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Abstract

Over a kilometer of sedimentary and volcanic rocks of the Santa Fe Group are exposed in the Hagan embayment, a structural re-entrant between the Albuquerque and Española Basins. We identify two new lithostratigraphic units, the Tanos and Blackshare Formations, that resulted from late Oligocene to late Miocene sedimentation along the northeastern margin of the Albuquerque Basin and Hagan embayment. We designate exposures in Arroyo de la Vega de los Tanos as the type section and the San Felipe Pueblo NE quadrangle as the type area for these two formations. The Tanos Formation is 279 m (915 ft) thick at the type locality where it disconformably overlies the Espinaso Formation. The Tanos Formation consists of a basal conglomerate overlain by mudstone and sandstone, representing deposition in a closed basin. The overlying Blackshare Formation is over 1,000 m (3,281 ft) thick and contains dominantly sandstone with interbeds of lenticular conglomerate, conglomeratic sandstone, and minor mudstone, commonly arranged in fining-upward sequences. Paleocurrent measurements, gravel composition, and field relationships indicate derivation from the neighboring Ortiz Mountains. The Blackshare Formation conformably overlies and interfingers with the Tanos Formation and represents a general westward progradation of the Ortiz Mountains piedmont during Miocene time. Stratal tilts of the Tanos–Blackshare succession decrease upsection, indicating that subsidence and deposition occurred concurrently. Subhorizontally bedded conglomerate and sandstone of the Pliocene–Pleistocene Tuerto formation* overlie the Blackshare Formation in angular unconformity. A basaltic flow near the base of the Tanos Formation yielded an $^{40}Ar/^{39}Ar$ age of 25.41 ± 0 .32 Ma. A volcanic ash within the Blackshare Formation yielded an $^{40}Ar/^{39}Ar$ age of 11.65 ± 0.38 Ma and geochemically resembles one of the middle Miocene Trapper Creek ashes from the northeastern Basin and Range province. The base of the Tanos Formation is older than the basal Zia Formation, which is exposed along the northwestern margin of the Albuquerque Basin, indicating that deposition of the Santa Fe Group began earlier to the east.

*Editor's note: It is the lead author's belief that the Tuerto gravels of Stearns (1953b) is a mappable and lithologically well devined unit that should be given formation-rank status. Elevation of the Tuerto gravels to formation rank will be proposed in a future publication.

Introduction

The Santa Fe Group (upper Oligocene–Pleistocene) comprises the sedimentary and volcanic fill of the Rio Grande rift (Chapin and Cather, 1994). Geologic mapping and stratigraphic studies of the Santa Fe Group exposed along Arroyo de la Vega de los Tanos in the Hagan embayment, northeast of Espinaso Ridge (Fig. 1), constrain the initial development of the Rio Grande rift in north-central New Mexico. According to a K–Ar age reported for a basalt flow near the base of the Santa Fe Group (Kautz et al., 1981), these deposits represent some of the oldest exposed rocks of the Albuquerque Basin area (cf. Bachman and Mehnert, 1978). These exposures provide an opportunity to study early rift sedimentation and to characterize lower Santa Fe Group deposits that are buried by younger rift-basin fill in the Santo Domingo sub-basin. The presence of upper Oligocene deposits supports conclusions from other studies of rift-related extension elsewhere in New Mexico (e.g., Chapin and Cather, 1994; Smith, 2000; Mack et al., 1994; Smith et al., in press).

This paper summarizes results of geologic mapping and stratigraphic studies of the San Felipe Pueblo NE quadrangle (Cather et al., 2000) and defines two new formation-rank lithostratigraphic units of upper Oligocene and Miocene deposits of the lower Santa Fe Group. In accordance with the North American Commission on Stratigraphic Nomenclature (NACSN, 1983), we describe three informal members of the Tanos Formation and four informal members of the Blackshare Formation. We conclude with some implications that this study has on models of the tectonic development of the Española and northern Albuquerque Basins (e.g., Ingersoll, 2001).

Geologic setting and previous studies

The Hagan embayment is a northeast-tilted structural re-entrant between the La Bajada and San Francisco fault zones. These fault zones define the eastern margin of the Rio Grande rift along different parts of their traces (Kelley, 1977). The Hagan embayment is bounded to the north by the Budaghers fault. The Hagan embayment lies just east of the Santo Domingo sub-basin, a deep structural sub-basin within the northern part of the Albuquerque Basin (Grauch et al., 1999). This tilted and fault-bounded embayment exposes one of the most complete Phanerozoic stratigraphic sections in central New Mexico (Pazzaglia et al., 1999). Paleogene nonvolcanic deposits exposed in the Hagan embayment include arkosic sandstone, conglomerate, and mudstone of the Diamond Tail and Galisteo Formations (Fig. 2; Stearns, 1953b; Gorham and Ingersoll, 1979; Lucas et al., 1997). Conglomerate beds of the Diamond Tail and Galisteo Formations contain rounded metaquartzite, chert, and petrified wood clasts (Stearns, 1953b; Gorham and Ingersoll, 1979). Conglomerate of the upper Eocene–Oligocene Espinaso Formation containing volcanic rocks and sandstone conformably overlies the Galisteo Formation (Stearns, 1953a, b; Erskine and Smith, 1993).

Volcanic products of the Espinaso Formation, which have been studied extensively (Kautz et al., 1981; Erskine and Smith, 1993), are associated with the emplacement of the Ortiz porphyry belt in the Ortiz Mountains and Cerrillos Hills (Stearns, 1953a; Kautz et al., 1981; Erskine and Smith, 1993). The Ortiz Mountains are a 26–36 Ma belt of Eocene–Oligocene porphyritic, hypabyssal-intrusive (subvolcanic) rocks exposed on the footwall of the La Bajada fault, just east of the study area (Kelley, 1977; Kautz et al., 1981; Maynard et al., 1990). The Espinaso Formation is divided into a lower calc-alkaline assemblage and an upper alkaline assemblage (Erskine and Smith, 1993). Rocks of the lower assemblage were erupted between 36 and 34 Ma, followed by eruption of the upper assemblage between 30 and 26 Ma (Maynard et al., 1990).

The stratigraphic nomenclature of rift-basin fill (i.e., Santa Fe Group) in the study area has undergone a number of changes over the years (Fig. 2). Stearns (1953a, b) first described the study area in detail and defined the subjacent Eocene Galisteo and Eocene–Oligocene Espinaso Formations. Lucas et al. (1997) replaced the lower part of Galisteo Formation with the Diamond Tail Formation. Stearns (1953b) tentatively assigned deposits overlying the Espinaso

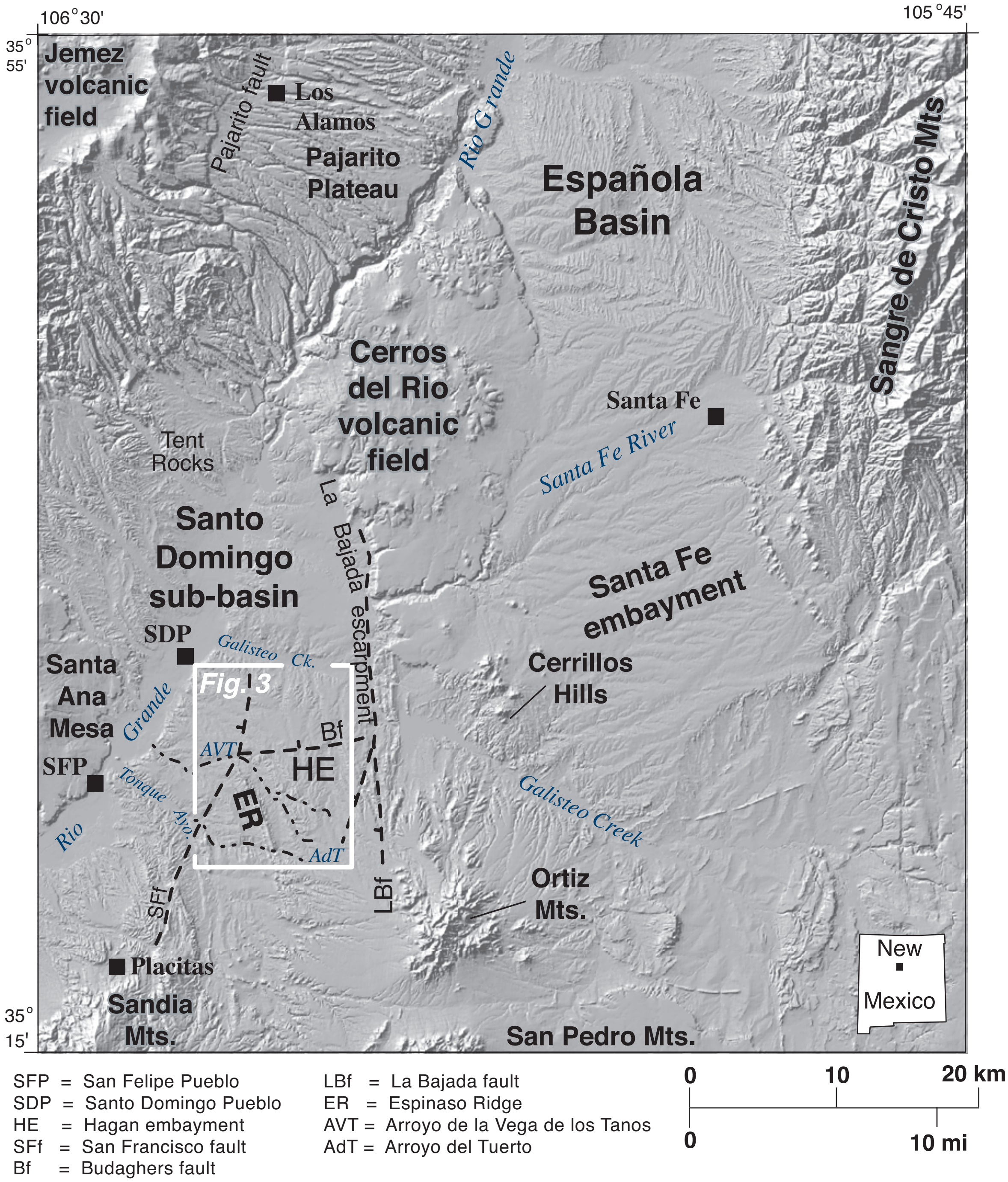


FIGURE 1—Location of the Santo Domingo sub-basin (Albuquerque Basin), Hagan embayment, Ortiz Mountains, San Felipe Pueblo 7.5-minute quadrangle study area (Fig. 3), and other major features of the northern Albuquerque and southern Española Basins. The Hagan embayment is bounded by the San Francisco, Budaghers, and La Bajada faults. The Tijeras fault (not shown) trends to the northeast through the Ortiz Mountains. Drainages of Arroyo de la Vega de los Tanos and Arroyo del Tuerto, San Felipe Pueblo, Santo Domingo Pueblo, Santa Fe, and Los Alamos are shown for reference.

