Group near Espanola, north-central New Mexico: tectonic and climatic implications: New Mexico Geological Society, 56th Field Conference, Guidebook, p. 237-257.

Koning, D.J., Skotnicki, S., Moore, J., and Kelley, S., 2005b, Geologic map of the Chili 7.5-minute quadrangle, Rio Arriba county, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM-81, scale 1:24,000.

Koning, D.J., Peters, L., Kelley, S., and McIntosh, W.C., 2007, Evidence for rhyodacitic volcanism in the northern Jemez Mountains at 11 - 13 Ma: New Mexico Geological Society, 58th Field Conference, Guidebook, p. 39-41.

Manley, K., 1977, Geologic map of the Cejita Member (new name) of the Tesuque Formation, Española Basin, New Mexico: U.S. Geological Survey, Miscellaneous Field Studies Map MF-877, scale 1:24,000.

Manley, K., 1979, Tertiary and Quaternary stratigraphy of the Northeast Plateau, Española Basin, New Mexico: New Mexico Geological Society, 30th Field Conference, Guidebook, p. 231-236.

NACSN (North American Commission on Stratigraphic Nomenclature), 2005, North American stratigraphic code: American Association of Petroleum Geologists Bulletin, v. 89, p. 1547-1591.

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

Purtymun, W.D., and Johansen, S., 1974, General geohydrology of the Pajarito Plateau: New Mexico Geologic Society, 25th Field Conference, Guidebook, p. 347-349.

Sawyer, D.A., Shroba, R.B., Minor, S.A., and Thompson, R.A., 2002, Geologic map of the Tetilla Peak quadrangle, Santa Fe and Sandoval Counties, New Mexico: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2352, scale 1:24,000.

Sigda, J.M., Paul, P.J., and Koning, D.J., 2004, Comparison of permeability and grain size differences in Tesuque Formation deposits at the Santa Fe River and Buckman well field areas, Española Basin, New Mexico (abs.), *in* Hudson, M., ed., Geologic and hydrogeologic framework of the Española Basin – proceedings of the 3rd Annual Española Basin workshop, Santa Fe, New Mexico, March 2-3, 2004, p. 19.

Smith, G.A., 2004, Middle to late Cenozoic development of the Rio Grande rift and adjacent regions in northern New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The geology of New Mexico, a geologic history: New Mexico Geological Society, Special Publication 11, p. 331-358.

Spell, T. L., McDougall, I., and Doulgeris, A.P., 1996, Cerro Toledo Rhyolite, Jemez volcanic field, New Mexico: $^{40}Ar/^{39}Ar$ geochronology of eruptions between two caldera-forming events: Geological Society of America Bulletin, v. 108, p. 1549–1566.

Spiegel, Z., and Baldwin, B., 1963, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geological Survey, Water-Supply Paper 1525, 258 p.

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 Pliocene-Pleistocene Puye alluvial fan: Journal of Volcanology and Geothermal Research, v. 36, p. 267-291.

Waresback, D.B., 1986, The Puye Formation, New Mexico – analysis of a continental rift-filling volcaniclastic alluvial fan sequence [M.S. thesis]: Arlington, University of Texas, 225 p.

Waresback, D.B., and Turbeville, B.N., 1990, Evolution of a Pliocene-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 Heizler, M., 1996. Temporal and geochemical trends of lavas in White Rock Canyon and the Pajarito Plateau, Jemez volcanic field, New Mexico, USA: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 251-262.

WoldeGabriel, G., Warren, R.G., Cole, G., Goff, F., Broxton, D., Vaniman, D., Peters, L., Naranjo, A., and Kluk, E., 2006, Volcanism, tectonics, and chronostratigraphic records in the Pajarito Plateau of the Española Basin, Rio Grande rift, north-central New Mexico, USA: Los Alamos National Laboratory, Report LA-UR-06-6089, 122 p.