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Hydrostratigraphic implications of new geological mapping in the Santo Domingo Basin, New Mexico

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Abstract

New geologic mapping in the Santo Domingo Basin suggests revisions to existing concepts of stratigraphy and faulting that affect ground-water flow in that area. Ancestral Rio Grande gravel is at least 500 m thick, extends over an east–west extent of 15 km, and dates back to at least 7 Ma. Large areas of volcaniclastic piedmont deposits of the Cochiti Formation are also dominantly gravel. These two extensive, coarse-grained facies require order-of-magnitude upward revisions to estimated hydraulic conductivity applied in regional flow models. The Santo Domingo Basin consists of a broad, low-relief accommodation zone between the northern Albuquerque and Española Basins. Intrabasinal NNW-striking faults may partition the aquifer by juxtaposing strata of contrasting permeability or because of excessive cementation along and near faults. We hypothesize that a trough in the water table west of the Rio Grande results from fault-related barriers to flow that separate the Rio Grande from a highly transmissive section containing axial gravel, which makes up part of the aquifer as much as 12 km west of the present river.

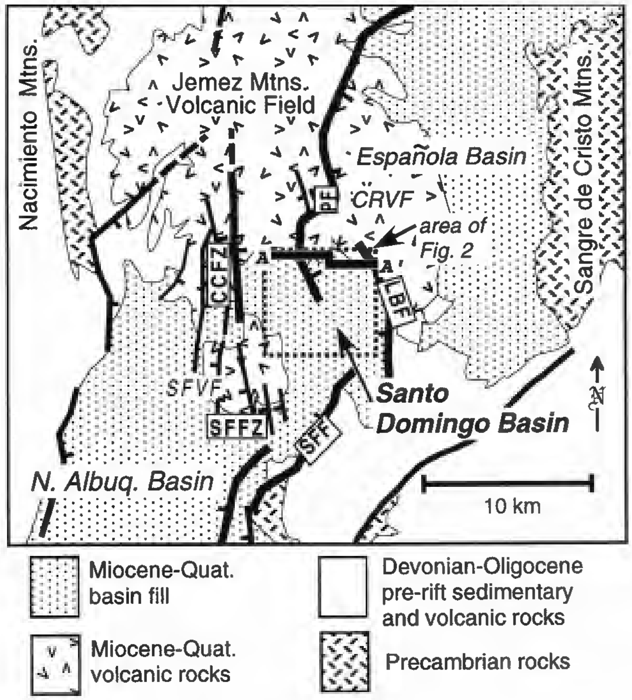


FIGURE 1—Generalized geologic map of the central New Mexico segment of the Rio Grande rift. Volcanic fields: **CRVF**, Cerros del Rio volcanic field; **SFVF**, San Felipe volcanic field. Principal faults: **PF**, Pajarito fault; **LBF**, La Bajada fault; **CCFZ**, Cañada de Cochiti fault zone; **SFFZ**, San Felipe fault zone; **SFF**, San Francisco fault. Cross section along line *A-A'* is in Fig. 3a.

Introduction

Recent ground-water modeling efforts, and geological studies in support of such modeling, have been undertaken to better understand the subsurface hydrology of the Albuquerque Basin (Hawley and Haase, 1992; Thorn et al., 1993; Kernodle et al., 1994). The simulation of Kernodle et al. (1994; hereafter referred to as the Kernodle model) encompasses an area of approximately 6,200 km^2, within which geologic mapping is of variable detail and subsurface stratigraphic data are very widely spaced, except in the city of Albuquerque. Particularly poorly known are the stratigraphic and structural architectures of the northern hydrologic basin because of limited access to pueblo reservations for mapping and near absence of logged wells. Nonetheless, because the north basin margin (between the Rio Jemez and Galisteo Creek) provides an estimated 25% of the Kernodle model boundary inflow (mountain-front and tributary recharge, subsurface inflow from adjacent regions), it is essential to better understand geological controls for ground-water pathways in this region.

The Santo Domingo Basin is a poorly defined area that has been treated as a part of (e.g., Kelley, 1977), or structurally distinct from (e.g., Lozinsky, 1994), the northern Albuquerque Basin. The basin (Fig. 1) is bounded on the east by La Bajada fault and on the west by the Cañada de Cochiti fault zone (Gardner et al., 1986). Southward, the Santo Domingo Basin merges across the San Felipe fault zone into the main part of the Albuquerque Basin, and northward there is an indistinct continuation into the Española Basin through the narrow structural constriction between La Bajada and Pajarito faults (Fig. 1). The Santo Domingo Basin is astride a large right-step in the structural axis of the Rio Grande rift, between the asymmetric, east-tilted northern Albuquerque Basin and the west-tilted Española Basin half-graben.