Formation to the Abiquiu(?) Formation, primarily on stratigraphic position and the presence of tuffaceous rocks exposed on the footwall of the La Bajada escarpment (Fig. 1). Overlying deposits were assigned to the Santa Fe Formation and Tuerto gravels by Stearns (1953b). Kelley (1977) assigned the Abiquiu(?) Formation (sensu Stearns, 1953b) to the Zia Formation. Spiegel and Baldwin (1963) elevated the Santa Fe Formation to group rank in the southern Española Basin. This group usage was extended throughout the rift (e.g., Hawley, 1978; Chapin and Cather, 1994). The lower Santa Fe Group represents deposition within internally drained basins (bolsons) that contain broad alluvial plains and ephemeral or intermittent playa lakes fed by streams draining emerging basin-margin uplifts (Chapin and Cather, 1994). Upper Santa Fe Group strata record deposition in externally drained basins where perennial streams and rivers associated with the ancestral Rio Grande flowed toward southern New Mexico (Hawley, 1978). Deposition of the upper Santa Fe Group ceased during Pleistocene time, when the Rio Grande began to incise into the earlier aggradational phase of the Santa Fe Group basin fill (Spiegel and Baldwin, 1963; Hawley, 1978).

Petrographic criteria (using only sandstone) define formal and informal units

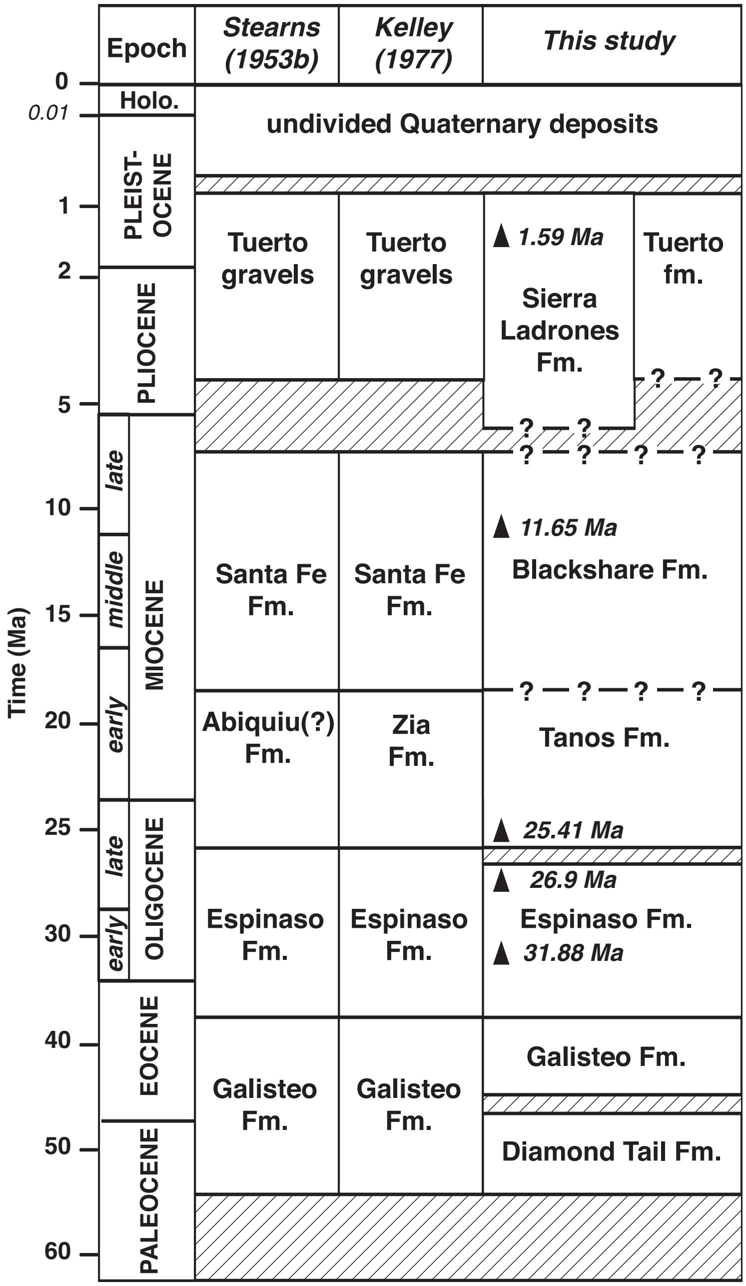


FIGURE 2—Comparison of stratigraphic nomenclature of Cenozoic deposits in the study area. Selected geologic time boundaries shown (not to scale). Radioisotopic age control points from Cather et al. (2000, 2002), Peters (2001a, b, 2002), and Kautz et al. (1981).

within the Santa Fe Group and subjacent strata in the Albuquerque and Española Basins. The Diamond Tail and Galisteo Formations contain mostly quartz rich arkose (Gorham and Ingersoll, 1979). Sandstones of the Espinaso Formation contain quartz-poor arkose and lithic arkose (Kautz et al., 1981). Large and Ingersoll (1997) studied the composition of medium- to very coarse grained sandstone from post-Espinaso Formation deposits in the Hagan embayment to define their volcanic-hypabyssal petrofacies. They concluded that this petrofacies is compositionally related to rocks of the Ortiz Mountains. This petrofacies is dominantly lithic arkose and feldspathic litharenite with a mean quartz content (QFL%Q) of 35 ± 17% (Large and Ingersoll, 1997) and is substantially greater than the lithic arkose of the subjacent Espinaso Formation, which has a mean quartz content of less than 5% (Kautz et al., 1981).

Methods

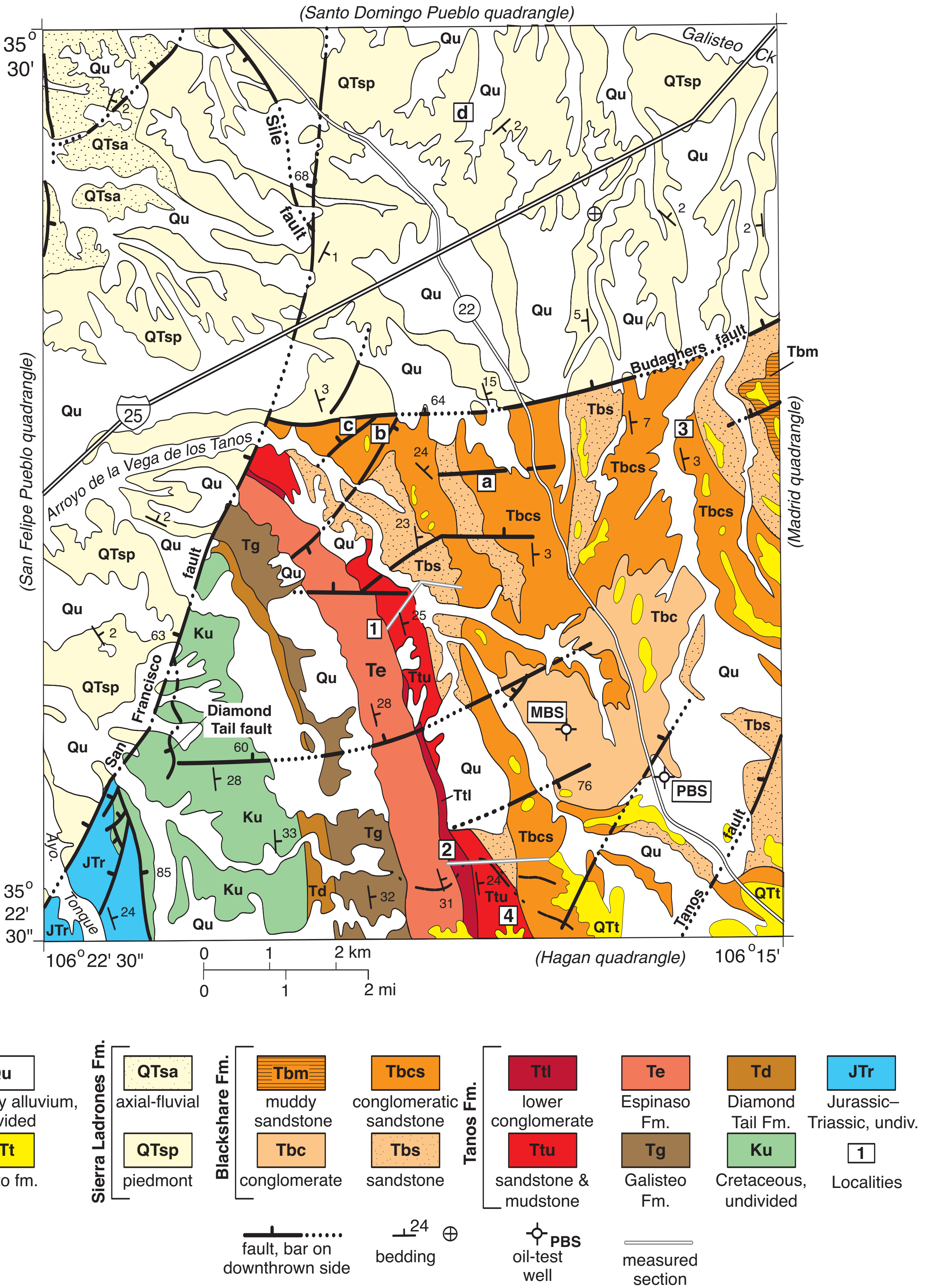
The study area was mapped at a scale of 1:24,000 (Fig. 3), and deposits of the Santa Fe Group were divided into textural lithofacies following the methods of Cather (1997). Two stratigraphic sections were measured in Arroyo de la Vega de los Tanos and Arroyo del Tuerto (Fig. 4; Appendix). Data from the Merrion Oil Blackshare Federal #1 (sec. 34 T14N R6E, New Mexico Bureau of Geology and Mineral Resources, NMBGMMR Subsurface Library #47490) and the Pelto Oil Blackshare Federal #1 (sec. 25 T14N R6E, NMBGMMR Subsurface Library #26091) oil-test wells were also examined. Colors were documented using the Munsell (1992) method. Texture and bedding were described according to Dutro et al. (1989) and Ehlers and Blatt (1982).

