Surface and subsurface stratigraphy of the Santa Fe Group near White Rock and the Buckman areas of the Espanola Basin, north-central New Mexico

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in:

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

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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-dominat sand that is locally fossil. Vallito Member gravels consist of very fine to coarse pebbles. The Vallito Member interfingers westward with light gray volcanioclastic 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 stratigraphic relations 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 km², 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 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...
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); Combínable 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
SURFACE AND SUBSURFACE STRATIGRAPHY OF THE SANTA FE GROUP

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). $^{40}\text{Ar}/^{39}\text{Ar}$ 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 (Tesequye 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 (Barghoorn, 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 $^{40}\text{Ar}/^{39}\text{Ar}$ methods (Broxton et al., 2001). This flow also appears to project to a basalt in the R-22 well that returned an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 8.97 ± 0.11 Ma (WoldeGabriel, personal commun., 2003) (Figs. 1, 8).

AGE CONTROL

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
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).
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
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 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.

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-
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 interdigitates 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 part of the Vallito Member interfingers 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 ed. 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 interfinger 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 gradationally overlies the Vallito Member throughout its areal extent, whereas west of the Rio Grande the two are in an interfinger 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).

Note: HNDZ = Hernandez Member of the Chamita Formation.
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 subordi- nate 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 (Kempet er 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 surrounded 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 dacties 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
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...
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 noticeably 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 ~ 1 m-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 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.

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 basal 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-
reduce 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 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 Maldonado, 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
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 (Tasuque 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-southwest onto the floor of the Española 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 northsouth, 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 dilatation 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.

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