Volcanism has been prominent in and marginal to this region. The middle Miocene–Pleistocene Jemez Mountains volcanic field forms the northwest topographic margin of the basin. Volcanic rocks of the Jemez Mountains are found through most of the northern basin and are present in the footwall of the Cañada de Cochiti fault zone on the west. The Pliocene–lower Pleistocene Cerros del Rio volcanic field lies at the northeast basin margin, and correlative basaltic lava flows are present in the subsurface to the west of La Bajada fault. Basalt lava and tuff were also erupted from a line of vents in the basin that are nearly coincident with Cochiti Dam (Smith et al., 1997). The San Felipe volcanic field, at the southwest margin, records at least three episodes of basalt-lava extrusion from fault-aligned vents that formed Santa Ana Mesa and other nearby volcanic features.

This report summarizes stratigraphic and structural information of hydrological significance that was obtained during geologic mapping in the central Santo Domingo Basin astride the Rio Grande (Figs. 1 and 2). Detailed mapping of the Santo Domingo Pueblo and Santo Domingo Pueblo SW quadrangles (Smith and Kuhle, 1998a,b) and reconnaissance mapping of adjacent parts of the Cañada, Cochiti Dam and Loma Creston quadrangles were undertaken during 1996–1997. The mapping was part of coordinated initiatives of the USGS–NMBMMR STATEMAP and Middle Rio Grande Basin Study (Sawyer et al., 1996) with cooperation from Cochiti and Santo Domingo Pueblos.

Lithostratigraphy and hydrostatigraphy

Inadequate knowledge of the stratigraphy of the Santo Domingo Basin required ad hoc assumptions in the construction of