Radioisotopic ages of volcanic material were measured using the $^{40}Ar/^{39}Ar$ technique at the New Mexico Geochronological Research Laboratory (NMGRL), New Mexico Institute of Mining and Technology in Socorro, New Mexico. Groundmass concentrates from basaltic units were analyzed by the furnace incremental heating age spectrum method (Peters, 2001a, 2002). Sanidine concentrates from an ash layer were analyzed using the single-crystal total fusion method (Peters, 2001b). Analytical methods and results of dating are in Peters (2001a, b, 2002).

The geochemical composition of the glassy component of tephra layers was quantitatively determined using a Cameca SX-100 electron microprobe. Tephra samples were mounted in epoxy disks and polished using pure diamond powder suspended in distilled water. Approximately 20 points on each sample were analyzed for major elements plus fluorine, chlorine, and sulfur. The largest possible beam size was used for the microprobe analyses in order to minimize volatilization of sodium, reaching a maximum size of 25 µm. Standard ZAF procedures were used for recalculation of analyses. Analyses were normalized to 100 wt%, and means and standard deviations were calculated for each data set, discarding any obvious statistical outliers. Data sets were compared using statistical difference calculations described by Perkins et al. (1995).

Tanos Formation

The Tanos Formation is a new lithostratigraphic unit herein named for Arroyo de la Vega de los Tanos, a tributary to the Rio Grande. The base of the type section is at a spring near the northwestern corner of sec. 28 T14N R6E, of the San Felipe Pueblo NE 7.5-min quadrangle (Fig. 3). At the type section (Fig. 4), the Tanos Formation is 279 m (915 ft) thick and consists of reddish-brown to reddish-yellow sandstone and reddish-brown and olive-gray mudstone overlying a very pale brown basal conglomerate (Appendix). Concretionary sandstone intervals and thin rhizoconcretionary beds are locally present. Bedding of the Tanos Formation dip 20–32° northeast. The Tanos Formation is exposed in the San Felipe Pueblo NE and Hagan


(Santo Domingo Pueblo quadrangle)
(San Felipe Pueblo quadrangle)
(Madrid quadrangle)
(Hagan quadrangle)
35° 30'
35° 22' 30"
106° 22' 30"
106° 15'
Galisteo Ck
Sile fault
San Francisco fault
Diamond Tail fault
Budaghers fault
Tanos fault
Arroyo de la Vega de los Tanos
Arroyo Tonque
25
22
MBS
PBS
0 1 2 km
0 1 2 mi
Qu
Quaternary alluvium, undivided
QTt
Tuerto fm.
Sierra Ladrones Fm.
QTsa
axial-fluvial
QTsp
piedmont
Blackshare Fm.
Tbm
muddy sandstone
Tbcs
conglomeratic sandstone
Tbc
conglomerate
Tbs
sandstone
Tanos Fm.
Ttl
lower conglomerate
Ttu
sandstone & mudstone
Te
Espinaso Fm.
Tg
Galisteo Fm.
Td
Diamond Tail Fm.
Ku
Cretaceous, undivided
JTr
Jurassic–Triassic, undiv.
1
Localities
fault, bar on downthrown side
24
bedding
PBS
oil-test well
measured section

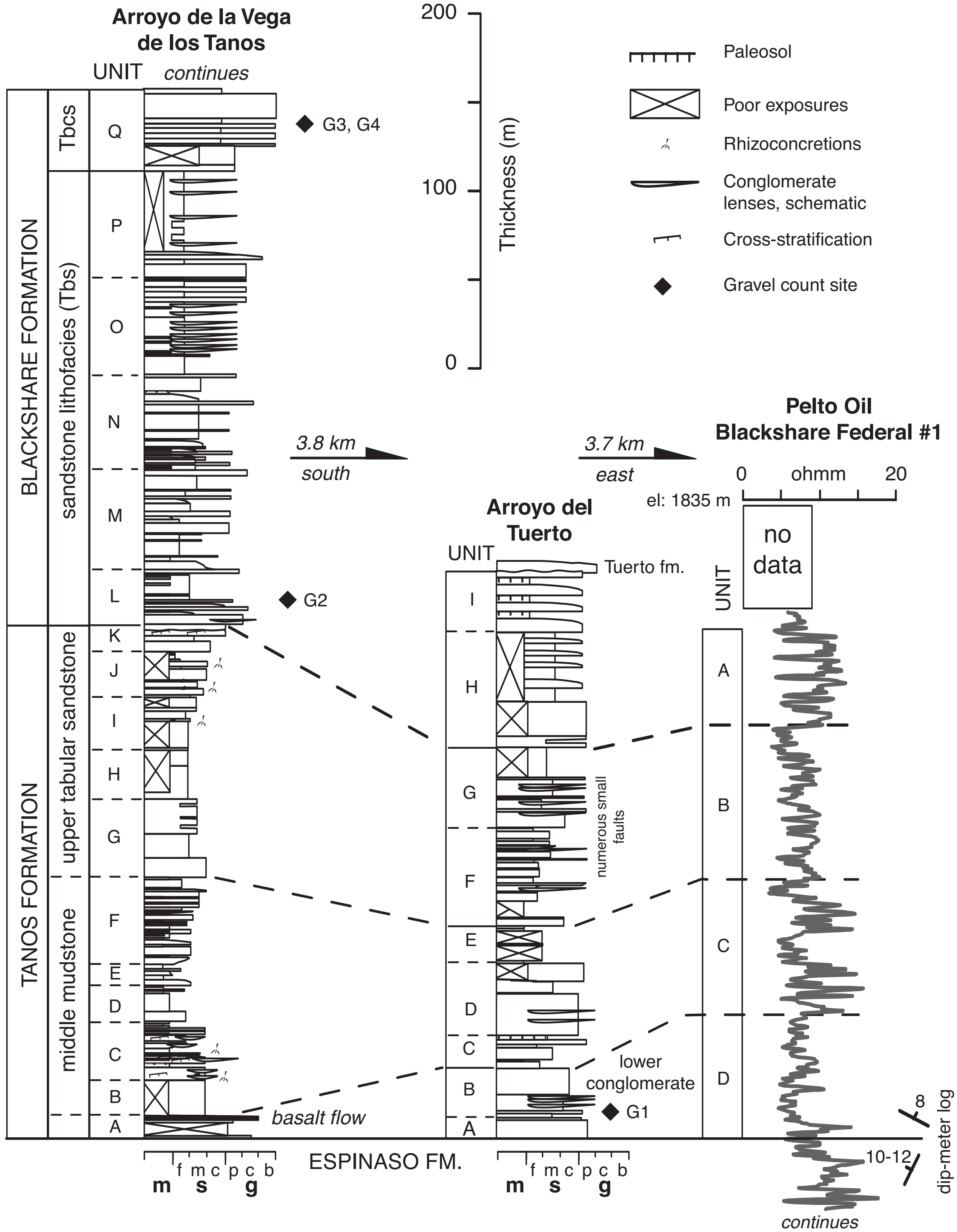


FIGURE 3—Simplified geologic map of the San Felipe Pueblo NE 7.5-min quadrangle (modified from Cather et al., 2000). Localities discussed in text include Arroyo de la Vega de los Tanos (**1**) and Arroyo del Tuerto (**2**) stratigraphic sections, the Pelto Oil Blackshare Federal #1 (**PBS**), and Merrion Blackshare Federal #1 (**MBS**) wells, and gravel count sites in the Tuerto formation (**3**) and upper Blackshare Formation (**4**). Volcanic units include a 25.41 Ma basaltic flow at the type section (**1**), a 11.65 Ma fallout ash (**a**), three correlative fluvially recycled fallout tephra, including the 11.65 Ma ash (**a**, **b**, **c**), and a 1.59 ±0.02 Ma lapilli of the lower Bandelier Tuff (**d**). Major structural features include the Budaghers, San Francisco, Diamond Tail, and Tanos faults. The La Bajada fault is 2–3 km (1–2 mi) east of the quadrangle.

FIGURE 4—Stratigraphic sections of the Tanos and Blackshare Formations at Arroyo de la Vega de los Tanos and Arroyo del Tuerto (Fig. 3). Comparisons to an induction resistivity log of the Pelto Oil Blackshare Federal #1 indicate that this well penetrated deposits similar to the type section. An angular unconformity between the projection of the Espinaso and Tanos Formations is interpreted from a continuous dip-meter log for this well. Strike and dip symbols indicate the average orientation of deposits above and below this contact. Horizontal scale indicates approximate maximum grade (**m** = mudstone; **s** = sandstone; **g** = conglomerate). Diamonds denote locations of gravel counts shown on Figure 5.

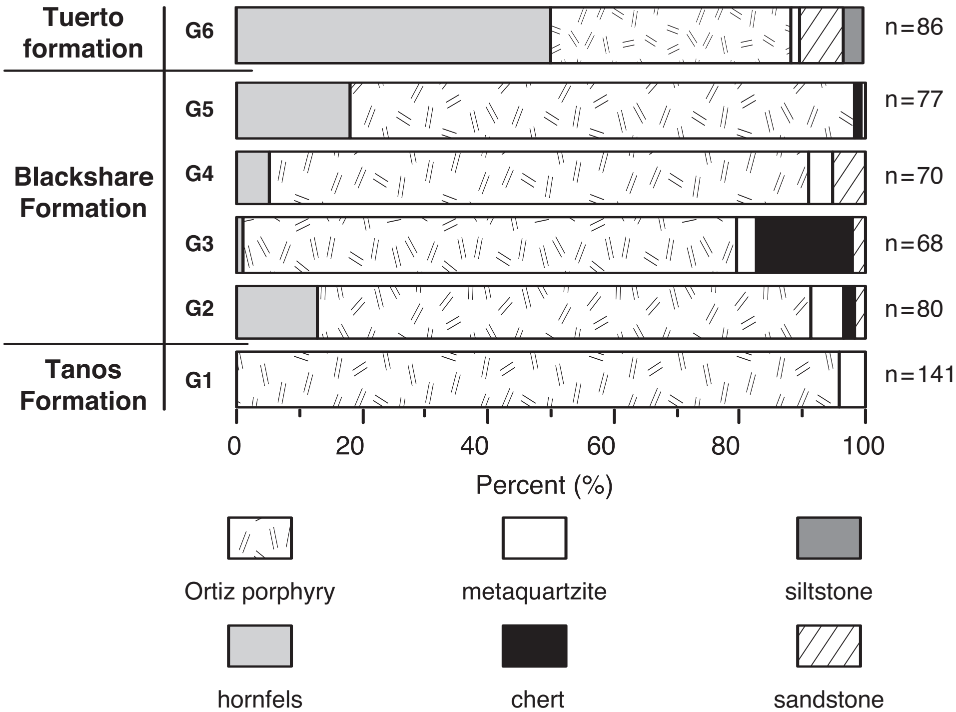


FIGURE 5—Stacked bar graph illustrating upsection variations in gravel composition in the Tanos, Blackshare, and Tuerto formations. Gravel of the Ortiz porphyry dominates the basal Tanos Formation (**G1**). Gravel in the Blackshare Formation (**G2–G4**; **G5** at locality **3**) becomes more diverse upsection. The Tuerto formation at locality **4** (**G6**) is heterolithic and contains a greater abundance of hornfels gravel (50%) than the underlying Blackshare Formation.

quadrangles. The Tanos Formation is subdivided into three informal members: a basal conglomerate, a middle mudstone, and an upper tabular sandstone.

