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Geology and Hydrogeology of the Southern Taos Valley, Taos County, New Mexico

By

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FINAL TECHNICAL REPORT

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CONTENTS

I. INTRODUCTION

II. METHODS

III. GEOLOGY

IV. HYDROGEOLOGY

V. PRELIMINARY BASIN-SCALE GEOLOGIC MODEL

VI. RECOMMENDATIONS AND DATA NEEDS

List of Tables

List of Figures

List of Plates (attachments)

1. Geologic map, cross sections A-A', B-B' and E-E' and potentiometric surface map of the southern Taos Valley, scale 1:12,000
2. Geologic map and cross sections C-C' and D-D' of the Talpa area, scale 1:6,000
3. Tectonic map of the southern Taos Valley, scale 1:24,000
4. Speculative geologic block diagram of the southern Taos Valley.

I. INTRODUCTION

A. Significance

There have been a variety of published and unpublished interpretations of the hydrogeology in the Taos area, yet the regional hydrogeologic framework is poorly understood. There are few or no compilations of basic subsurface data at an area-wide scale, and thus no adequate base of information for evaluating the hydrogeologic framework of the Taos embayment. Barring the installation of numerous deep exploration test holes around the Taos Valley and valley margins to provide spatially distributed subsurface geologic and ground-water data (a necessary, but extraordinarily costly endeavor), the only alternative approach to development of a sound hydrogeologic understanding of the basin is through collection and synthesis of various types of surface geologic, geophysical, and hydrologic data. This study synthesizes new and existing geologic data with all existing and publicly available geophysical and hydrologic data, and provides a preliminary conceptual hydrogeologic model for use in making decisions about the exploration and development of ground-water resources in the Taos area. The model and interpretations presented here are intended to provide direction for the future collection of new subsurface hydrogeologic data, as well as a geologic framework within which to interpret future data.

B. Scope and Objectives

The study was designed to collect new surface geologic data in the southern Taos valley, and to synthesize surface and subsurface geologic and hydrogeologic data into geologic and hydrogeologic conceptual models. The study area is restricted to the Taos embayment, and specifically includes non-pueblo land in the northwest corner of the Ranchos de Taos quad and the southwest corner of the Taos quad. We have added small areas of the Taos SW and Los Cordovas quads in order to include relevant geologic features. Mapping was concentrated on the high piedmont terrain within the embayment. The primary objectives of the study are:

(1) To develop a geometric model of the surface and subsurface geology of the Taos embayment. This model will assist in locating areas for drilling exploratory water wells, and in locating critical areas for hydrologic monitoring.

(2) To better understand the detailed basin-margin hydrogeology in the rapidly developing high piedmont area between Cañon and Talpa. This understanding will assist planners and developers in making decisions concerning water supply and water quality, and support geologists and drillers in developing domestic water supplies.

(3) To investigate the influence of stratigraphy and structure on mountain-front recharge, and determine what recharge mechanisms are active at various locations.

(4) To evaluate existing data resources and recommend directions of future data collection. Such an evaluation will assist agencies in making decisions about future water studies in the Taos area.

The following deliverables are included in this report: geologic maps at scales of 1:12,000 and 1:6000, six geologic cross sections and block diagrams, a tectonic/geologic/geophysical map (1:24,000 scale) and preliminary model, a potentiometric surface map (1:12,000 scale) of the basin margin along the southern Taos embayment, and evaluation of mountain-front recharge mechanisms and routes of recharge. These data and interpretations are synthesized into a conceptual geologic and hydrogeologic models. In addition, we provide a discussion of areas for future ground water development and monitoring.

C. Participants

Principal Investigators:

Dr. Paul W. Bauer, New Mexico Bureau of Mines and Mineral Resources
Senior Geologist, Assistant Director, Manager of Geologic Mapping Program
Project tasks: Geologic mapping, structural geology, geologic model, cross sections, report

Peggy S. Johnson, New Mexico Bureau of Mines and Mineral Resources
Hydrogeologist
Project tasks: Hydrologic analysis, hydrogeologic model, report

Principal Contractor:
Keith I. Kelson, William Lettis & Associates, Inc., Walnut Creek, CA
Senior Geologist, expertise in Quaternary geology, neotectonics, seismic hazards
Project tasks: Geologic mapping, air photo interpretations, geologic model, report

Research Assistant:
Annie Kearns, New Mexico Institute of Mining and Technology
Hydrologist
Project tasks: Domestic well database, field checking well locations

Other Contractor:
Paul Drakos and Jay Lazarus, Glorieta Geoscience, Inc., Santa Fe
Consulting geologists with expertise in water supply of Taos area
Project tasks: Provide Taos area subsurface data and hydrogeologic input

Technical assistance:
Mic Heynekamp, New Mexico Bureau of Mines and Mineral Resources
Geologic lab associate
Project tasks: Computer drafting, scanning, report production

D. Previous Work

1. Geology

Dozens of geologic studies have been conducted within the Taos area. Rather than list them here, we present a comprehensive reference list at the end of this report. Prior to our mapping, no quad-scale, detailed geologic maps existed for the study area. Instead, there existed regional maps (Miller and others, 1963; Lipman and Mehnert, 1975; Machette and Personius, 1984; Garrabrant, 1993) and thesis maps of generally small areas or specialized subjects (Chapin, 1981; Peterson, 1981; Leininger, 1982; Rehder, 1986; Kelson, 1986; Bauer, 1988). Kelson and others (1997) recently completed a USGS-funded study of the earthquake potential of the Embudo fault zone. The study included detailed geomorphic mapping and kinematic analysis of faults on the Picuris piedmont from Pilar to Talpa. Of particular relevance to the current study, the work by Kelson and others (1997) and Bauer and Kelson (1998) provides a detailed database on the location and complexity of the Embudo fault zone, which appears to strongly influence subsurface stratigraphy and hydrogeologic relations along the southern margin of the Taos embayment. Where appropriate, we incorporated previous map data into our 1:24,000 scale tectonic map (e.g., locations of Los Cordovas faults from Machette and Personius (1984) and Kelson (1986)).

2. Hydrology

Several general and reconnaissance level hydrogeologic studies have been conducted in the Taos Valley over the past 40 years, beginning with work by Winograd (1959) in the Sunshine Valley. Though located north of our area of interest, Winograd's descriptions of the various rock formations in the Sunshine Valley and their water-bearing characteristics are still pertinent today, and provide a sound conceptual model that is applicable in general terms to the region's aquifer systems. Reconnaissance studies were undertaken cooperatively by the U.S. Geological Survey, the New Mexico State Engineer's Office, and the U.S. Bureau of Reclamation beginning in the late 1960's as part of San Juan-Chama Project studies in the Taos Unit, and are summarized in memoranda and letter reports (Spiegel and Couse, 1969; Cooper, 1972; Hearne, 1975). These studies produced the first test wells in the area, the first contour map of water levels, and the first aquifer tests evaluating stream-aquifer interactions. Subsequent studies conducted as part of regional water planning for Taos County and the City of Taos have focused on regional water quality and availability (Wilson and others, 1978, 1980; Garrabrant, 1993), and exploratory drilling (Turney, Sayre and Turney; 1982; and Drakos and Lazarus, 1998). Other regional hydrogeologic studies of interest include Hearne and Dewey (1988) and Coons and Kelly (1984). A water budget developed by Hearne and Dewey quantifies water yield from the Sangre de Cristo Mountains to the Costilla Plains, and the contribution of mountain front recharge to the basin aquifer system. A conceptual model of the regional flow system presented by Coons and Kelly infers a two-layer aquifer system that consists of a deep zone of transient storage extending from the basement to the bed of the Rio Grande, and a shallow, dynamic zone of saturation influenced by meteoric processes, stream infiltration, pumping, and discharge to streams. It is important to note that no persistent and identifiable confining layer between these upper and lower zones has yet been recognized. Collection of original hydrogeologic data has only occurred during the early San Juan-Chama studies and recent ground-water exploration projects. NMOSE well records provide the only other source of subsurface geologic data, water level data, and well productivity data; these are the data on which this study relies.