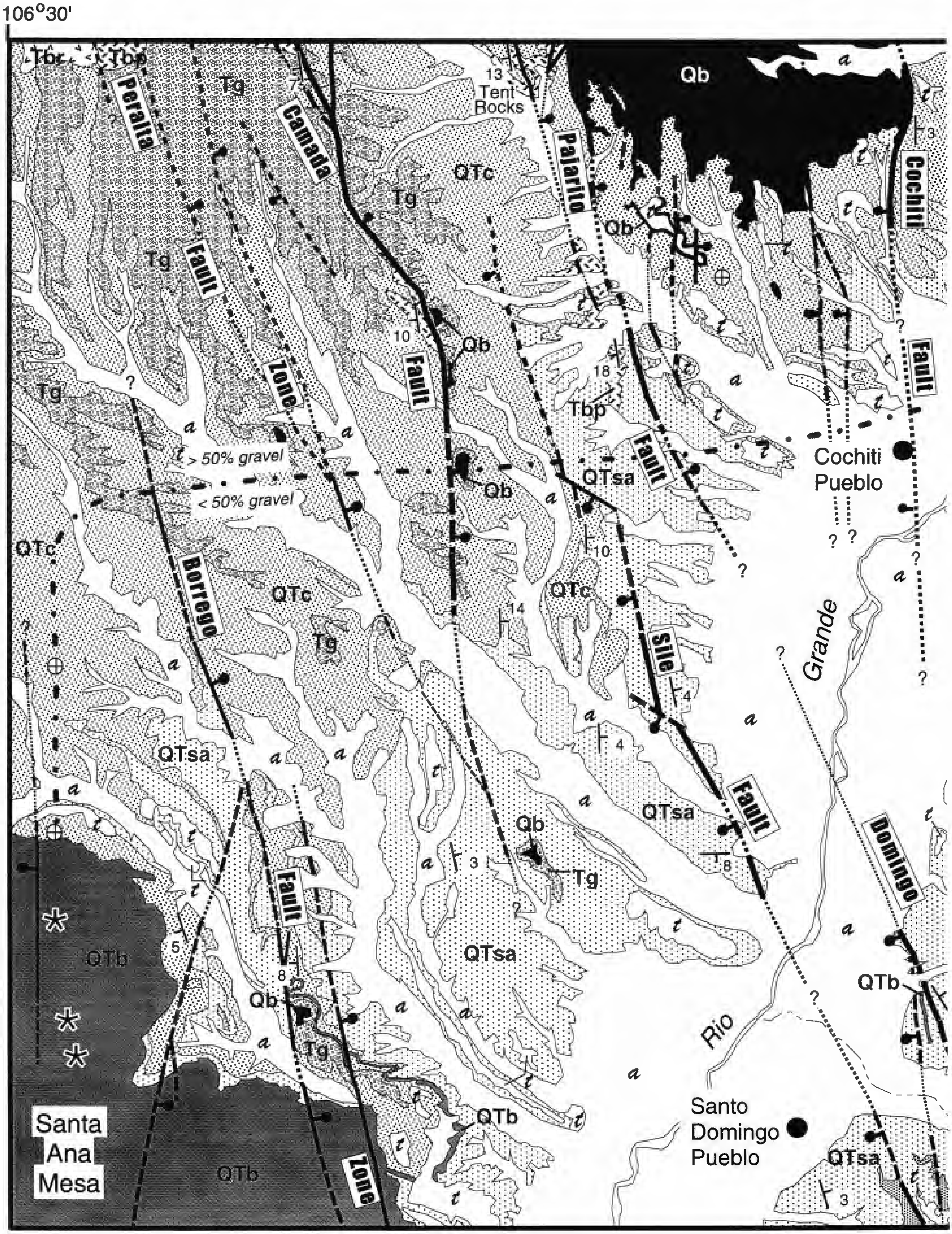
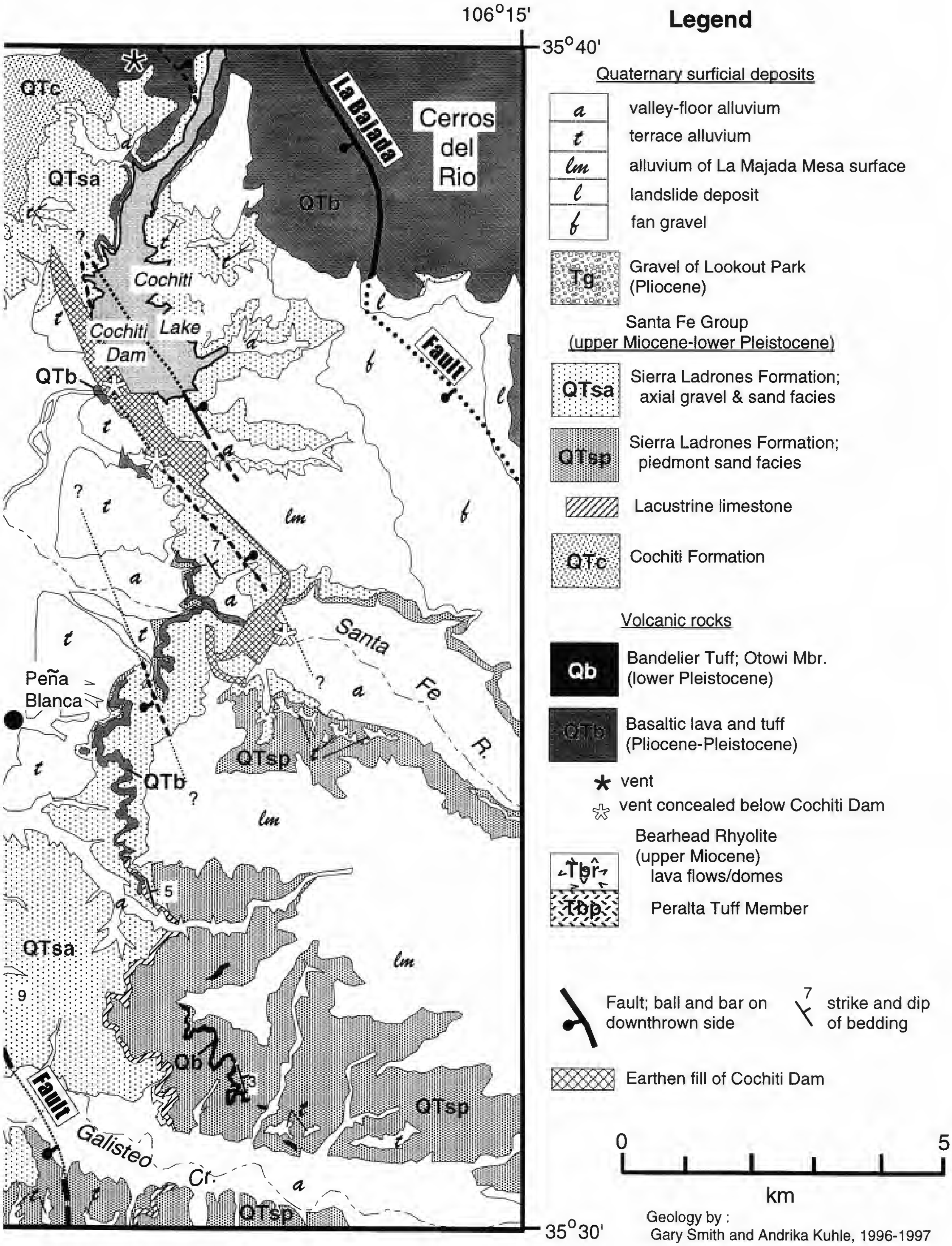


FIGURE 2—Geologic map of the central Santo Domingo Basin. Approximate 50%-gravel isopleth line delineates the transition from dominant gravel in the Cochiti Formation to the north and domi-



nant sand to the south. Map covers all of the Santo Domingo Pueblo and Santo Domingo Pueblo SW 7.5- minute quadrangles and parts of the Cañada and Cochiti Dam 7.5-minute quadrangles.