The lower conglomerate member is approximately 12 m (39 ft) thick at the type section and thickens to approximately 31 m (102 ft) at Arroyo del Tuerto (Arroyo Pinovetito of Stearns, 1953b), approximately 4 km (2 mi) to the south (Fig. 1). This unit thickens to as much as 100 m (328 ft) based on interpretations of borehole geophysical logs from the Pelto Oil Blackshare Federal #1 well (Fig. 4). At the type section the lower conglomerate is very pale brown to reddish-yellow, thinly to medium-bedded conglomerate and pebbly to cobbly sandstone. Gravel contains recycled porphyritic volcanic and hypabyssal-intrusive detritus, derived from the neighboring Ortiz Mountains, and sparse, rounded metaquartzite pebbles that were probably derived from the Galisteo Formation (Fig. 5). Sparse paleocurrent observations (n = 8) indicate a westerly paleoflow direction with mean azimuth of 287 ± 19° (Fig. 6). Erskine and Smith (1993) report calc-alkaline porphyry gravel in the basal Santa Fe Group in the Hagan embayment that is compositionally related to the lower Espinaso Formation; however, no attempt was made to differentiate volcanic or hypabyssal-intrusive gravel in the Tanos or Blackshare Formations in this study.

The lower Tanos Formation contains a black, 2.5–3.0-m-thick (8–10-ft-thick), basaltic lava flow that is discontinuously exposed along the northeastern flank of Espinaso Ridge. At the type section, this flow is approximately 9 m (30 ft) above the base and contains white to olive-yellow, spheroidal nodules of celadonite(?) and altered olivine crystals. The underlying pebbly sandstone is reddened, indicating thermal alteration of underlying deposits during emplacement of the basalt. The top of the basalt is not reddened, suggesting emplacement as a subaerial lava flow.

The middle mudstone member is 144 m (472 ft) thick at the type section, where it conformably overlies the lower member. The base of the middle member is chosen at the lowest ripple-laminated sandstone, a common sediment type in the lower part of this member. Most of this member is a thick succession of medium- to thick-bedded, reddish-brown mudstone and claystone with thin- to medium-bedded, olive-gray mudstone interbeds. Sandstone beds increase in abundance upsection toward the upper tabular sandstone member. Mudstone beds thin southeast of the type area. Thin, discontinuous gypsiferous mudstone beds are locally present in the middle mudstone and upper tabular sandstone members in Arroyo del Tuerto (Appendix).

The upper tabular sandstone member is 123 m (404 ft) thick at the type section, where it consists of very pale brown to light yellowish-brown tabular sandstone with thinly bedded rhizoconcretionary intervals with sparse scattered pebbles. This unit is characterized by medium- to thick-bedded, massive to cross-stratified sandstone. The contact with the overlying Blackshare Formation is gradational and placed at the lowest lenticular, pebbly to cobbly sandstone in the upper tabular sandstone member. The Tanos Formation may interfinger with the Blackshare Formation; however, the degree of interfingering is obscured by the Tuerto formation. The Tanos–Blackshare contact chosen at the measured sections differs slightly from the mapped contact, which was placed at the top of the highest, thickly bedded tabular sandstone. This boundary can be resolved within a few tens of meters depending upon the criterion used (i.e., highest tabular sandstone vs. lowest lenticular conglomerate).

The resistivity log for the Pelto Oil Blackshare Federal #1, drilled nearly 5 km (3 mi) southeast of the Tanos Formation typesection (Fig. 3), indicates the presence of four somewhat distinctive intervals in the upper part of this well that roughly correspond to the rocks exposed at the type section (Fig. 4). Resistivity signatures in units A and C show greater variability compared to units B and D, suggesting the presence of interbedded coarse-grained and fine-grained intervals. Units B and D lack the major resistivity shifts of A and C, suggesting that B and D are lithologically similar. Correlation of unit B to the upper tabular sandstone member is reasonable because exposures are of relatively uniform sandstone.

Gravels of the Tanos and Blackshare Formations indicate a general increase in compositional diversity upsection (Fig. 5). The Tanos Formation contains only a few percent of nonigneous pebbles, such as petrified wood and rounded metaquartzite. The Blackshare Formation contains more diverse gravel types, most notably, variably colored, thermally metamorphosed sandstone and shale (hornfels), and petrified wood. The overlying Tuerto formation contains the most diverse clast assemblage and contains abundant hornfels.

The boundary between the Espinaso and Tanos Formations is relatively easy to distinguish in the field, where the lower Tanos Formation conglomerate rests on the Espinaso Formation with a sharp and scoured contact (Fig. 7). The upper part of the Espinaso Formation is a well-consolidated but poorly cemented succession of light-gray to white sandstone and conglomerate. The Tanos Formation is very pale brown to reddish yellow and cemented with calcium carbonate. The uppermost Espinaso Formation is commonly white to gray and contains alkaline volcanic gravels that contain biotite and clinopyroxene crystals (Erskine and Smith, 1993). The Tanos Formation contains a wider diversity of volcanic gravel types than in the underlying upper Espinaso Formation. These Tanos Formation gravels range in color from dark gray to reddish brown and black, and contain sparse nonvolcanic constituents, such as rounded quartzite pebbles and petrified wood.

Additional information on the character of the Tanos–Espinaso Formation contact comes from an interpretation of borehole geophysical data from nearby oil-test wells. The Pelto Oil Blackshare Federal #1 fully penetrated the Cenozoic section. The scout ticket for this well places the Espinaso–Santa Fe Group contact at approximately 451 m (1,480 ft) below land surface (bls). A continuous dip-meter log for this well indicates the presence of an angular unconformity at approximately 460 m (1,510 ft) bls. The underlying strata are oriented N25°E, 10–12° northwest; overlying deposits are N60°W, 8° northeast. This contact likely corresponds to the disconformable Espinaso–Tanos Formation contact exposed at the type section (Fig 4).

Blackshare Formation

The Blackshare Formation is a new lithostratigraphic unit herein named for the Blackshare Ranch site in Arroyo de la Vega de los Tanos. The Blackshare Formation is more than 1,000 m (3,281 ft) thick as estimated from stratigraphic sections and geologic mapping. Conglomerate beds are lenticular, and sandstone intervals commonly fine upward into thinly bedded mudstone. Dips in the Blackshare Formation progressively decrease upsection, from 16° to 1° northeast; stratal tilts are typically greater near faults.

The type section of the Blackshare Formation begins north of Arroyo de la Vega de los Tanos, approximately 280 m (919 ft) above the base of the type section of the Tanos Formation (Fig. 3, Appendix). Paleocurrent observations (n = 60) on conglomeratic beds indicate a westerly paleoflow direction with mean azimuth of 284 ± 8° (Fig. 6). A complete section of the Blackshare Formation was not measured because exposures are quite poor east of highway NM–22. The top is overlain by the Pliocene–Pleistocene Tuerto formation in an angular unconformity, and the succession is cut by the La Bajada fault. The minimum thickness for the Blackshare Formation is estimated to be at least 1,260 m (4,134 ft). Gravel in the Blackshare Formation contains mostly monzanite and latite porphyry with sparse rounded metaquartzite, petrified wood, iron-stained sandstone, and hornfels. The Blackshare Formation is exposed in the San Felipe Pueblo NE, Hagan, and Madrid quadrangles.

The Blackshare Formation, as mapped in the study area (Fig. 3), contains four texturally based members, two of which are represented at the type section. These textural lithofacies do not occur in any particular stratigraphic order, but the lower part of the Blackshare Formation exhibits a crude upward-coarsening trend beginning with the sandstone lithofacies (Tbs), and coarsening upward into conglomeratic sandstone (Tbcs) and conglomerate (Tbc) units. The muddy sandstone unit (Tbm) follows this coarsening-upward trend to the northeast.

The conglomeratic member (Tbc) consists of well-cemented conglomerate and subordinate sandstone. The conglomeratic sandstone member (Tbcs) contains roughly subequal amounts of sandstone and conglomerate. Conglomerate is similar to the conglomeratic lithofacies and forms beds that are 50–200 cm (20–79 inches) thick. Although most of the conglomeratic sandstone lithofacies is coarse-grained, thick-bedded mudstone is locally present. The sandstone member (Tbs) contains sandstone with subordinate conglomerate and mudstone, commonly arranged in fining-upward sequences. A 10-m-thick (33-ft-thick) interval of well-sorted sandstone and olive-gray mudstone containing sparse scattered selenite gypsum is recognized in the sandstone member approximately 70 m (230 ft) stratigraphically below locality **a** (Fig. 3). The fine-grained muddy sandstone member (Tbm) is exposed along the eastern margin of the study area and contains subequal proportions of sandstone and weakly cemented, commonly reddish-brown mudstone. Weakly developed paleosols are locally common in the muddy sandstone and sandstone members.