3. Concurrent Studies

Several concurrent geology/hydrogeology investigations in the Taos area are pertinent to our study. The New Mexico Bureau of Mines and Mineral Resources is producing 7.5-minute geologic quadrangle maps as part of the STATEMAP program (contact Paul Bauer for information). The Taos SW and Carson quads have been released as Open-File Digital Geologic Maps, and the Ranchos de Taos quad is being mapped at present. These quads are mapped at a scale of 1:12,000, will be released at scales of 1:12,000 and 1:24,000, and eventually will be available as digital geologic maps.

The U.S. Bureau of Indian Affairs, in cooperation with the Pueblo of Taos, is involved in a water supply investigation of Tribal lands on the Taos plateau. This program has included the drilling of exploration wells and interpretation of the subsurface geology and hydrology. Contact Chris Banet or Bill White for information.

Glorieta Geoscience, Inc. of Santa Fe continues to work for the Town of Taos as consultant for town water supply studies. The town has drilled wells and conducted hydrologic investigations of water quality and availability. Contact Jay Lazarus or Paul Drakos for information.

A doctoral student from the University of Texas at Dallas, David McDonald, is currently finishing a dissertation on the geometry and kinematics of the northern Picuris-Pecos fault and La Serna fault in Taos County. He has found complex fault histories, similar to our own findings in the Talpa area.

II. METHODS

Our approach for investigating the geology and hydrogeology of the study area consisted of three general phases:

A. Geologic Mapping and Air Photo Analysis.

Geologic mapping was done by P. Bauer and K. Kelson during a number of field trips in 1997. Bauer concentrated on mapping basement (Proterozoic, Paleozoic, and Tertiary) rocks and structures, and fault scarps in Quaternary deposits. Kelson concentrated on air photo interpretation, geologic and geomorphic mapping of surficial deposits and Tertiary rocks in the Talpa area, and fault scarps in Quaternary deposits. We completed geologic mapping of bedrock units along the mountain-front/piedmont interface at a scale of 1:12,000. Due to complexities encountered in the Talpa area, we also produced a 1:6,000 map of that area. Mapping involved a determination of lithology and analysis of structures such as faults, fracture zones, and folds.

The 1:12,000 scale geologic map includes parts of four 7.5-minute quadrangles: Taos SW, Ranchos de Taos, Taos, and Los Cordovas (Plate 1). The map represents new field mapping of the mountain front and piedmont, new air photo interpretation of the lower part of the basin, compilation of some preexisting mapping by Rehder (1986) in the Pennsylvanian bedrock, and compilation of the locations of Los Cordovas faults from Kelson (1986) and the 1:250,000 map of Machette and Personius (1984).

A primary goal of this project is to provide a conceptual model of the large-scale geologic structure of the basin beneath the southern Taos valley. Our approach first is to understand the surficial structural geology around the edge of the basin by careful mapping, and then to infer the subsurface basin structure using that knowledge and all other available data sets (e.g., boreholes, geophysics, surface structure, geomorphology, hydrology). In an area such as Taos, which has experienced at least four major orogenic episodes, the key to understanding the structure of the basin is based on insights into the geometry and kinematic history of each of the superimposed tectonic events (Proterozoic, Ancestral Rocky Mountain, Laramide, and Rio Grande rift).

As part of delineating bedrock units, faults, and basin-fill sediments, we analyzed multiple sets of photographic imagery. These included color infrared images at a scale of 1:58,000 taken for the USGS National High-Altitude Program (NHAP) in 1981, black-and-white photography as a scale of 1:45,000 taken for the USGS in 1961, color photography at a scale of 1:24,000 taken for the USDA in 1981, color photography at a scale of 1:15,840 taken for the USFS from 1973-1975, and color photography at a scale of 1:6000 taken for the Town of Taos in 1995. Our air-photo analysis utilized primarily the 1:15,840 USFS images because of good coverage and high quality, although each of the photo sets have a high degree of clarity and provide good information on surficial deposits and fault-related features. Following our analysis of aerial photography, we conducted detailed mapping of geologic units and geomorphic features at scales of 1:12,000 and 1:6000. Our mapping included delineation of Quaternary deposits and surfaces, and of Quaternary faults, fault scarps, and lineaments. Analysis of faults in all units (Proterozoic to Quaternary) included evaluations of fault geometries and kinematic data. On bedrock faults, fault striations (slickenlines) were combined with kinematic indicators such as offset piercing lines or planes, and calcite steps to infer slip directions. In Quaternary deposits, the limited number of fault exposures precluded collection of many kinematic data. We infer slip directions based on fault scarp geometry, map pattern of fault strands, and deflected drainages, following the earlier work by Kelson and others (1997).

Final mylar maps were scanned, drafted onscreen using Freehand on a Macintosh, merged with base data from ARCINFO in our GIS lab, and plotted as color maps. Individual data sets (e.g., faults, strikes and dips, breccia zones, etc.) were digitized as separate layers so that maps can then contain any combination of data sets.

B. Compilation of Existing Geologic, Geophysical, Subsurface, and Hydrologic Data.

This approach allowed us to infer subsurface stratigraphy and structure over the region, and then project important features (such as buried faults and basalt flows) into our study area. Other geologic maps, geophysical surveys, satellite photos, and deep well locations were scanned and plotted at a scale of 1:24,000. Essential data were transferred to a master map, which was scanned, drafted on a Macintosh, and plotted on an HP 3500 color plotter.

C. Collection and Compilation of Domestic Well Data.

Because Quaternary deposits cover bedrock over much of the study area, we evaluated well data along the bedrock/piedmont interface in order to better understand the shallow basin bedrock architecture in the area of the Embudo and Sangre de Cristo fault systems, and its control of ground-water flow into the basin. Approximately 250 NMOSE well records from the study area were copied and reviewed, focusing on those wells located along the mountain front-piedmont margin. Records of wells that penetrated bedrock, and those that were relatively deep were prioritized for evaluation. We also used information from six experienced local well drillers in locating wells of particular interest. Several drillers are very knowledgeable about the various aquifer rock types in the Taos valley. Well locations were checked in the field by verifying locations with well owners, and recording UTM coordinates from a Garmin™ GPS II Plus location device. In a few instances when satellite coverage was inadequate for GPS location, UTM coordinates were obtained from the USGS 7.5-minute quadrangle maps. Well owners also often provided additional relevant information regarding well construction, water level, water temperature and water quality. From the field, each well was also plotted on Town of Taos aerial survey photographs (1:6000 color photographs, flown June 1996) and on the quadrangle maps. Surface elevations for each well were interpolated from 7.5-minute maps. Elevations of water levels in wells were determined by subtracting the “depth to water” as reported on NMOSE well records or by the well owner, from the interpolated land surface elevation. These potentiometric surface points were then contoured on an overlay to a 1:12,000 scale geologic map (Plate 2). No direct water level measurements were taken due to lack of well access. Well data are summarized in Appendix 2.

III. GEOLOGY

A. Structural and Physiographic Elements

1. Geologic setting and history

The southern Rocky Mountains of northern New Mexico record a complex geologic history, from Early Proterozoic crustal genesis, to the Paleozoic Ancestral Rocky Mountain orogeny, to the Cretaceous/Tertiary Laramide orogeny, to Neogene rifting and contemporary extension and sedimentation. The rocks of the Sangre de Cristo Mountains contain evidence of each of these orogenic events. For the purposes of this report, we will emphasize the Cenozoic history, although it is likely that earlier geologic events produced faults and large-scale crustal relations that helped focus Laramide and rift deformation, and therefore influence the present-day geologic structure of the Taos area.

The following summary of Cenozoic paleogeography for north-central New Mexico (Ingersoll and others, 1990) provides a regional framework for our synthesis of the geology of the southern Taos embayment.