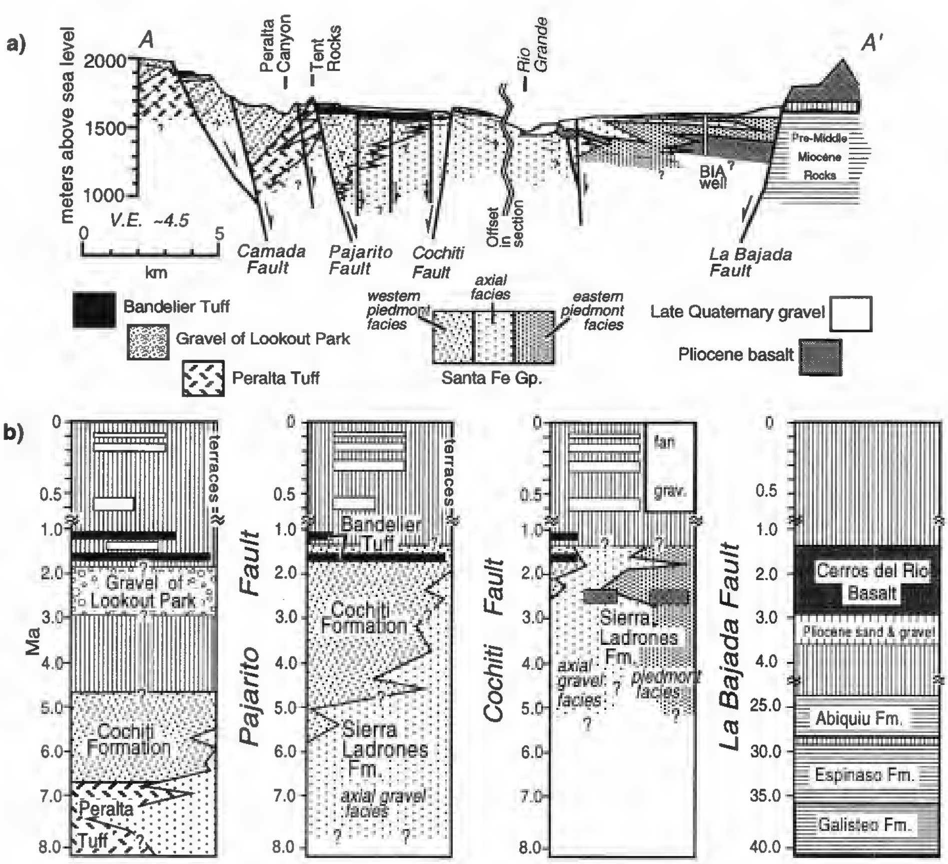


FIGURE 3—**a)** Generalized geologic cross-section across the northern Santo Domingo Basin. Line of section is in Fig. 1. **b)** Chronostratigraphic diagram for the northern Santo Domingo Basin and its east margin.

the Kernodle model. Notably, this model applied a hydraulic conductivity of 4 ft/day (1.4×10^{-3} cm/s) to all 11 model layers throughout the area covered by this report. Kelley (1977) provided neither stratigraphic subdivisions nor descriptions of strata exposed in the Santo Domingo Basin, and reconnaissance mapping by Smith et al. (1970), also without lithologic or stratigraphic descriptions in conjunction with virtually no subsurface data, led to the necessary generalizations in the Kernodle model. Our geologic mapping, though still lacking complementary subsurface data, provides new insights into the stratigraphy of this region and suggests that, for near-surface layers at least, the hydraulic conductivity of the basin fill is probably considerably greater than that assumed by the Kernodle model.

The stratigraphy of the study area consists of Santa Fe Group basin-filling sediment, volcanic rocks related to the marginal volcanic fields, and unconformably overlying Pliocene and Pleistocene alluvial strata (Fig. 3). Santa Fe Group strata consist of gravel and sand deposited by an ancestral Rio Grande flanked by piedmont alluvium that entered the basin from the east and northeast and from the west and northwest. Because of apparent continuity with strata in the Albuquerque area, the axial facies and eastern piedmont facies were mapped as Sierra Ladrones Formation (cf., May and Russell, 1994). The volcaniclastic gravel and sand in the west basin were mapped as Cochiti Formation, as defined by Bailey et al. (1969) with modifications by Smith and Lavine (1996). Poor outcrop quality prevented use of the facies-mapping scheme proposed by Cather (1997); gravel float dominates most slopes even where locally good exposures indicate a dominance of finer-grain sizes. Nonetheless, inferences can be made about general grain-size trends in the basin fill (Fig. 2).