The sandstone member conformably overlies the Tanos Formation at the type section. This lower sandstone pinches out to the south, and south of Arroyo del Tuerto the conglomeratic sandstone conformably overlies the Tanos Formation. At the type section, the sand-

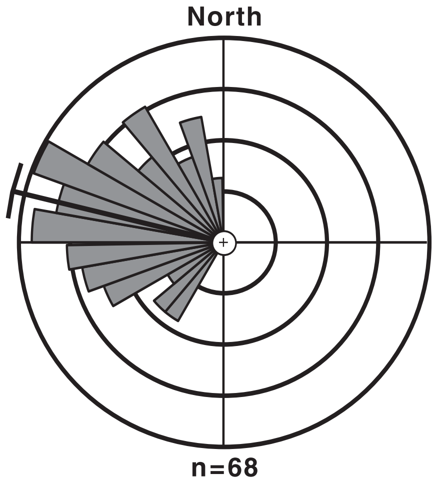


FIGURE 6—Rose diagram of paleocurrent data (grouped into 10° intervals) determined from gravel imbrication, channel orientations, and cross-stratification in the Tanos (n = 8) and Blackshare (n = 60) Formations, indicating westward paleoflow from the Ortiz Mountains. A mean paleocurrent azimuth of 284 ± 8° was determined for 68 measurements. Paleocurrent data compiled from data on the geologic map of the San Felipe Pueblo NE quadrangle (Cather et al., 2000) and supplemented by additional measurements taken during stratigraphic descriptions.

FIGURE 7—Contact between white sandstone and conglomerate of the Espinaso Formation (left) and pale-brown conglomerate of the Tanos Formation (right). Scale is 1.5 m high.

stone-dominated members are very pale brown to reddish-brown sandstone with interbedded mudstone and scattered lenticular pebble to cobble conglomerate.

Ash beds are recognized in the conglomeratic sandstone member near the Budaghers fault. These white to light-gray ashes range from a few centimeters to approximately 3 m (10 ft) in thickness and contain no obvious nonvolcanic detritus. The thickest bed is cross-stratified and contains scattered lapilli. Faults obscure physical correlation of these ashes; however, geochemical analyses indicate these ashes are geochemically indistinguishable (Table 1) and are similar when imaged with backscattered electrons on the electron microprobe. These ashes are composed mainly of glassy shards, mostly between 50 and 200 µm (0.002–0.008 inches) in the longest dimension. Many shards are rectangular in backscattered electrons, suggesting a platy morphology in three dimensions. Many tricuspate shards are observed. These shards represent remnants of the intersection of three bubbles, and they are formed by explosive eruptions driven by vesiculation (Fisher and Schmincke, 1984). The shard shapes and purity and the well-sorted nature of the samples suggest derivation from a primary ashfall event (Heiken and Wohletz, 1984). The shards in both samples are unbraided and contain delicate glass structures that are unbroken, suggesting that little transport occurred after primary deposition; however, the ash at locality **b** is approximately 3 m (10 ft) thick and cross-stratified, indicating some fluvial reworking of this deposit.

Depositional environments

Mudstone in the Tanos Formation is thinly to thickly bedded and comprises about a third of the type section. The abundance of mudstone suggests deposition in quiet water settings near the basin floor. The presence of olive-gray mudstone beds within a dominantly reddish-brown mudstone succession suggests deposition in an oxidizing, alluvial- or mud-flat environment with occasional deposition in shallow lakes or ponds under reducing conditions. The presence of rhizoconcretionary zones in the Tanos Formation and general lack of evaporitic beds within the mudstone-dominated intervals suggest that the basin floor may represent deposition in a ground-water recharge or through-flow playa-lake system (Rosen, 1994); however, a detailed evaluation of basin-floor depositional environments and paleohydrology was not attempted. Mudstone and ripple-laminated and tabular sandstone are similar to descriptions of fluviolacustrine facies of the Popotosa Formation (lower Santa Fe Group) exposed at the southern end of the Albuquerque Basin and in the Socorro Basin (Asher-Bolinder, 1988). The presence of low-angle ripple laminations in the middle mudstone and upper, tabular sandstone members indicates fluvial deposition of sandstone interbeds, probably associated with streams along the distal piedmont and margin of the basin floor.

The Blackshare Formation contains mostly fluvial sandstone and conglomerate. Sparse mudstone beds, some of which are similar to the Tanos Formation mudstones, are locally present. The presence of abundant Ortiz porphyry detritus in cross-stratified sandstone beds supports stream-flow-dominated deposition from the Ortiz Mountains. Fining-upward sequences of conglomerate and sandstone, generally capped by thin, discontinuous mudstone, are common in this unit. The lack of medium- to thick-bedded mudstone and presence of fining-upward sequences of conglomeratic sandstone, sandstone, and minor mudstone and paleosols indicate deposition along a stream-flow dominated piedmont derived from the Ortiz Mountains. However, a general upward- and southeastward-coarsening trend in much of the Blackshare Formation suggests that deposition first occurred as a prograding piedmont wedge along the eastern margin of the Rio Grande rift.

Age and correlation

The ages of the Tanos and Blackshare Formations are constrained by $^{40}Ar/^{39}Ar$ dating and geochemical correlations. Groundmass concentrates from an olivine-bearing basaltic flow near the base of the Tanos Formation type section yielded a whole-rock $^{40}Ar/^{39}Ar$ age of 25.41 ± 0.32 Ma (NMGRL#51451; Peters, 2001a). The age of this basaltic flow is similar to the Cieneguilla basanite (Cieneguilla limburgite of Stearns, 1953a, b), which was dated using the K–Ar method at 25.1 ± 0.7 Ma (Baldridge et al., 1980). The Cieneguilla basanite has been recently re-mapped in the southwestern Santa Fe embayment and dated using the $^{40}Ar/^{39}Ar$ method at 26.08 ± 0.62 Ma (Koning and Hallett, 2000). Although these two flow units are similar in age, the Tanos Formation flow was not petrographically or chemically compared to the Cieneguilla basanite.

The magnitude of the Tanos–Espinaso Formation unconformity is poorly constrained but represents less than 4–5 m.y. of erosion or nondeposition at Espinaso Ridge. Work is currently underway to date the top of the Espinaso Formation in the Hagan embayment. Some age constraints for the Espinaso Formation are known and help constrain the magnitude of this unconformity. Huerfano Butte (E½ sec. 22 and W½ sec. 23 T13N R6E), a low hill on the northern part of the Hagan quadrangle, which was informally named by Stearns (1953b), lies within the upper part of the Espinaso Formation (Cather et al., 2002). Groundmass concentrates from Huerfano Butte rock yielded an age of 31.88 ± 0.24 Ma (NMGRL#2566, Peters, 2002). Work is currently underway to radioisotopically date an ash-flow tuff in the upper Espinaso Formation approximately 100 m (328 ft) below the Tanos–Blackshare contact at the type area. Preliminary results of $^{40}Ar/^{39}Ar$ dating of this tuff suggest emplacement around 30 Ma (R. Esser, pers. comm. 2002). Kautz et al. (1981) report a K–Ar age for a nephelene syenite of 26.9 ± 0.6 Ma on Espinaso Ridge. Projections of their locality indicate it is approximately 160 m (525 ft) below the top of the Espinaso Formation. This rock lies below the ca 30 Ma tuff, suggesting that the 27 Ma age reported by Kautz et al. (1981) may be in error, and indicating that additional $^{40}Ar/^{39}Ar$ dating is required to constrain the age of the top of the Espinaso Formation.

The age of the Blackshare Formation is constrained by a dated volcanic ash at locality **a**, which is stratigraphically located approximatley 1,060 m (3,478 ft) above

TABLE 1—Mean of electron microprobe analysis (n) of tephra in the Blackshare Formation at tephra localities illustrated in Figure 3. All analyses normalized and reported in weight percent. Major elements, chlorine (Cl), and fluorine (F) were analyzed by electron microprobe. Errors (± σ) of determination for the electron microprobe are based on replicate analyses of homogeneous reference materials and counting statistics, in weight percent: P_2O_5 = ± 0.1, SiO_2 = ± 0.5, TiO_2 = ± 0 .01, Al_2O_3 = ± 0 .03, MgO = ± 0.12, CaO = ± 0.05; MnO = ± 0.03, FeO = ± 0.07, Na_2O = ± 0.09, K_2O = ± 0.19, Cl = ± 0.01; F = ± 0.1.

Sample	n	P_2O_5	SiO_2	TiO_2	Al_2O_3	MgO	CaO	MnO	FeO	Na_2O	K_2O	F	Cl
Mean, locality **a**	19	0.02	77.37	0.22	12.15	0.04	0.64	0.03	1.86	2.88	4.62	0.12	0.04
± 1σ		0.02	0.67	0.03	0.28	0.02	0.04	0.02	0.07	0.18	0.75	0.08	0.01
Mean, locality **b**	20	0.01	76.60	0.20	12.51	0.04	0.62	0.01	1.86	2.97	4.96	0.15	0.05
± 1σ		0.01	0.34	0.03	0.17	0.02	0.05	0.02	0.12	0.10	0.38	0.09	0.01
Mean, locality **c**	20	0.01	76.97	0.21	12.52	0.04	0.63	0.01	1.86	2.92	4.60	0.16	0.05
± 1σ		0.02	0.64	0.03	0.18	0.02	0.04	0.02	0.07	0.17	0.63	0.08	0.01

the base of the Tanos Formation. Sanidine concentrates from this ash yielded a laser fusion $^{40}Ar/^{39}Ar$ age of 11.65 ± 0.38 Ma (NMGRL#51627, Peters, 2001b). The volcanic ashes of localities **a**, **b**, and **c** are chemically and morphologically indistinguishable from ashes in the upper part of the Cerro Conejo Member of the Zia Formation, exposed approximately 30 km (19 mi) west of the study area and south of Santa Ana Mesa. Koning and Personius (in press) correlated the Cerro Conejo ashes to three ashes, ranging from ca 10 to 12 Ma, that were derived from the Trapper Creek tephra succession from the northeastern Basin and Range province (Perkins et al., 1998). The upper age limit of the Blackshare Formation is not known, but it is older than the overlying Pliocene–Pleistocene Tuerto formation. More than 200 m (656 ft) of Blackshare Formation lies above the 11.65 Ma ash, indicating that deposition continued into late Miocene time.

The Tanos Formation was originally assigned to the Abiquiu(?) Formation by Stearns (1953b), mainly based on stratigraphic position (age equivalence) and the presence of tuffaceous sediment. The Abiquiu Formation was deposited between 26 and 18 Ma (Tedford and Barghoorn, 1993). Deposits of the Abiquiu Formation in its type area, approximately 70 km (43 mi) northwest of the Hagan embayment, consist largely of volcanic sediment derived from the Latir volcanic field of northern New Mexico (Lipman and Reed, 1989; Smith et al., in press). Most notably, the rhyolitic Amalia Tuff, a significant constituent in the Abiquiu Formation (Smith, 1995), is not present in the Tanos and Blackshare Formations. A Latir source would require deposition via south-flowing streams to reach the Hagan embayment. Such a paleoflow trend is not supported by west-trending paleocurrent observations from the Tanos and Blackshare Formations. Furthermore, an Abiquiu Formation assignment for Tanos Formation is not supported by petrographic studies of sandstone that indicate derivation from the Ortiz Mountains area (Large and Ingersoll, 1997).