- Eocene (58-37 Ma) – A single, large, amagmatic sedimentary basin (El Rito-Galisteo basin) was bounded by the Laramide Brazos-Sangre de Cristo uplift on the east, and the Nacimiento-Gallina-Archuleta uplift on the west.
- Early to late Oligocene (37-28 Ma) – Intermediate magmatism with volcaniclastic aprons derived from the San Juan volcanic field and relict Laramide highs. Picuris Formation accumulates.
- Late Oligocene to early Miocene (28-21 Ma) – Bimodal volcanism and associated sedimentation from Latir volcanic field and Questa caldera. Picuris Formation continues to accumulate.
- Early to middle Miocene (21-15 Ma) – Continued erosion of silicic volcanic centers coeval with initial block faulting of rift. Taos Range begins to form, and Phanerozoic and Proterozoic rocks are eroded. Tesuque Formation begins to accumulate in incipient San Luis rift basin.
- Middle to late Miocene (15-8 Ma) – Rift basins continue to evolve into deep half-grabens with extensive unroofing of Proterozoic-cored ranges. Complex depositional centers form in basins, including Chama-El Rito Member, Ojo Caliente Member and Dixon Member of Tesuque Formation in Taos area. Bimodal volcanism continues. Picuris and Tusas Mountains begin to form.
- Late Miocene to present (8-0 Ma) – Concentration of extension in San Luis and Española basins linked by the Embudo accommodation zone. Major basaltic volcanism in Taos plateau (Servilleta basalt), with regional uplift, and integration of the Rio Grande drainage. Picuris Mountains unroofing, with deposition of Chamita Formation along north and west flanks of range.

The Taos area straddles the boundary between Proterozoic and Paleozoic basement rocks of the Sangre de Cristo and Picuris Mountains and Cenozoic sedimentary and igneous rocks of the southern San Luis basin (Fig. 1). Three major fault systems intersect within the study area: 1) the Picuris-Pecos fault system; 2) the Embudo fault zone; and 3) the Sangre de Cristo fault zone (Fig. 2).

2. Picuris-Pecos fault system

The Picuris Range is a Proterozoic-cored, wedge-shaped uplift that projects westward from the southern Sangre de Cristo Mountains, southwest of Taos. The Picuris-Pecos fault zone and parallel fault zones to the east (La Serna, Miranda, McGaffey, and Rio Grande del Rancho fault zones [see Plate 1]) are high-angle, north-striking systems that separate the Picuris Mountains block from the main block of the Sangre de Cristo Mountains. In this report, these fault zones will be collectively referred to as the Picuris-Pecos fault system. Montgomery (1953) recognized the Picuris-Pecos fault (originally named the Alamo Canyon tear fault) in the Picuris Mountains. He later mapped its southward continuation in the southernmost Sangre de Cristo Mountains (Miller et al., 1963). The fault is a north-striking, vertical to near-vertical structure that appears to consist of a single large-displacement fault over much of its length. Subsidiary, map-scale, sub-parallel faults exist locally, and in the study area we have mapped several parallel, large-displacement faults with similar geometries.

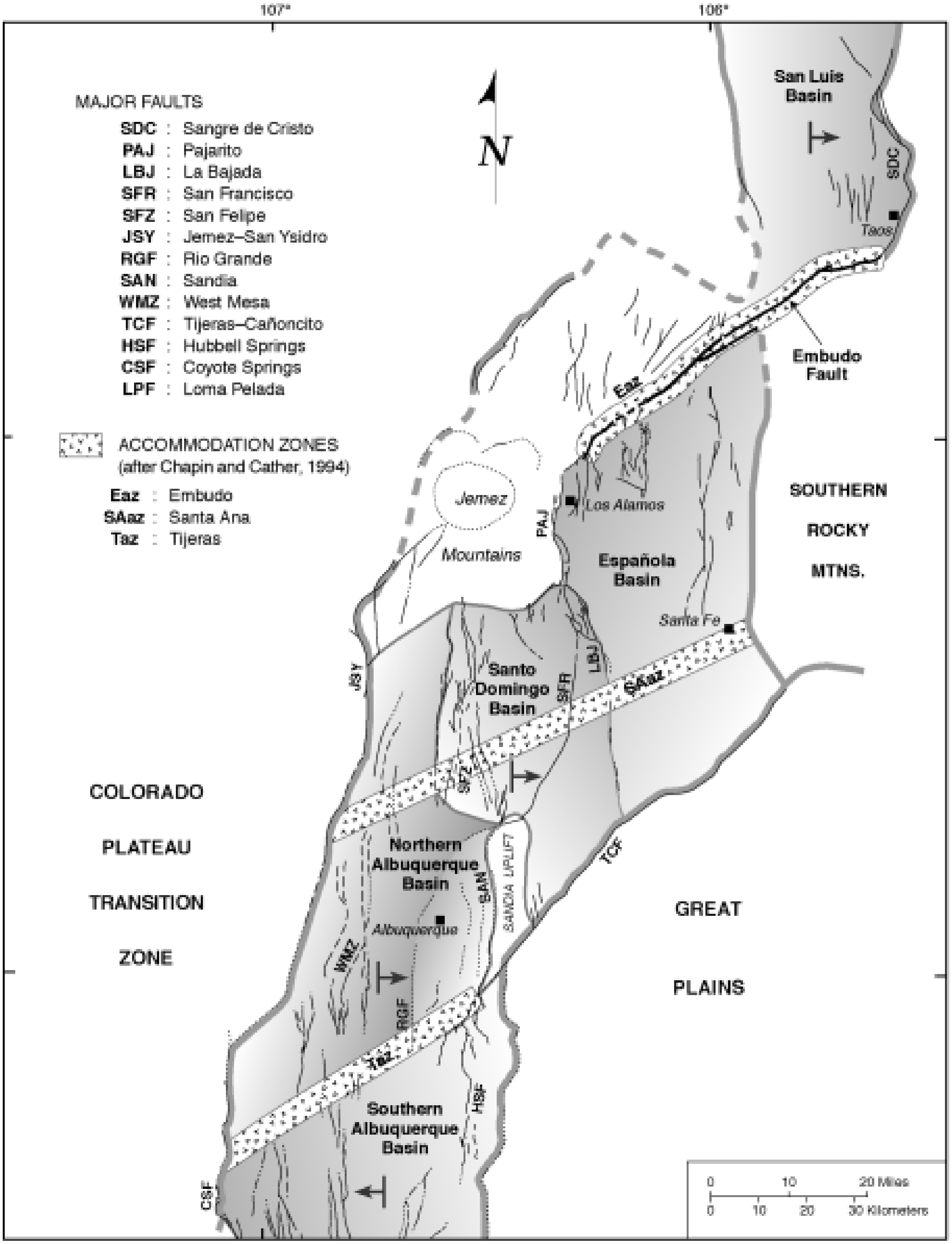


Figure 1. Generalized tectonic map of the northern Rio Grande rift. From Kelson and others (1997).