Volcanic rock

Volcanic rock forms only a minor component of exposures in the map area but offers important geochronological constraints for discussing the rest of the basin fill. Subsurface distribution of volcanic rock is too poorly known to discuss its hydrological significance, although downfaulted Cerros del Rio basalt flows do host aquifers in the northeast map area (Fig. 3; J. Sorrell, Bureau of Indian Affairs, oral comm., 1996).

Jemez Mountains extrusive rocks in the map area include the upper Miocene Bearhead Rhyolite and lower Pleistocene Bandelier Tuff. Pyroclastic strata and fluvial gravel deposited synchronously with the Bearhead Rhyolite are assigned to the Peralta Tuff Member (Bailey et al., 1969; Smith et al., 1991), which in the Tent Rocks area (Fig. 2) is about 7.0–6.75 Ma (Smith et al., 1991; McIntosh and Quade, 1995). These tuffaceous strata extend much farther south into the basin (Fig. 2) than have been represented on previous maps (Smith et al., 1970; Kelley, 1977). Primary and reworked upper Miocene tuff is found in axial gravel facies of the Sierra Ladrones Formation as far as 6 km south of Cochiti Pueblo and forms important structural and chronostratigraphic markers. Older middle Miocene volcanic rocks of the Paliza Canyon and Canovas Canyon Formations (Bailey et al., 1969; Gardner et al., 1986) likely exist in the subsurface beneath the north and west parts of the basin, and upland areas of these rocks contributed abundant clasts to the basin fill. The Bandelier Tuff, particularly the widespread 1.61 Ma Otowi Member, forms an important marker throughout the map area (Fig. 2) but is of limited hydrostratigraphic significance; its presence below the water table is limited to the extreme east margin of the basin where it is not continuously present.

Basalt lava and tuff of the Cerros del Rio and San Felipe volcanic fields are present in the map area (Fig. 2). San Felipe basalt flows capping Santa Ana Mesa in the southeast map area are nowhere present in the subsurface, although these flows and related hydrovolcanic tuff form important marker horizons for delineating faults, as also noted by Kelley (1977).

Basalt in the Peña Blanca/Santa Fe River area is associated with hydrovolcanic tuff and both rock types were contemporaneously erupted from a chain of three or more vents that roughly coincide with the foundation of Cochiti Dam (Smith et al., 1997). The lava flows are vesicular and fractured and quite likely have relatively high conductivity but are of limited areal extent. The tuff, which underlies and extends northward and southwestward from the lava-flow outcrops, is well indurated and probably forms the vertical-flow barrier that accounts for Cochiti Springs along the Santa Fe River. Notably, the contemporaneous Pliocene magmatic and hydrovolcanic eruptions recorded by the lava and tuff do suggest considerable lateral transmissivity variability to account for the varied degree of water–magma interaction during the eruptions. Smith et al. (1997) postulated this lateral variability to represent the shallow facies boundary between axial-gravel-dominated stratigraphy and piedmont-sand-and-silt-dominated stratigraphy. Lacustrine clay present in outcrop and shallow subsurface beneath and upstream from Cochiti Dam resulted from drainage impoundment by lava-flow and tuff-ring dams (Smith et al., 1997). These deposits are, however, of only local extent and have little bearing on basin-scale hydrologic models.

Axial gravel and sand

Unconsolidated to slightly cemented gravel and sand, interbedded with lenticular tuffaceous mud and a locally persistant lacustrine limestone bed, are widespread in the Santo Domingo Basin (Fig. 2). Prominence of clasts derived from sources in northern New Mexico (e.g., quartzite, gneiss, metavolcanic rocks, Pedernal Chert, and rare Amalia Tuff) indicate deposition along the course of a south-flowing, axial river analogous to the modern Rio Grande. These strata range in age from late Miocene to early Pleistocene as constrained by interbedding with the Peralta Tuff Member and inclusion of reworked Bandelier Tuff pumice. Where exposures are adequate, gravel makes up 50% or more of most outcrops of this facies, although an ~200-m-thick interval of dominantly medium- to coarse-grained sand forms the section along the east side of the Rio Grande, south of Peña Blanca.