Kelley (1977) assigned these rocks to the Zia Formation of Galusha (1966), presumably because of the low stratigraphic position within the Santa Fe Group, and because of the light color of the sandstone beds. The Zia Formation, exposed 30–45 km (19–28 mi) to the west, contains thick eolianite that was deposited by westerly winds with sparse, widely spaced, southeast-flowing streams (Beckner and Mozley, 1998; Gawne, 1981). Aside from scattered intermediate volcanic pebbles of Oligocene age (Tedford and Barghoorn, 1999; Connell et al., 2001b) at the base of the Zia Formation, there are virtually no volcanic gravels in this deposit. Assignment of the Hagan embayment succession to the Zia Formation is not warranted because of these differences in composition, source area, depositional environment, and location in the basin. Deposits of the Tanos Formation are also slightly older than the basal Zia Formation, which is biostratigraphically constrained between 19 and 22 Ma (Tedford and Barghoorn, 1999). Extrapolation of Tedford and Barghoorn's magnetostratigraphically determined stratal accumulation rates to the base of the Zia Formation suggests that deposition of the Zia Formation began around 19 Ma.

The Tanos and Blackshare Formations are similar in age to the Popotosa Formation, which is exposed at the southern margin of the Albuquerque Basin and in the adjacent Socorro Basin. Deposits of the Popotosa Formation are interpreted to record deposition within fault-bounded, internally drained basins (Chapin and Cather, 1994). The Blackshare Formation is older than the Cochiti Formation, which is associated with deposition of volcaniclastic detritus derived from the Keres Group along the western margin of the Santo Domingo sub-basin and southeastern Jemez volcanic field (Smith et al., 2001). Although the upper age limit of the Blackshare Formation has not been established, it is probably older than the ancestral Rio Grande fluvial facies of the Sierra Ladrones Formation (Smith et al., 2001), which marks the end of closed-basin deposition in the Albuquerque Basin.

Discussion

Results of this stratigraphic study allow inferences to be made regarding the geologic evolution of the Hagan embayment and the eastern margin of the Rio Grande rift. The Tanos–Blackshare succession records deposition in an actively subsiding basin, part of which is now exposed in the Hagan embayment. Deposition of the Tanos Formation began after erosion removed part of the Espinaso Formation. The Tanos Formation is interpreted to represent deposition near the margin of a basin-floor fluviolacustrine or playa-lake system that was fed by streams draining the Ortiz Mountains. Although thick evaporite beds were not observed, these deposits were probably laid down in a low-gradient or quiet-water basin-floor environment within a closed basin. Mudstone beds within the Blackshare Formation may also indicate continued fluviolacustrine sedimentation through middle Miocene time. Because the mudstone of the Tanos Formation extends to the north and northwest, where the San Francisco and Budaghers faults truncate it, fluviolacustrine deposits probably once extended beyond the present structural limits of the Hagan embayment. Correlative deposits are probably preserved on the hanging wall of the San Francisco fault, where they are buried by the (upper Miocene–Pleistocene) Sierra Ladrones Formation.

Stratal tilts within the Tanos and Blackshare Formations tend to decrease upsection, indicating coeval sedimentation and subsidence occurred during Oligocene through late Miocene times. A period of tilting and extensive erosion occurred after deposition of the Blackshare and before aggradation of the Pliocene–Pleistocene Tuerto formation. The lack of regional tilting of the Tuerto formation indicates little deformation occurred since Pliocene time. The timing of late Miocene deformation and erosion of the Hagan embayment is not well constrained, but they may have happened during a time of increased subsidence along the western structural margin of the Santo Domingo sub-basin (Smith et al., 2001).

A $^{40}Ar/^{39}Ar$ age on a basalt flow near the base of the Tanos Formation demonstrates a late Oligocene age and confirms a K–Ar age from the northern tip of Espinaso Ridge (Kautz et al., 1981). These ages make the Tanos Formation the oldest exposed unit of the Santa Fe Group in the Albuquerque Basin area. Given an estimated thickness of approximately 1,060 m (3,478 ft) of Tanos and Blackshare deposits preserved between dated volcanic units, Oligocene–Miocene stratal accumulation rates (not corrected for compaction or the presence of intraformational unconformities or hiatuses) in the Hagan embayment were approximately 76 m/m.y. (249 ft/m.y.). The presence of paleosols and compaction of the mudstone beds indicate a minimum estimate of accumulation. This rate is similar to estimates of 69–83 m/m.y. (226–272 ft/m.y.) for early and middle Miocene sediments exposed along the northwestern margin of the Albuquerque Basin (Tedford and Barghoorn, 1999). These late Oligocene–middle Miocene values are significantly lower than 600 m/m.y. (1,968 ft/m.y.) estimates for late Miocene accumulation of fluviolacustrine deposits of the Popotosa Formation in the southern part of the Albuquerque Basin (Lozinsky, 1994). High late Miocene rates were probably due to increased basin subsidence or to geographically variable subsidence rates. Pliocene accumulation rates slowed to approximately 22–33 m/m.y. (72–108 ft/m.y.; Lozinsky, 1994).

The composition of gravels in the Tanos and Blackshare Formations indicates local derivation from the adjacent Ortiz Mountains. Hornfels gravels are interpreted to be sandstone and shale from underlying upper Paleozoic and Mesozoic strata that were thermally metamorphosed during emplacement of the Ortiz porphyry belt. Greenish-gray banded and dark-gray hornfels probably originated from Cretaceous rocks (S. Maynard, pers. comm. 2000). The general upsection increase in compositional diversity of gravel and increase in hornfels through the Tanos–Blackshare and Tuerto succession reflects a progressive unroofing of the Ortiz Mountains. An Ortiz Mountains provenance interpretation is also supported by paleocurrent data indicating deposition from west-flowing streams and supports the findings of Large and Ingersoll (1997).

Gravity data indicate that the Albuquerque Basin is greatly segmented by faults (Grauch et al., 1999), which hamper reconstruction of early rift structure across the Rio Grande rift at this latitude. The greater antiquity of the Santa Fe Group within the Hagan embayment compared with the northwestern Albuquerque Basin is contrary to expectations of a recently proposed tectonic model of the northern Rio Grande rift (Large and Ingersoll, 1997; Ingersoll, 2001). This model proposes that the Albuquerque and Española Basins were once part of a single, west-tilted half-graben basin called the Tesuque Basin. According to this model, the development of the east-tilted Albuquerque Basin occurred during late Miocene time as the Sandia Mountains rose. Comparison of depositional patterns across the northern Albuquerque Basin and Hagan embayment indicate deposition of piedmont and basin-floor fluviolacustrine strata began along the eastern margin of the rift. Slight erosion of the Espinaso Formation occurred before deposition of the Tanos Formation; however, erosion removed nearly all of Oligocene volcaniclastic rocks along the northwestern margin of the Albuquerque Basin before deposition of the Zia Formation at around 19 Ma. Age relationships support initial deposition along the Hagan embayment, rather than along the northwestern margin of the Albuquerque Basin, as required by the model of Ingersoll (2001).

Petrographic studies of the Galisteo, Espinaso, and Tanos–Blackshare Formations yield additional information regarding the tectonic development of the Hagan embayment and vicinity. Sandstone of the Espinaso Formation is nearly devoid of detrital quartz (Kautz et al., 1981), whereas, the quartz content of the Tanos and Blackshare Formations ranges from approximately 20% to 70% (Large and Ingersoll, 1997; see discussion in Connell and Cather, 2001; Connell et al., 2001a). This abrupt increase in quartz content suggests rapid exposure of quartz-rich rocks, such as the Galisteo Formation and older sedimentary rocks. Sparse pebbles of rounded metaquartzite and petrified wood present in conglomeratic beds of the Tanos and Blackshare Formations also support derivation from the Galisteo or Diamond Tail Formations. This abrupt increase in quartz content could originate from Oligocene–Miocene uplift of the La Bajada or Tijeras fault zones, or possibly other faults now buried by the Tuerto formation. Another possibility is that progressive exposure of quartz-rich strata occurred by erosion of the formerly extensive cover of Oligocene volcanic and intrusive rocks. In the former case, quartz content should increase sharply at the Espinaso–Tanos boundary. In the latter case, quartz content should gradually increase upsection from the Espinaso Formation.

Conclusions

The Tanos and Blackshare Formations are new lithostratigraphic units proposed for over a kilometer of upper Oligocene–upper Miocene deposits exposed in the Hagan embayment. Conglomeratic units of the Tanos and Blackshare Formations contain abundant rocks of the Ortiz porphyry belt, indicating local derivation from the adjacent Ortiz Mountains. Paleocurrent observations indicate deposition to the west and support petrographic data for an Ortiz Mountains provenance.

The Tanos Formation unconformably overlies the Espinaso Formation. Exposures of this contact along the northeastern flank of Espinaso Ridge are disconformable; however, examination of a continuous dip-meter log from a nearby oil-test well suggests that this boundary is an angular unconformity toward the structural margin of the Hagan embayment, southeast of the type section. The Blackshare Formation conformably overlies the Tanos Formation and represents continued sedimentation from the Ortiz Mountains. Stratal tilts of the Tanos–Blackshare succession decrease upsection in a continually subsiding basin. Subhorizontally bedded conglomerate and sandstone of the Pliocene–Pleistocene Tuerto formation overlie the Blackshare Formation in an angular unconformity.

The Tanos Formation contains mudstone and sandstone with minor conglomerate interbeds that represent deposition in playa-lake and piedmont settings within a hydrologically closed basin. The Blackshare Formation contains sandstone with interbeds of lenticular conglomerate, conglomeratic sandstone, and minor mudstone, commonly forming fining-upward sequences. The Blackshare Formation represents deposition of a westward prograding piedmont derived from the Ortiz Mountains. Local mudstone beds in the Blackshare Formation may indicate continued closed-basin deposition.

The Tanos and Blackshare Formations contain ashes and a basalt flow that constrain ages of deposition. A basalt flow near the base of the Tanos Formation yielded an $^{40}Ar/^{39}Ar$ age of 25.41 ± 0.32 Ma. Sanidine concentrates from one of these fallout ashes yielded a $^{40}Ar/^{39}Ar$ age of 11.65 ± 0.38 Ma. This ash geochemically resembles the middle Miocene Trapper Creek succession of the northeastern Basin and Range, and tephra in the upper part of the Cerro Conejo Member of the Zia Formation. The ages of these volcanic units indicate that stratal accumulation rates, not corrected for compaction, were on the order of approximately 76 m/m.y. (249 ft/m.y.) for the late Oligocene and middle Miocene interval.