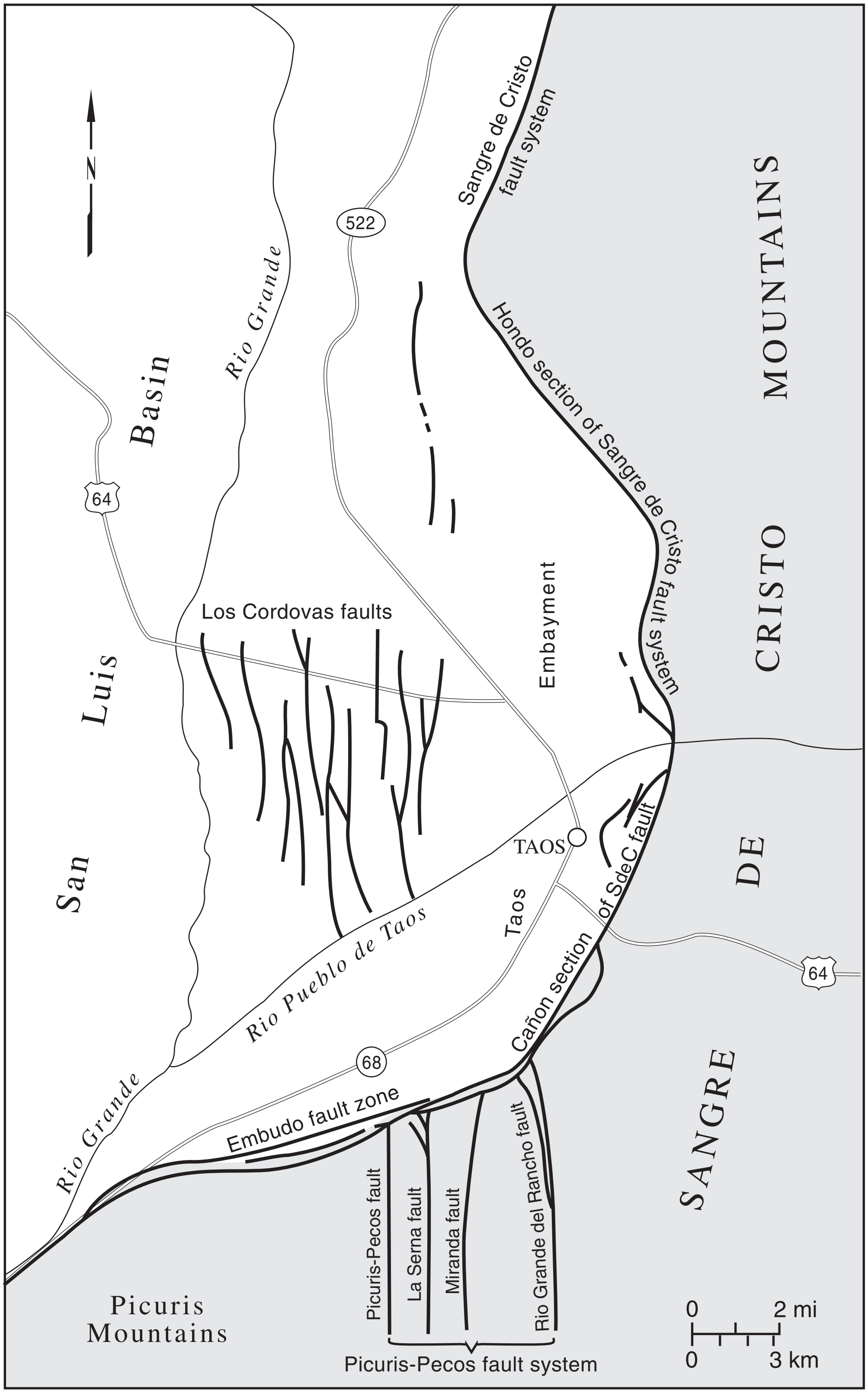


Figure 2. Generalized tectonic map of the Taos area.

The Picuris-Pecos fault zone has been traced for more than 60 km, from the northern Picuris Mountains south of Taos, to I-25 near the village of Cañoncito, east of Santa Fe. From Cañoncito, it can be traced southward into the Estancia Basin for an additional 24 km, yielding a documented trace of 84 km. The fault probably extends considerably farther southward and northward, yielding a total length of 160+ km.

Bauer and Ralser (1995) summarized the geologic history of the Picuris-Pecos fault zone as follows:

1) Proterozoic(?), post-1.4 Ga displacement on the Picuris-Pecos fault resulted in some unknown amount of right slip (perhaps 11 km?) and deflection and attenuation of Proterozoic supracrustal rocks and older ductile structures;

2) As noted by Sutherland (in Miller et al., 1963), a series of Mississippian and Pennsylvanian west -up movements on the Picuris-Pecos fault resulted in deposition of sediments along the northern part of the fault. Although no strike-slip component is documented, some amount was likely;

3) During the Laramide orogeny, at least 26(?) km of right-slip occurred on the Picuris-Pecos fault, with coeval, subsidiary displacement on north-striking, high-angle faults east and west of the main fault. The overall geometry of the fault system was a positive flower structure, with dip-slip displacement dominating some subsidiary faults. Strike-slip, oblique-slip, and dip-slip fault striae all developed contemporaneously on different fault strands. Perhaps the timing of this contractional duplex corresponds with the Eocene opening of the transtensional Galisteo Basin along the Tijeras-Cañoncito fault;

4) During the Neogene, rift-related faulting was concentrated in the Santa Fe Range, rather than the Picuris Mountains, perhaps due to greater extension in the southern Española Basin versus the northern Española Basin (Chapin and Cather, 1994). Normal faulting may have been distributed over many reactivated(?), high-angle faults in the southernmost Sangre de Cristo Mountains.

Only the northern end of the Picuris-Pecos fault system has been mapped for this study (Plate 1). All five of the fault zones share some common features. They are all near-vertical, they are wide, complex structures with many splays, they are mostly located in valleys, and they are all cut by the Embudo fault system. We suspect that each of the fault zones share similar kinematic histories of multiple reactivation.

Importantly, for the current study, these faults cut rocks as young as the middle Picuris Formation (ca. 19 Ma). This means that these faults were active during initial rift formation, and perhaps later as well, as we suspect that some may also cut the Chama-El Rito member of the Tesuque Formation. Because the N-S faults are cut by the Embudo fault, they pre-date the Embudo system and, importantly, must exist in the subsurface north of the Embudo fault. Based on the north-south orientation of the Taos graben, we suspect that these faults have helped control the geometry of the Taos graben.

The large N-S faults are located in valleys because the pervasive brittle deformational features (fractures, fault gouge, fault breccia) are relatively easily weathered and eroded. One implication of this phenomenon is that in the southern part of the valley, runoff is concentrated along the fault zones. A second is that the fault zones themselves display hydrologic properties that differ from those of the unfractured areas.

The most complex, exposed deformational zones are mapped in the Talpa area, where exposures of the Picuris Formation are cut by both the N-S faults and the Embudo fault zone. For this reason, we have produced a 1:6000 scale geologic map of the Talpa area (Plate 3). Where Tertiary rocks are exposed, the map shows numerous faults that are either north- or north-east striking. Most of the N-S faults in the Tertiary appear to be small structures, with map separations measured on the order of tens of meters. The main strand of the Miranda fault is not exposed, but can be inferred by the juxtaposition of Picuris Formation against Proterozoic granite across Arroyo Miranda. Several splays of the Miranda fault are exposed west and east of the arroyo. In the southwest corner of the 1:6000 map, on hill 7365 ft, a tectonic sliver of Llano Quemado breccia is bounded by two steeply east-dipping, strike-slip(?) faults. A system of branching faults (herein named the McGaffey fault) on the bedrock ridge of Cuchilla del Ojo offsets Proterozoic and Paleozoic rocks, and is probably responsible for the location of Ponce de Leon thermal springs.

Although Proterozoic rocks underlie all of the study area, they are only exposed in the southwest corner of the map area. The Picuris-Pecos fault appears to represent a major boundary that has experienced enough slip to juxtapose very different rock packages. West of the fault is the layered supracrustal Hondo Group, a metasedimentary terrain consisting mostly of quartzite and schist. Exposures in between the Picuris-Pecos and La Serna faults, and in the Ponce de Leon area east of the Miranda fault, are of similar, medium-grained, orange weathered granite. Several water wells in the northern Miranda graben are completed in granite at depths of about 400 ft. All three of these occurrences are probably of a single granitic terrain, sliced up by the Miranda graben. If so, it follows that the strike-slip components of net slip on the faults of the Miranda graben are modest with respect to that of the Picuris-Pecos fault. This granitic terrain probably continues eastward beneath the Paleozoic section, and exists at depth in the basin to the north. Presumably, the Picuris-Pecos fault also extends northward into the basin, and must represent a profound subsurface boundary in at least the Proterozoic and Paleozoic sections. Although the Miranda graben must also extend northward into the basin (because the graben faults are older than the Embudo fault system), it probably does not represent such a profound structure in the Proterozoic and Paleozoic sections.