Our mapping illustrates a greater lateral and vertical distribution of these hydrologically important facies than has been previously portrayed (Fig. 2). Smith et al. (1970) represented the axial gravel as forming a narrow belt less than 100 m thick overlying the Cochiti Formation, which is composed entirely of detritus from the Jemez Mountains. Outcrops in the Cañada and Santo Domingo Southwest 7.5-minute quadrangles demonstrate, however, that the axial-gravel facies of the Sierra Ladrones Formation is interbedded not only with the Cochiti Formation but also with the underlying Peralta Tuff (Fig. 3). Hydrovolcanic eruptions at 6.96 Ma from a rhyolite vent 2.4 km northwest of Tent Rocks expelled axial-composition clasts and large (up to 6 m) blocks of axial-facies sediment (Smith et al., 1991; Gay and Smith, 1996). Axial Rio Grande gravel in the Albuquerque Basin has generally been perceived as being less than 5 Ma (e.g., Hawley and Haase, 1992; Lozinsky, 1994), and the recognition of such deposits back to at least 7 Ma suggests a greater vertical distribution than previously appreciated. We estimate that this facies is more than 500 m thick in the northern Santo Domingo Basin and, at some stratigraphic levels, may form a facies belt as much as 15 km wide (Fig. 3). Many cells in the Kernodle model for this region would, therefore, be better characterized with hydraulic conductivities of 70 ft/day (2.5×10^{-2} cm/s), or more, rather than the 4 ft/day (1.4×10^{-3} cm/s) currently applied (Kernodle et al., 1994).

Eastern piedmont sand and gravel

The eastern piedmont facies of the Sierra Ladrones Formation is composed primarily of pink fine-grained sand and silt with approximately 10–20% sandy, pebble-to-cobble gravel. Variable proportions of clasts derived from Sangre de Cristo Mountains granitic rocks, Cerros del Rio basalt, Espinaso Formation porphyry, and Galisteo Formation red beds indicate deposition by drainages analogous to modern Santa Fe River and Galisteo Creek. The Otowi Member of the Bandelier Tuff is present in this facies north of Galisteo Creek (Fig. 2). The dominantly fine-grained nature of the piedmont facies is consistent with the low hydraulic conductivities included in the Kernodle model. The subsurface extent of these deposits relative to the more conductive axial facies remains, however, uncertain (Fig. 3).

Western piedmont gravel and sand

Gravel and sand of the Cochiti Formation are widespread in the west part of the map area. In revising the definition of the Cochiti Formation, Smith and Lavine (1996) reviewed past ambiguity and inconsistencies in the definition and mapping of the formation. Most significantly, they distinguished the Cochiti Formation from volcaniclastic strata interbedded with middle Miocene volcanic rocks north and west of the area in Fig. 2 that were mapped as Cochiti Formation by Goff et al. (1990) and Smith et al. (1970), respectively. Smith and Lavine (1996) proposed a gradational contact between Cochiti Formation and underlying Peralta Tuff Member. We have applied the proposed restriction of Cochiti Formation with two minor differences. First, rather than placing the Peralta–Cochiti contact at the highest primary pyroclastic bed (Smith and Lavine, 1996), we were able to more consistently map the contact as an abrupt color (tan up to gray) change in gravel beds and shift in the ratio of glassy rhyolite to lithoidal rhyolite (from 3–5 to less than 2). This contact is about 10 m above the tuff of Cañada Camada near the top of the Peralta Tuff Member (Smith et al., 1991); one discontinuous rhyolite ash bed has been observed in the Cochiti Formation, 30 m above this contact. Second, Smith and Lavine (1996) advocated maintaining unnamed upper Pliocene–lower Pleistocene alluvium associated with the Bandelier Tuff as separate and unconformably overlying the Cochiti Formation. These strata, mapped as Quaternary–Tertiary alluvium (QTal) by Smith et al. (1970), are lithologically indistinguishable from the Cochiti Formation, and there is no evidence for an unconformity in the central Santo Domingo Basin. We, therefore, include these beds in the Cochiti Formation and, because they include the Otowi Member of the Bandelier Tuff, substantiate an earliest Pleistocene age for the uppermost Cochiti Formation (Fig. 3).

Cochiti Formation becomes finer grained south of the Jemez Mountains and east of the Cañada de Cochiti fault zone. A line approximating the 50% gravel isopleth is interpreted in Fig. 2 although outcrop quality prohibits detailed assessment of lateral grain-size variability in the formation. Fine- to medium-grained sand and silt with less than 15% gravel clearly characterizes southern outcrops and may justify the 4 ft/day (1.4×10^{-3} cm/s) conductivity applied in the Kernodle model. In western, and especially northern, outcrops, however, dominance of sandy pebble-to-boulder gravel suggests that the Kernodle model underestimates hydraulic conductivity by about one order of magnitude. Even where gravel is dominant, however, the coarser-grained layers are interbedded with continuous layers of pedogenically modified fine-grained sand and silt that likely impart a strong anisotropy in conductivity.