Deposition of the Tanos Formation is partly coeval with deposition of the Abiquiu Formation; however, paleocurrent measurements, field relationships, and petrographic data indicate derivation from the neighboring Ortiz Mountains. The base of the Tanos Formation is older than the Zia Formation at the northwestern margin of the Albuquerque Basin, suggesting that deposition began earlier along the eastern basin margin, rather than along the western margin of the Albuquerque Basin.

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Appendix A

Type section of Tanos and Blackshare Formations in Arroyo de la Vega de los Tanos, Hagan embayment, San Felipe Pueblo NE 7.5-min quadrangle. Base of measured section at N: 3,919,920 m; E: 380,530 m and top of measured section at N: 3,921,000 m; E: 381,360 m; (UTM zone 13S, NAD 1983). Measured upsection from unit 1 by S. D. Connell and K. McLeroy using an Abney level and Jacob staff. Stratigraphic offset across Arroyo de la Vega de los Tanos measured using tape and compass. Colors are dry. Textural abbreviations include: very fine, vfL, vfU; fine, fL, fU; medium, mL, mU; coarse, cL, cU; and very coarse, vcL, vcU. Numerical unit designations established upsection and listed in descending stratigraphic order.

Unit	Description	Thickness (m)	(ft)
Blackshare Formation, conglomeratic sandstone (Tbc, 43 m)			
Q.	Conglomerate and conglomeratic sandstone; massive to crudely bedded, clast- and matrix-supported, cobble to boulder conglomerate. Matrix is light-brown to pink (7.5YR 6/4–7/4), very coarse grained (vcU), poorly sorted pebbly sandstone. Cobbles and boulders are subrounded to subangular and range from 30 to 100 cm in diameter (mostly 20–40 cm). Clast count near middle of unit (n = 68) indicates gravels composed of Ortiz porphyry (79%), black and brown subrounded polished chert (15%), rounded metaquartzite (3%), sandstone (2%), and hornfels (1%). Clast count near top of unit (n = 70) indicates gravels composed of Ortiz porphyry (73%), black hornfels and rounded chert (19%), rounded metaquartzite (3%), and sandstone (5%). Section ends on hill top where deposits are poorly exposed.	43.0	141.0
Blackshare Formation, sandstone (Tbs, 260 m)			
P.	Sandstone and pebbly sandstone; light-brown to pink (7.5YR 6/4–7/3) and very pale brown (10YR 7/3), massive to thin-bedded, fine-grained (fL–fU) and very coarse grained (vcU), well-sorted sandstone with reddish-yellow (5YR 6/6), medium-bedded, very fine to fine-grained (vfU–fL) sandstone interbeds and medium- to thick-bedded mudstone and poorly sorted pebbly to cobbly sandstone lenses; pebbles are 2–10 cm in diameter. Measurements of the westward projection of the Tbc/Tbs (unit Q/P) contact indicate that the 11.65 Ma ash of locality **a** is approximately 525 m above this unit.	59.2	194
O.	Sandstone and mudstone; very pale brown to pale-brown (10YR 8/3–6/3) and light yellowish-brown (10YR 6/4), medium- to thick-bedded, moderately to well-sorted, very fine to medium-grained (vfU–mU) sandstone and cemented sandstone (~20–30%) with thick-bedded, coarse pebbly sandstone and <5% reddish-brown (5YR 5/4), medium-bedded mudstone interbeds. Pebbles are mostly rounded to subangular and range between 3 and 7 cm in diameter. Contains thick-bedded, well-cemented concretionary sandstone that weathers into 30–40-cm-diameter spheroidal concretions.	63.7	209
N.	Conglomeratic sandstone and mudstone; pink (7.5YR 7/3–7/4), fine- to very coarse grained (fL–fU and vcU), poorly sorted (and medium-grained [mU], moderately sorted) sandstone with medium- to thick-bedded, medium-grained (mU), well-cemented sandstone and pebbly sandstone interbeds. Sandstone interbeds are spaced <2 m apart, comprise 15% of unit, and contain low-angle crossbeds. Mudstone (10–15%) is reddish brown (5YR 5/3–5/4) and medium to thick bedded. Gravel is generally <5 mm but reaches a maximum of 6–20 cm in diameter. Pebbly to cobbly sandstone contains abundant rounded to subrounded Ortiz porphyry; <5% of clasts are metaquartzite and chert. Approximately 2–5 m below the top, the section grades upward to the reddish-brown claystone that contains scattered (1–2-cm-diameter) calcium carbonate-cemented nodules.	70.7	232
M.	Sandstone and mudstone; very pale brown (10YR 7/3) and pink (7.5YR 7/3–7/4), medium- to thick-bedded, very fine to fine-grained (vfL–fU) and coarse-grained (cL–cU), well-sorted sandstone and cemented sandstone with reddish-brown (5YR 5/3–7/4), medium- to thick-bedded, cemented mudstone interbeds that comprise 15–20% of unit. Sandstone exhibits normal grading. Gravelly intervals comprise 5–15% of unit and consist of matrix-supported pebbly to cobbly sandstone; gravel ranges from 2 mm to 20 cm in diameter. Unit also contains scattered, <4-cm-thick, low-angle planar crossbeds and <4-cm-thick, matrix-supported, pebbly sandstone and reddish-yellow (7.5YR 7/6), lenticular, concretionary sandstone interbeds. Top contains thick-bedded, reddish-brown (5YR 5/3) mudstone.	31.5	103
L.	Sandstone and conglomeratic sandstone; conglomerate comprises 70% of unit, mostly clast- and matrix-supported, thin- to medium-bedded pebble to cobble conglomerate and pebbly sandstone. Forms series of fining-upward sequences. Gravel size ranges from 1 cm to 8 cm in diameter. Conglomerate is subrounded to subangular, matrix supported with clast-supported lenses predominantly composed of Ortiz porphyry. Gravel (n = 80) composed of Ortiz porphyry (75%), hornfels (13%), and sandstone (12%). Interbedded with very pale brown (10YR 7/3), medium-bedded, poorly sorted pebbly sandstone. Contains ~15-cm-thick, scattered, very coarse grained (vcU), well-cemented sandstone lenses and very pale brown (10YR 7/4) and massive, clast-supported pebbly sandstone and conglomerate interbeds. Weakly cemented with calcium carbonate. Contains interbedded, reddish-yellow (5YR 6/6), muddy sandstone beds as much as 3 m thick. Upper 19 m is pink (7.5YR 7/4), fine- to medium-grained (fU–mL), moderately sorted, cemented sandstone that grades into reddish-brown mudstone.	35.2	115
Tanos Formation, upper tabular sandstone (Ttu, 123 m)			
K.	Sandstone; pink (7.5YR 7/4) and very pale brown (10YR 7/4), very fine to medium-grained (vfU–mL), carbonate-cemented sandstone and thin- to medium-bedded, reddish-brown (5YR 5/4) sandstone and mudstone interbeds. Grains are well sorted and rounded to subrounded. Unit grades upward into claystone. Upper contact is scoured by pebbly sandstone of overlying Blackshare Formation.	9.0	52
J.	Sandstone; pink (7.5YR 7/4–8/3) and very pale brown (10YR 7/3), medium- to coarse-grained (mL–cL), poorly sorted, slightly cemented sandstone and reddish-yellow and reddish-brown (5YR 5/4–7/6), slightly silty sandstone and mudstone with <5-cm-thick pebbly sandstone interbeds.	16.0	52
I.	Sandstone; very pale brown (10YR 7/4–8/2) and gray (10YR 5/1), fine- to medium-grained (fU–mU), thin- to medium-bedded, well-cemented sandstone with subhorizontal laminations. Upper part of unit is a massive, fine- to coarse-grained (fU–cU), poorly sorted sandstone with scattered (10%), fine- to coarse-grained (fL–cU), slightly bioturbated concretionary sandstone. Lower part of unit is crudely bedded. Weathers to a brown (7.5YR 4/3) to very dark gray (7.5 YR 3/1). Contains subhorizontal (5-mm-diameter), cylindrical concretions and rhizoconcretions. Moderately to poorly exposed. Locally contains 1–2-cm-diameter spheroidal concretions. Upper part of unit contains light-gray (10YR 7/2), fine- to medium-grained (fL–mL), moderately sorted, calcium carbon-		