3. Embudo fault zone

The southeastern margin of the San Luis basin is a major Neogene-age fault system, called the Embudo fault zone, that separates the east-tilted San Luis basin from the west-tilted Picuris block (Baltz, 1978). Along the northwest flank of the Picuris Mountains, the Embudo fault zone is distinguished topographically by precipitous cliffs that parallel the Rio Grande and NM-68. The 65-km-long Embudo fault zone is a segment of a much larger structural/volcanic trend, the Jemez lineament, that may have been a zone of crustal weakness since late Precambrian time (Muehlberger, 1979). Muehlberger (1979) estimated that structural relief across the fault is at least 10,000 ft.

A number of different interpretations of this fault zone have been published (Montgomery, 1953; Kelley, 1978; Manley, 1978, 1979; Muehlberger, 1979; Aldrich, 1986). Recent work documents Quaternary northwest-down, left-oblique normal slip along multiple, near-vertical strands on the northeastern part of the fault (Kelson and others, 1996, 1997; Bauer and Kelson, 1997; Kelson and Bauer, 1998). Our mapping shows that the fault zone is several kilometers wide, and extends from basement rocks in the Picuris Mountains onto the piedmont north of the range. Aldrich (1986) stated that major transcurrent movement occurred on the Embudo fault zone during the Pliocene, and has subsequently slowed. Within our study area, Personius and Machette (1984) and Kelson and others (1997) described fault scarps on the Embudo trend that could be as young as 10,000 years old.

In the map area, the Embudo fault zone is a complex system of left-oblique, north-down, strike-slip fault strands that is over two kilometers wide. We have defined the terminus of the Embudo fault at the Rio Grande del Rancho, where the dominantly strike-slip, east-striking Embudo fault system swings northward and merges with the dominantly dip-slip Cañon section of the Sangre de Cristo fault. It is noteworthy that the transition zone from the Embudo fault to the Sangre de Cristo fault is coincident with the Picuris-Pecos fault system and the Miranda graben.

In Proterozoic bedrock units, the major strands of the Embudo fault are well developed, high-angle, brittle deformation zones. Some are many tens of meters wide, typically consisting of central zones of intense strain (breccia, fault gouge, closely spaced fractures) flanked by wide zones of fractured rock. The fault strands anastomose, locally around pods of relatively undeformed rock. In Pennsylvanian sandstones and conglomerates, fault striations (slickenlines) are common, and generally plunge gently to the west. Fractures typically are open, with only minor carbonate cementation. Commonly, the massive sandstone and conglomerate beds contain thoroughgoing fractures, whereas the interlayered shales do not contain fractures. Such a mechanical response to strain of rocks with different ductilities is common.

A different style of deformation is present in the several places where we found good exposures of Embudo faults in the Tertiary rocks (Picuris Formation and Chama-El Rito member). In these zones, the bedrock has been reduced to a clay-rich fault gouge that contains a strong tectonic foliation and clasts rotated into the foliation plane. Away from the fault plane, these gouge zones grade into altered and fractured bedrock, and then into relatively unstrained bedrock. In places, these fault zones can be traced along strike into bedrock faults and into Quaternary scarps. A third style of deformation is seen where the fault zones cut Quaternary deposits. Typically, the alluvium is laced with thin, anastomosing, calcite-filled fracture veins. Alteration zones are common, and clasts are rotated into the foliation plane. However, the overall fabric of shearing is substantially less in the Quaternary deposits than in older units.

The variations in the nature of the Embudo faults in units of different ages are probably due to a combination of factors. First, there are dramatic differences in the mechanical properties between consolidated granite/sandstone/conglomerate, semiconsolidated Tertiary siltstone, and unconsolidated alluvium. Each of these units responds to brittle strain differently. Secondly, the history of faulting along the Embudo system is one of episodic reactivation (Kelson and others, 1997). Therefore, in general, we believe that the oldest rocks record the greatest slip; that is, a Pennsylvanian sedimentary rock has experienced more fault displacement than an overlying Pleistocene alluvial fan.

A variety of physical features help to define fault scarps and photolineaments along the Embudo fault zone. These include springs and deciduous trees such as willows and cottonwoods.

4. Cañon section of the Sangre de Cristo fault zone

The Sangre de Cristo Mountains are composed primarily of Early Proterozoic supracrustal and plutonic rocks north of the latitude of Taos Pueblo, and Paleozoic sedimentary strata to the south. North of Taos, the mountains are bordered on the west by the 160-km-long, north-striking, steeply west-dipping, normal Sangre de Cristo fault zone, the major rift-bounding structure of the San Luis basin. Prominent fault scarps exist only along most of the fault zone, which consists of a series of parallel and subparallel faults with individual strain histories. Nonetheless, the zone shows significant Pleistocene and Pliocene normal offset (Machette and Personius, 1984; Machette and others, 1998).

Following the usage of Machette and others (1998), the southern section of the fault zone, between Rio Grande del Rancho and Rio Pueblo de Taos, is called the Cañon section of the Southern Sangre de Cristo fault. The Cañon section therefore includes the Taos Pueblo fault of Machette and Personius (1984). The Cañon section shows complex surface expressions and is interpreted as having ruptured during either early(?) Holocene or latest Pleistocene. The Cañon fault represents the transition between the Embudo strike-slip fault zone and the Sangre de Cristo normal fault zone (Kelson and others, 1997).

The Cañon section is a complex system of branching faults that define the boundary between the mountains and the basin. In general, the surface expression of the Cañon section is narrower than the Embudo fault zone. With the exception of the Rio Fernando area, fault scarps in Quaternary deposits are mostly confined to the mountain front zone where Quaternary is in contact with Pennsylvanian. Individual fault planes typically dip steeply west to northwest, with slickenlines plunging moderately to steeply westward. The transition from strike-slip to dip-slip in the Talpa area is gradational, with a prevalence of oblique-slip (plus some strike-slip) faults in the bedrock just southeast of Talpa. The physical characteristics of the bedrock and alluvium faults are similar to those of the Embudo system.

Several small springs exist along fault splays in the Cañon map area (Plates 1 & 2). The springs are located in arroyos overlying the footwall block, just upstream (east) from the fault plane. Presumably, movement of ground water through the sedimentary strata and arroyo alluvium is attenuated by the Sangre de Cristo fault, and at least partially discharging upgradient of the fault. We also found two inactive travertine deposits, located on major fault strands, that are probably associated with extinct springs (Qt on Plate 1).

5. Taos Plateau of the southern San Luis basin

The San Luis basin is one of the major structural elements of the Rio Grande rift. It is approximately 240 km long, and is bordered by the Sangre de Cristo Mountains on the east, and the Tusas and San Juan Mountains on the west. The southern part of the basin is a physiographically and geologically unique terrain known as the Taos Plateau. The plateau is composed mostly of Pliocene basaltic rocks that were erupted locally, and have only been mildly deformed by rift processes. Basalt flows dip very gently to the east, at about 6 m/km or 0.4° (Lipman and Mehnert, 1979). The plateau surface shows only minor dissection, although the Rio Grande and its tributaries are confined to deep canyons cut through the volcanic rocks. The 1000-ft-deep Rio Grande gorge contains the best exposures of these flat-lying Tertiary volcanic rocks, as well as the interlayered sands and gravels of the Chamita

Formation that represent westward-prograding alluvial fans of the Taos Range. The basalt flows pinch out eastward and southward towards the edge of the basin.