Differential subsidence caused preferential accumulation of the uppermost Cochiti Formation close to the modern Rio Grande in the north basin. Contemporaneous erosional beveling of upper Miocene and lower Pliocene Cochiti Formation in the structurally higher, west basin was followed by deposition of upper Pliocene pediment gravel (Fig. 3). This deposit, the gravel of Lookout Park, unconformably overlies relatively old Cochiti Formation in the west part of the map area and is chronostratigraphically correlative with part of the younger Cochiti Formation in the central basin (Fig. 3). Because it is a surficial unit, the gravel of Lookout Park has no hydrostratigraphic significance, but displacement of the associated geomorphic surface provides critical definition of late Cenozoic faults that are otherwise difficult to trace in the generally poor-quality Santa Fe Group exposures.

Principal faults

This study (Fig. 2) establishes the presence of many normal faults that were not previously mapped and extends and/or modifies the traces of previously identified structures. A complex history of faulting influenced the distribution of axial-facies strata in the basin fill (Smith and Kuhle, 1996, 1997) and potentially partitioned the aquifer at depth. The basin is a complex graben bounded by down-to-the-west faults, which continue southward into the Albuquerque Basin, and down-to-the-east faults, which project northward to form the western, stepped margin of the Española Basin. Where definable, displacement on down-to-the-east faults diminishes southward, and the down-to-the-west Sile and Domingo faults similarly disappear northward. The prominent Pajarito fault appears to terminate southward along strike with the projection of the Domingo fault with opposite sense of throw (Fig. 2). The boundary between east-tilted and west-tilted strata steps to the right along the axis of the basin, reflecting the shifting dominance of faults with opposite senses of motion (Fig. 2).

Faults illustrated in Fig. 2 exhibit evidence for Pliocene, and likely Quaternary, motion. Quaternary offset, demonstrated from displacement of the Bandelier Tuff, is about 120 m for the Pajarito fault, 200 m for the Domingo fault, and at least 50 m for the Cochiti fault. Post-middle Pliocene displacement across the Borrego fault zone is about 50 m.

The Santo Domingo Basin is interpreted (Smith and Kuhle, 1996, 1997) as part of a low-relief, rift-parallel accommodation zone (Rosendahl, 1987) between the Albuquerque and Española Basins. This interpretation contrasts with a discrete, northeast-striking, transverse "Santa Ana accommodation zone" as implied by illustrations in Chapin and Cather (1994) and Russell and Snelson (1994), but is consistent with Cather's (1992) inference that this is a complex zone of en echelon, rift-parallel faults. The prominent NNW strike of intrabasinal faults (Fig. 2) contrasts with the primarily northerly strike of basin-margin structures (Fig. 2). The intrabasinal faults may reflect northeast–southwest extension across a diffuse accommodation zone, which would be consistent with the model of Chapin and Cather (1994) relating opening of the Rio Grande rift to Colorado Plateau rotation.

Two en echelon grabens are found in the basin. The north graben, between the Pajarito and Cochiti faults (Fig. 3), is defined from the north margin of the map area to somewhere south of Cochiti Pueblo where the Cochiti fault is concealed beneath Rio Grande valley alluvium. A complex zone of intersection between the Cochiti, Pajarito, and Domingo faults likely is present beneath the valley fill (Fig. 2). The Domingo fault continues southward as a prominent photolineament to the vicinity of Espinaso Ridge and suggests that splays of the San Francisco fault (Fig. 1) continue northward to the Cochiti Pueblo area, although not in the simple fashion interpreted by Kelley (1977). The second graben is bounded by the Borrego and Sile faults. Upper Miocene axial-facies gravel interbedded with Peralta Tuff crops out in the horst block between the Sile and Pajarito faults. Assuming that the axial-gravel facies does not substantially predate 7 Ma, highly conductive aquifer materials may not persist downward for more than 100 m in this horst block along the west side of the Rio Grande. Firmly lithified Peralta Tuff is also present in the footwall of the north trace of the Camada fault suggesting a likely shallow extent of high-conductivity facies in that area.

We do not find the Borrego fault zone to be as complicated as portrayed by Kelley (1977), who apparently relied heavily on drainage lineaments to establish locations of faults. The parallel-striking Peralta fault zone continues northward into the southern Jemez Mountains and forms the west boundary of a late Miocene–early Pliocene graben that contains most of the Bearhead Rhyolite eruptive products and coeval sediment (Smith and Kuhle, 1997).