Unit	Description	Thickness (m)	Thickness (ft)
	ate-cemented concretionary sandstone that weathers into spheroids and ellipsoids	36.9	121
H.	Sandstone; (mostly covered) very pale brown (10YR 7/3), massive to thin-bedded, very fine to medium-grained (vfU–mU) sandstone with faint, 1–5-mm-thick, subhorizontal laminations and planar cross-stratification and 1.5–1.8-cm-thick, lenticular, calcium carbonate-cemented concretionary zones. Near the top of the unit is 1–10-cm-thick, fine- to coarse-grained (fU–cL) sandstone with low-angle planar crossbeds. Top of unit at floor of Arroyo de la Vega de los Tanos. Projected stratigraphic offset across arroyo may yield ~15-m error in thickness estimate.	28.5	93
G.	Sandstone; (mostly covered) pale-brown to white (7.5YR 6/4–8/1), fine- to medium-grained (fL–mL), well-sorted sandstone interbedded with medium- to thick-bedded, yellowish-brown (10YR 6/4–5/4) sandstone and medium- to thick-bedded, light reddish-brown mudstone.	33.0	108
Tanos Formation, middle mudstone (Ttu, 144 m)			
F.	Mudstone and sandstone; interbedded light olive-gray (5Y 6/2–6/4) and light reddish-brown (5YR 6/4), medium- to thick-bedded mudstone (~60%) and very pale brown (10YR 7/4–8/2), fine- to medium-grained (fU–mL), moderately sorted sandstone (~40%). Mudstone contains carbonate nodules and 2–3-cm-thick fibrous calcite layer. White (2.5Y 8/1), very fine grained (vfL), thin altered volcanic ash approximately 18–19 m above base. Contains minor, discontinuous, yellow (2.5Y 7/6), fine-grained (fL), thick-bedded, well-sorted sandstone. Upper 12 m is a thin- to medium-bedded sandstone with well-cemented sandstone lenses near the top. Gradational with overlying unit.	61.4	201
E.	Mudstone and sandstone; basal 2.3 m is light reddish-brown (5YR 6/4), thin-bedded mudstone; upper 1.5 m is very pale brown (10YR 7/3), fine-grained (fL) and thin-bedded, tabular sandstone.	3.8	12
D.	Mudstone; light greenish-gray (5GY 7/1), very fine grained (vfL) and well-sorted mudstone. Basal 1 m is a thin-bedded, greenish-gray (10Y 6/1), silty claystone. Contains yellow (10YR 7/8), fine- to medium-grained (fL–mU), well-sorted, thin-bedded sandstone with 1–3-cm-thick, strong-brown (7.5YR 5/6) banded stains. White (2.5YR 8/1), thin-bedded, very fine grained (vfL) altered volcanic ash(?) is approximately 23.5 m above base. Top is 2.4-m-thick, greenish-gray (5GY 6/1) mudstone.	29.9	98
C.	Sandstone; pink (7.5YR 7/3) and very pale brown (10YR 7/3), fine- to medium-grained (fU–mL), well-sorted sandstone with very thin bedded and light-pink (7.5YR 8/2), lenticular, cemented, ledge-forming sandstone interbeds (<5% of unit) and reddish-brown (5YR 5/4) mudstone interbeds. Sandstone exhibits 5–10-mm-thick ripple laminations. Middle of unit contains a 2-m-thick, massive, reddish-brown to yellowish-red (5YR 4/4–4/6) mudstone; upper 40 cm contains scattered spheroidal to ellipsoidal calcium carbonate nodules. Contains thin, discontinuous altered volcanic ash beds.	29.5	97
B.	Sandstone; (mostly covered) pink to light-brown (7.5YR 7/4–6/4), fine- to medium-grained (fU–mU) sandstone and slightly silty sandstone.	19.5	64
Tanos Formation, lower conglomerate (Ttl, 12 m)			
A2.	Basaltic flow; very dark gray (N 3/0) to yellowish-brown (10YR 5/6) olivine basalt. Olivine crystals are deeply weathered. Lower 1.5 m contains 50–80% white (10YR 7/4) and yellow to olive-yellow (2.5Y 7–6/6), 2–5-mm-diameter spheroidal nodules of celadonite(?). Weathers to olive yellow (5Y 6/6) and weak red (2.5YR 4/2). Rests on reddish-brown to reddish-yellow pebbly sandstone, and base appears to be thermally altered. Upper contact is poorly exposed but does not contain reddish-brown baked zone.	2.5–3.0	8–10
A1.	Conglomeratic sandstone and conglomerate; (mostly covered) very pale brown (10YR 8/3) to reddish-yellow and yellow (7.5–10YR 7/6), massive to crudely bedded, thin- to medium-bedded, very fine to very coarse grained (vfL–vcU) sandstone and poorly sorted pebbly sandstone and conglomerate with scattered ~30-cm-thick cobble-boulder conglomerate lenses that comprise ~30% of unit. Gravel locally coated by red (10R 4/6–4/8) clay films. Pebbles comprise 15–25% of the unit and range from 1 cm to 5 cm and 20–60 cm in diameter; mostly ranging from 2 cm to 10 cm in diameter. Contains pebbles and cobbles of Ortiz porphyry (98%), rounded metaquartzite and chert (2%). Overlies Espinaso Formation with sharp, slightly scoured, bedding-parallel contact.	9.2	30
Espinaso Formation (Te, 460 m; Kautz et al., 1981)			
	White to light-gray volcaniclastic sandstone and conglomerate. Not described.		

Appendix B

Reference section of Tanos and Blackshare Formations in Arroyo del Tuerto, Hagan embayment, San Felipe Pueblo NE 7.5-min quadrangle. Base of measured section at E: 381,470 m; N: 3,916,240 m (UTM zone 13S, NAD 1927). Top at E: 381,860 m; N: 3,916,960 m (UTM zone 13S, NAD 1983). Measured upsection from unit 1 by S. D. Connell and K. McLeroy using a Brunton compass and Jacob staff. Colors are dry. See Appendix A for textural abbreviations. Numerical unit designations established upsection, but listed in descending stratigraphic order.

Unit	Description	Thickness (m)	Thickness (ft)
Tuerto formation			
	Not described.		
Blackshare Formation, conglomeratic sandstone (Tbc, 104 m)			
I.	Pebbly sandstone and sandstone; (poorly exposed) 40–50% pebbly sandstone and 15% conglomerate containing Ortiz porphyry (83%), hornfels (7%), quartzite (4%), chert (4%), and sandstone (2%) clasts ranging from 6 cm to 12 cm in diameter. Grades upsection to pink (7.5YR 7/4), medium- to coarse-grained (mU–cL), weakly cemented sandstone with yellowish-red (5YR 5/6), very fine grained (vfL) silty sand near the top.	39.0	28
H.	Pebbly sandstone; (poorly exposed) pinkish-white (7.5YR 7/4–8/2), medium-grained (mL–mU), thick-bedded pebbly sandstone (50–70% of unit) interbedded with pink (7.5YR 7/3–4), fine- to medium-grained (fU–mL), thickly bedded silty sandstone (~20% of unit). Grades up into pink (7.5YR 7/4), medium- to coarse-grained (mU–cL), weakly cemented sandstone that grades upward into yellowish-red (5YR 5/6), very fine grained (vfL) silty sandstone.	64.5	216
Tanos Formation, upper tabular sandstone (Ttu, 84 m)			
G.	Sandstone and pebbly sandstone; very pale brown (10YR 8/2), very fine grained (vfU), thin- to medium-bedded, tabular to low-angle planar crossbedded and ripple laminated sandstone with lenticular pebbly sandstone interbeds. Approximately 5% of the unit contains well-cemented, ledge-forming pebbly sandstone beds. Pebbles range from 4 cm to 11 cm in diameter. Lower 16 m is transition between sandstone of Tanos Formation and piedmont facies of Blackshare Formation. Upper part contains pale-yellow (2.5YR 8/2), thinly bedded, well-sorted sandstone and light olive-brown (2.5Y 5/4) claystone and light-gray (2.5Y 7/2), tabular sandstone with nodular carbonate. Top contains very pale brown (10YR 7/3) and pink (7.5YR 7/3), well-sorted, medium-grained (mL), planar crossbedded sandstone with scattered 30-cm-thick gravel lenses.	36.5	120
F.	Sandstone and mudstone; very pale brown (10YR 7/3) to light reddish-brown (5YR 6/4) and white (7.5YR 8/1), moderately to well-sorted, thin- to medium-bedded, medium- to coarse-grained (mL–cL), tabular sandstone with silty sandstone 2–5-mm-thick laminae. Interbedded with light greenish-gray (5GY 7/1) and light reddish-brown (5YR 4/4–6/4), thin- to medium-bedded mudstone, brownish-yellow (10YR 6/6) concretionary sandstone, and light greenish-gray (8/1 10Y), very fine to fine-grained (vfU–fL) pebbly sandstone lenses. Thinly laminated to thin-bedded, light-brown (7.5YR 6/4) gypsiferous mudstone interbeds scattered in tabular sandstones. Contains scattered thin to medium beds of pale-brown (10YR 6/3) pebbly sandstone. Several sandstone and mudstone beds are faulted. Upper part of unit contains light greenish-gray (5GY 8/1) mudstone and white (2.5YR 8/1) siltstone. Upper contact is irregular and scoured by conglomeratic sandstone of overlying unit.	47.8	57
Tanos Formation, middle mudstone (Ttu, 93 m)			
E.	Sandstone and mudstone; (mostly covered) very pale brown (10YR 7/3–4), fine-grained (fL), thin-bedded, cemented sandstone and light greenish-gray (5GY 7/1) to reddish-brown, thin- to medium-bedded mudstone. Also contains very pale brown (10YR 8/2–3), coarse-grained (cL–cU), poorly sorted pebbly sandstone and brownish-yellow (10YR 6/6), thin-bedded concretionary sandstone.	32.5	107
D.	Sandstone and pebbly sandstone; very pale brown (10YR 8/2) to pink (7.5YR 8/2), thin-bedded, fine- to coarse-grained (fL–cU), cemented sandstone with reddish-brown silty sandstone laminae and brownish-yellow (10YR 6/6), 50–100-cm-thick, well-cemented, well-sorted, fine-grained (fL–fU) concretionary sandstone. Top contains 1.5-m-thick, reddish-brown (5YR 5/4) mudstone.	38.5	126
C.	Silty sandstone and pebbly sandstone; pink to pinkish-white (7.5YR 8/2–7/4), massive, fine- to coarse-grained (fL–cU) silty sandstone with scattered rounded pebbles (< 2 cm in diameter). Contains brown (7.5YR 5/3–4), medium-bedded, fine- to medium-grained (fU–mL) concretionary sandstone and very pale brown (10YR 7/3), fine- to medium-grained (fL–mL) silty sandstone interbeds and brown (7.5YR 4/4) clay with scattered carbonate nodules. Pebbles are predominantly Ortiz porphyry with sparse quartzite. Gravelly intervals commonly grade up into sandstone with weakly developed paleosols.	21.8	72
Tanos Formation, lower conglomerate (Ttl, 41 m)			
B.	Pebbly sandstone; pink and very pale brown (7.5YR 7/3–4 & 10YR 7/3–4), fine- to coarse-grained (fU–cL), poorly sorted, well-cemented, thin- to medium-bedded, clast-supported pebbly sandstone. Pebbles compose 25–70% of unit. Contains interbeds of pink (7.5YR 7/4), thin, cross-laminated silty sandstone and slightly silty sandstone and brown (7.5YR 5/4–5/3), laminated mudstone and concretionary sandstone lenses. Base of unit is reddish-yellow (7.5YR 6/6) sandstone. Gravels contain 96% Ortiz porphyry and ~4% subrounded metaquartzite. Fining-upward sequences of conglomerate and sandstone common. Upper contact gradational.	30.7	101
A.	Pebbly sandstone and conglomerate; pinkish-white to pink (7.5YR 8/2–3) sandstone with very dark gray (7.5YR 3/1) pebbles and small cobbles of Ortiz porphyry. Sandstone is poorly sorted, medium to coarse grained (mL–cU) with subrounded to subangular grains. Lower contact is sharp, poorly exposed, and recognized by color change.	10.5	34
Espinaso Formation (Te)			
	Pebbly to cobbly sandstone and conglomerate; white pebbly to cobbly sandstone with dark-gray specks (10YR 8/1–3/1) and pebble to cobble conglomerate; well-cemented, medium-bedded, tabular, medium- to coarse-grained (mU–cU), moderately sorted sandstone.		