In the Taos area, the rift is a 30-km-wide, asymmetrical, Basin and Range-style basin with the major flanking fault system along its eastern border (Sangre de Cristo fault system). The total throw on the Sangre de Cristo fault system might be as much as 7 or 8 km (Lipman and Mehnert, 1979). Gravity data indicate that at the latitude of Taos, the basin consists of a very deep N-S graben (maybe >5km deep; herein called the Taos graben) along the eastern edge of the rift (Cordell, 1978). The west edge of the graben (herein called the Gorge fault zone) is buried approximately under the Rio Grande (Cordell and Keller, 1984), resulting in a graben that is less than half the width of the topographic valley. The structural bench west of the Taos graben rises gently towards the Tusas Mountains, and is cut by numerous small-displacement normal faults. To the north, the bench becomes an intra-rift horst with Oligocene volcanic rocks exposed in the middle of the rift at the San Luis Hills of southern Colorado (Lipman and Mehnert, 1979).

6. Los Cordovas faults

Los Cordovas faults were not mapped for this project, but their southern extent, as mapped by Kelson (1986), is included in the map area (Plates 1 and 4). Previous workers described a 5-8 km wide zone of north-striking faults in the Taos plateau (Lambert, 1966; Machette and Personius,1984). Where separation is greatest, the faults juxtapose piedmont- slope alluvium down to the west against older Servilleta Formation basalt. Machette and Personius (1984) stated that the fault offset is greater than the 15-30 m high erosional scarps that now define the surface expression, and that faulting may be as old as early Pleistocene, but could be as young as middle(?) Pleistocene. Profiles of stream terraces along the Rio Pueblo de Taos suggest that the faults displace the early(?) to middle Pleistocene piedmont surface, but not the middle Pleistocene Qt_2 terrace (Plate 1; Kelson, 1986; Machette and others, 1998).

B. Stratigraphy

Because the accompanying geologic maps contain descriptions of all lithologic units mapped in the study area, the following discussion of stratigraphy focuses on stratigraphic relationships, field relationships, paleogeography, and hydrogeologic significance rather than lithology. This section is a synthesis of previous work and our current study.

1. Proterozoic

A great variety of Early Proterozoic units is exposed in the Taos Range and Picuris Mountains; these units are also present in the subsurface of the San Luis basin. In general, the Taos Range contains large areas of plutonic and gneissic complexes (including greenstones), whereas the northern Picuris Mountains are composed of metasedimentary rocks (quartzite, schist, phyllite) in fault contact with granitic rocks to the east. The eastern granitic rock, known as the Miranda granite, is exposed in the ridges between Arroyo Miranda and Rio Grande del Rancho. For more information on the local Proterozoic, see references cited in Montgomery (1953, 1963), Bauer (1988, 1993), Bauer and Helper (1994), Lipman and Reed (1989), and Condie (1980).

Proterozoic crystalline rocks have generally limited primary porosity and permeability. They store and transmit ground water almost entirely through interconnected fractures, including widely distributed microfractures and joints, as well as more localized and linear fracture systems associated with faults. Near-surface local flow systems, intermediate, and deep, regional flow systems can all play roles in the movement of ground water through crystalline rocks, although local flow systems operating in the upper 150 ft or so are the most quantitatively significant (Trainer, 1988). The distribution of Proterozoic units, and specifically the locations and geometries of faults in these rock units, are very important in understanding how, where, and on what time-scale, ground water is transmitted from the mountain recharge areas to the Taos Valley.

2. Paleozoic

Most of the bedrock exposed in the study area consists of Paleozoic sedimentary strata of Mississippian and Pennsylvanian age. If earlier Paleozoic rocks ever covered this area of New Mexico, they were probably removed during Silurian and Early Devonian time (Armstrong and Mamet, 1990). In early Mississippian time, the Taos region was an area of positive relief on the Proterozoic basement. At the end of Osagean time, northern New Mexico was covered by shallow marine waters that deposited a basal sand and carbonates of the Espiritu Santo Formation of the Arroyo Penasco Group. At the end of the Osagean, erosion of these rocks occurred during regional uplift. A thin section of carbonates of the Tererro Formation of the Arroyo Penasco Group then accumulated unconformably on the Espiritu Santo rocks. During latest Mississippian to earliest Pennsylvanian time, all of these sediments were subject to erosion and karsting, before deposition of the thick Pennsylvanian section. For more information on the Mississippian strata, see Armstrong and Mamet (1979, 1990)

In the Talpa area, near Ponce de Leon spring, a thin section of the Mississippian (Osagean) Espiritu Santo Formation of the Arroyo Penasco Group rests unconformably on the Miranda granite. The Espiritu Santo Formation consists of basal Del Padre Sandstone member of thin basal conglomerate, quartz sandstone, and minor limestone beds at top, grading upward into the overlying Tererro Formation. The upper, carbonate-rich part of the Espiritu Santo Formation is mostly absent from the Ponce de Leon springs area.

Major tectonic activity of the Ancestral Rocky Mountains, probably associated with Ouachita deformation to the southeast, occurred during the Early to Middle Pennsylvanian. The Taos area was part of a north-trending trough (the Taos trough or Rowe-Mora basin) located between the nearby Uncompahgre highland to the west, and the Sierra Grande uplift farther to the east. Thick sequences of marine, deltaic, and continental sediments were deposited in the Taos area until late Desmoinesian time when the trough was topped off with arkosic clastic sediments of the Sangre de Cristo Formation during a second orogenic pulse. The trough opened southward across the Pecos carbonate shelf, and so the clastic-dominated Early to Middle Pennsylvanian rocks of the Taos area grade southward into the cyclic carbonate strata of the Pecos area.

Pennsylvanian stratigraphic nomenclature is somewhat complicated by the concurrent use of two sets of names for the same rocks. Read and Wood (1947) named these early to mid-Pennsylvanian, marine sedimentary rocks the Magdalena Group, with a lower Sandia Formation and an upper Madera Formation. After a detailed study of these rocks between Taos and Pecos, Sutherland (1963) rejected these names, and defined three new formations. The Flechado and La Posada Formations represent the northern (deeper marine) and southern (carbonate shelf) equivalents of the Sandia Formation and the lower part of the Madera Formation (the so-called gray limestone member). The overlying Alamitos Formation represents the upper part of the Madera Formation (the so-called arkosic limestone member), and interfingers with the overlying Sangre de Cristo Formation. Although most workers have used Sutherland's names, Soegaard and Caldwell (1990) chose to use the original nomenclature. In this report, we will use Sutherland's names.

Within the study area, the Pennsylvanian strata exposed from the top of the Mississippian section on Cuchilla del Ojo near Ponce de Leon spring eastward into the Sangre de Cristo Mountains is probably entirely Flechado Formation, although a series of large, north-striking faults have repeated and/or deleted parts of the section. The exposures consist mostly of olive, brown, and dark gray shales and siltstones, and low-feldspar sandstones and conglomerates. Limestone is a very minor component of the section. The shales and siltstones are typically poorly exposed, whereas the sandstones are moderately to very well exposed, and the conglomerates and limestones are ridge- and cliff-formers. Casey and Scott (1979) measured sections near Talpa, and concluded that the rocks represent a series of clastic wedges that record an eastward and southeastward progradation of coarse fan-delta lobes in the Taos trough. The fan deltas contain complex interrelationships of thin, laterally discontinuous facies that make traditional mapping of rock-stratigraphic units problematic. The only units that we mapped in detail in this section were limestone beds and thick, ridge-forming sandstone horizons. Both rock types were useful for helping to delineate faults with large separations. For more information on Pennsylvanian sedimentary strata, see Sutherland (1963), Casey and Scott (1979), Casey (1980), Kues (1984), and Soegaard and Caldwell (1990).

Although only a small portion of the study area contains Paleozoic rocks at the surface, it is likely that much of the area is underlain at depth by these rocks. Thus, many geologic characteristics of these rocks are important for understanding the subsurface hydrogeology of the area. For example, the Mississippian section near Ponce de Leon spring contains paleokarst features. Similar Mississippian rocks presumably exist at depth in the basin, and therefore can be considered a possible zone of increased, solution-enhanced permeability. In well-indurated units, fractures and faults play a similar role in transmitting ground water as described above with Proterozoic crystalline rocks. In layered sedimentary strata, faults can also create barriers to ground-water flow either by impermeable segments of the fault itself, or by interrupting a flow path with a less permeable unit. This combination of faulting and layered stratigraphy typically produces compartmentalized aquifer systems with preferential flow paths through the more permeable stratigraphic units.