Distribution of axial and piedmont strata suggest that differential subsidence along the many intrabasinal faults influenced paleogeography and depositional patterns. Presence of axial-facies gravel as far as 12 km west of the modern river in the upper Miocene section near and west of Tent Rocks suggests an early period of intense westward tilting that favored the position of the Rio Grande in a more westward location (Fig. 3). The youngest basin-fill strata are, however, found near and east of the Rio Grande and upper Miocene and lower Pliocene strata are beveled and unconformably overlain by gravel of Lookout Park in the west basin (Fig. 3), suggesting that late Pliocene and Pleistocene subsidence was greater in the central and east parts of the basin. South of the mapped trace of the Pajarito fault, and where displacement on the Camada fault is also probably less, axial gravel is distributed much farther to the west in the Pliocene section than is true in the north basin (Fig. 2). The ancestral Rio Grande may have stepped westward from the north graben into the south graben and, at times, shifted farther west. Nonetheless, all Pleistocene Santa Fe Group strata, identified by intercalation with or containing clasts of Bandelier Tuff, are restricted to east of the Pajarito fault and then east of the Rio Grande south of the apparent termination of the fault.

Cementation along faults is present locally but is not a prominent aspect of surface exposures. Both calcite and chalcedony cementation characterizes axial-facies gravel in the footwall of the Pajarito fault, although the fault plane itself exhibits little cementation. Calcite cementation is also present locally along the Sile, Domingo, and Borrego faults. In other places, unexposed fault traces pass through or near relatively high standing topographic features suggesting that materials near the fault have greater resistance to erosion despite the lack of obvious excess cementation in surface exposures. Middle Miocene sandstone in the Cañada de Cochiti fault zone is intensely cemented up to 2 km from principal faults and is deeply reddened in a fashion comparable to potassium-metasomatized rocks elsewhere in the rift (Chapin and Lindley, 1986). Similar alteration may be present in middle Miocene strata in the subsurface of the Santo Domingo Basin.

Discussion and conclusions

New geologic mapping, though unaccompanied by any substantive increase in knowledge of the subsurface, suggests a more optimistic view of hydraulic conductivity in the Santo Domingo Basin than was necessarily adopted in the model of Kernodle et al. (1994) and possible revisions to how basin-margin recharge is transmitted southward. Axial Rio Grande gravel and sand, a significant aquifer in the city of Albuquerque, is laterally more widespread than mapped previously and, rather than being a thin Pliocene–Pleistocene surficial layer, is shown to persist chronostratigraphically back to at least the late Miocene and should, therefore, be in excess of 500 m thick in the central basin. The widespread lateral extent of these excellent aquifer materials in outcrop, and likely also in the subsurface, probably results from a complicated subsidence history of changes in dominant basin-floor tilting directions and development of intrabasinal grabens that caused large shifts in the long-term course of the ancestral Rio Grande. In addition, Cochiti Formation deposited near the north and west basin margins is mostly coarse-grained gravel and sand that should be an order of magnitude more conductive than values ascribed in the Kernodle model.

Intrabasinal faults not only affect the basin hydrology by influencing distribution of hydraulically conductive facies but also may partition the aquifer through juxtaposition of materials of contrasting properties or by providing planes of preferential cementation. A curious feature of ground-water levels in the Albuquerque area is that the lowest heads, rather than corresponding with the Rio Grande, are found west of the river and define a trough in the water-table surface, of unknown origin, that persists roughly parallel to the river (Bjorklund and Maxwell, 1961; Titus, 1961). Although data in the Santo Domingo Basin are very sparse, they do suggest the persistance of this trough in the water table through the southwestern quadrant of the map area (Anderson, 1960). Wells located 2–8 km west of the river record water levels 30–50 m lower than the elevation of the Rio Grande at the same latitude. One possible explanation for this phenomenon is that highly transmissive axial-gravel facies is present within the aquifer in this region and drains water out to the south but is somehow isolated from recharge from the Rio Grande. Such facies are present in outcrop at sufficiently westerly locations (Fig. 2) as to make it reasonable to assume that they are also present there in the aquifer. Many faults intervene between the wells with low water levels and the Rio Grande and may affect the hydraulic connection between the river and the aquifer. Discontinuous cementation is associated with faults at the surface and and may be more prevalent at depth. The presence of upper Miocene deposits at the surface along the west side of the valley, south of

Cochiti Pueblo, raises the possibility that faults juxtapose a thick section of axial gravel in the west basin against a relatively thin section in the horst block closer to the river that may not persist far below the water table. This hypothesis requires more water-level and stratigraphic data for testing, but it suggests that a combination of faulting and hydrostratigraphy of the basin fill ultimately controls water level more than either characteristic alone.

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