In 1996, the Town of Taos drilled an exploration well in the town yard, behind the Wal-Mart on Paseo del Norte Sur. At 720 ft, Pennsylvanian sedimentary rocks were encountered. Before the well was abandoned at 1020 ft, 300 ft of limestone, shale, and sandstone had been penetrated. Prior to this well, no control points existed for the location of the Paleozoic section in the southern Taos valley. The well is located nearly two miles from the nearest surface exposures of Pennsylvanian, near Cañon. Clearly, Paleozoic strata exist in the subsurface of the basin, and in places, at shallow depths. The fact that fossiliferous limestone was a prominent lithology in the well cuttings, suggests that the rocks encountered at depth might come from higher in the Pennsylvanian section, perhaps in the upper Flechado Formation or the Alamitos Formation. If so, then Proterozoic basement could lie as much as several thousand feet deeper, because the Alamitos Formation can be over 4000 ft thick, and the Alamitos can be 2500 ft thick in the Taos trough.

The thick section of Pennsylvanian strata of the Taos trough thins westward against the former Uncompahgre uplift, but the rate of thinning, and the location of its termination are unknown (Baltz, 1978). Because of its existence in the Town Yard well, our cross sections (see section A-A') show a reasonably thick Pennsylvanian section that thins westward in the Taos graben.

3. Tertiary

Ingersoll and others (1990) wrote "Cenozoic stratigraphic nomenclature of the study area is extraordinarily complex......due to interfingering of distantly and locally derived nonmarine units of widely differing provenance and lithology. There are many examples of published geologic maps with different stratigraphic units mapped in the same places by different geologists. This confusion of nomenclature results from both the complex stratigraphy and poor exposure of some slightly consolidated lithologies." We agree. However, we also believe that the Tertiary units of the study area are consistent with previous stratigraphic frameworks. Within the area, investigations of Cenozoic geology have been conducted by Manley (1976), Muehlberger (1979), Steinpress (1980), Leininger (1982), Dungan et al. (1984), Aldrich and Dethier (1990), and Ingersoll and others (1990).

Picuris Formation. The oldest Cenozoic unit in the study area is the Picuris Formation; a local package of mostly volcaniclastic sedimentary rocks that represents pre-rift and early-rift activity. It is thought that the early shallow rift basins of northern New Mexico were initially infilled by a combination of volcanic eruptions and volcaniclastic alluvial fans with sources in the San Juan volcanic field to the north (Baltz, 1978). The Picuris Formation probably represents such a deposit (Manley, 1984).

The only previous study of the Picuris Formation divided it into three members; the lower member, the Llano Quemado breccia member, and the upper member (Rehder, 1986). These subdivisions were made by examining and then correlating 11 scattered exposures. This work was a major contribution to understanding this important unit, but we are uncertain of the validity of some the interpretations due mainly to new isotopic ages and the remarkably extensive faulting present in the study area. Although the Llano Quemado breccia is an excellent marker bed, in the Talpa area it crops out as a scattering of fault-bounded exposures (Plate 1) that complicate straightforward stratigraphic reconstructions. Nonetheless, we have retained Rehder's stratigraphy, with the addition of several modifications proposed by Ingersoll and others (1990). These latter workers included the Llano Quemado breccia within the lower member of the formation, renamed Rehder's "upper Picuris Formation" as the "middle Picuris Formation", and included the "upper Picuris Formation" with the lower part of the Chama-El

Rito Member of the Tesuque Formation. We will therefore use Ingersoll and others (1990) nomenclature (Fig. 3) with our new chronostratigraphy.

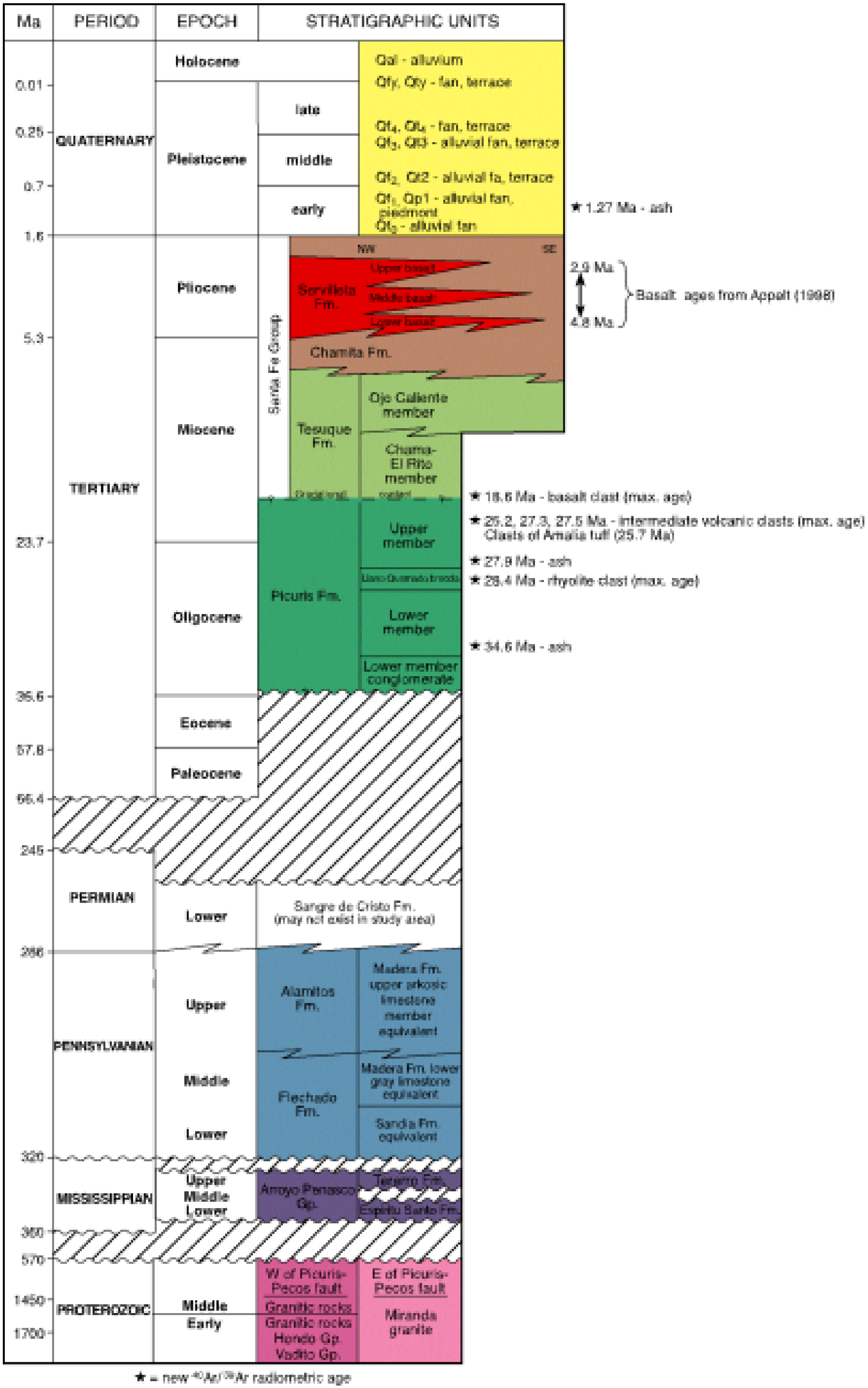
Within our study area, the lower member of the Picuris Formation appears to consist of a basal boulder and cobble conglomerate and conglomeratic sandstone interbedded with thinly bedded sandstones. The boulder unit is distinctive, composed of well rounded, poorly sorted, mostly clast supported, Proterozoic quartzite clasts, with minor altered clasts of intermediate Tertiary volcanic rocks and Paleozoic sedimentary rocks. The boulder unit grades (fines) upward to less indurated pebble conglomerate and conglomeratic sandstone, and variegated green, red, and white siltstone and mudrock. Local layers of primary(?) white to gray to yellow to brown air-fall ash are well sorted and contain sanidine and biotite crystals. This member was interpreted as a sequence of debris flow and alluvial fan deposits derived from the Sangre de Cristo Mountains and Latir volcanic field to the north and northeast (Rehder, 1986). However, as noted below, the deposit (34-27 Ma) cannot be older than the source (26 Ma), and therefore, the volcanic component of the unit was probably derived from the older San Juan volcanic field to the north and northwest. Alternatively, the source could be a buried or eroded, unrecognized, older volcanic unit from the Latir field.

Llano Quemado breccia (perhaps part of lower member) is a light gray to red, monolithologic volcanic breccia of distinctive extremely angular, poorly sorted, light-gray, recrystallized rhyolite clasts in a generally reddish matrix. Rhyolite clasts contain phenocrysts of biotite, sanidine, and quartz. The rock is highly indurated and crops out as a ridge-former. The breccia was interpreted as a series of flows from a now buried, nearby rhyolite vent (Rehder, 1986). However, excellent exposures in Arroyo Miranda display layering and sedimentary structures such as cross bedding that indicate that at least parts of the unit are reworked volcaniclastic sediments.

The middle member of the Picuris Formation (Rehder's upper member) is a gray to pinkish gray, immature, pumice-rich, ashy, polylithologic, conglomeratic sandstone. It consists mainly of sandstones with gravel-sized clasts of pumice and silicic volcanic rocks (mostly 25.7 Ma Amalia Tuff), and minor Precambrian quartzite and intermediate composition volcanic rocks (including the 26.0 Ma Latir Peak quartz latite). Most of gravel-sized fraction is pumice, with some clasts up to 25cm in diameter. Most clasts are rounded to well rounded. Some cobble-rich conglomerates are interlayered with easily eroded, weakly cemented pebble conglomerates. Paleoflow measurements indicate a source to the north, and Rehder (1986) interpreted the unit as an alluvial fan deposit derived from the Latir volcanic field at around 26 Ma (Rehder, 1986). We agree, and would add that a new basalt clast date of 18.59+/-0.70 Ma from the middle member (see below) indicates that at least part of the section accumulated much later. Based on our mapping along the northern Picuris Mountains piedmont, where the tilted, pedimented Tertiary rocks are locally exposed beneath Quaternary fans, we prefer to interpret a continuous section of Picuris Formation to Tesuque Formation, perhaps punctuated locally by unconformities.

The NMBMMR Geochronology Lab recently provided us with several new ^{40}Ar/^{39}Ar isotopic ages for the Picuris Formation (Table 1), which further refine the stratigraphy (Table 1). For the current study, the important geochronological findings are summarized below:

- A white ash that crops out near Talpa, and is interbedded with clastic sediments of the lower Picuris Formation, yielded an age of 34.64±0.16 Ma. This date pushes back the age of the Picuris Formation to early Oligocene, and, if our stratigraphy is correct, it means that the oldest exposed part of the Picuris Formation (Tplc, the basal quartzite boulder conglomerate near Talpa) is older still.
- A rhyolite clast from the Llano Quemado breccia yielded a plateau age of 28.35±0.11 Ma. This probably represents the eruptive age of a rhyolite dome that was later eroded or buried. The breccia is therefore older than any rock known from the Latir volcanic field, the oldest of which is a 26.0 Ma quartz latite that was interpreted as a pre-caldera feeder (Czamanski and others, 1990). Because we believe that the breccia is actually a sedimentary rock, the clast age is therefore a maximum age for the unit.
- A poorly indurated, white ash from south of hill 7365ft was dated at 27.93±0.08 Ma, confirming that parts of the lower Picuris Formation are approximately time equivalent to the Llano Quemado breccia.



- Figure 3. Composite stratigraphic chart for the Taos area.

- Additional new control on the age of the Picuris Formation comes from a vesicular basalt clast from the upper Picuris Formation on the west side of Arroyo Miranda, collected by D. McDonald of the University of Texas at Dallas. The date of 18.59±0.70 Ma is a minimum age due to some argon loss, but nonetheless indicates that Picuris Formation deposition continued into the Miocene, and possibly overlaps in time with the Chama-El Rito Member (18-14 Ma in the Dixon area, according to Steinpress, 1981).

Table 1. New 40Ar/39Ar Geochronology from the Taos Area

Sample #	Ar/Ar age	Unit Name	Rock Type	Analyzed	Lab #	Quad	UTM N	UTM E	Description
RdT-8	34.64 +/- 0.16	Picuris Fm lower	ash	15 sanidine crystals	ASH-23	Ranchos de Taos	4020550	446350	10-cm white ash between lower red and greenish-gray claystones, W of Pete Tafoya's house. Good eruptive age. Coarse-grained, so near source.
Car-7	34.5 +/- 1.2	Picuris Fm?	ash	17 sanidine crystals		Carson	4013600	431070	white ash near Pilar. Sanidines altered. Fine-grained. Confidence uncertain
RdT-4	28.35 +/- 0.11	Picuris Fm, Llano Quemado breccia	rhyolite clast	15 sanidine crystals		Ranchos de Taos	4019200	444900	white rhyolite clast in red groundmass. Good eruptive age.
RdT-5	27.93 +/- 0.08	Picuris Fm, upper?	ash	15 sanidine crystals		Ranchos de Taos	4019200	444900	white ash, poorly indurated, just below RdT-4. Good eruptive age.
PB-3	27.5 +/- 2.0	Tesuque Fm?	volcanic cobble	single flake biotite		Taos SW			Tv cobble in float in Tesuque(?) Fm.
PB-5	27.29 +/- 0.15	Tesuque Fm?	volcanic cobble	single flake biotite		Taos SW			Tv cobble in float in Tesuque(?) Fm.
PB-2	25.16 +/- 0.10	Tesuque Fm?	volcanic cobble	15 sanidine crystals		Taos SW			Tv cobble in float in Tesuque(?) Fm.
RdT-13	18.59 +/- 0.70	Picuris Fm, upper	basalt clast	ground- mass		Taos SW	4016380	443800	David McDonald vesicular basalt sample from upper Picuris Fm layered white tuff. Disturbed spectrum, so minimum date.
TresRitos-1c	5.44 +/- 0.20	basalt	basalt	ground- mass		Tres Ritos	4004600	444300	mildly vesicular basalt outcrop from S or US Hill. Some alteration?
TaosSW-1	1.27 +/- 0.02	Qf2	ash	15 sanidine crystals	ASH-14	Taos SW	4021630	438400	white ash, cross bedded, coarse & fine layers, reworked Plinian. Roadcut on NM-64, .65 mi W of Steakout Rd.

Surface exposures of the Picuris Formation exist only west of the Rio Grande del Rancho (Plates 1 & 3). It is not known for sure whether the Picuris Formation exists in the subsurface of the basin east of the Rio Grande del Rancho, but the numerous well records reviewed in this study do not support its presence there. The presence or absence of the Picuris Formation is important to the hydrogeologic work, as the Picuris Formation and the Santa Fe Group have dissimilar hydraulic properties. Whereas the basal conglomeratic and volcanic breccia units have the potential to store and transmit ample amounts of ground water, the overlying siltstone, mudstone, and middle, immature, ashy sandstone are expected to exhibit low to very low hydraulic conductivities.

In summary, in the map area, the stratigraphy generally agrees with that of Rehder (1986). The base of the Picuris Formation is exposed just west of the mouth of the Rio Grande del Rancho, where a quartz-cobble conglomerate rests unconformably on Pennsylvanian strata. The conglomerate fines upward to a sequence of quartz-pebble conglomerates, sandstones, and siltstones. This part of the section is extensively faulted, by north- and northeast-striking faults. Well data indicate that the basal boulder conglomerate has west-down vertical separation across a series of faults within the Embudo fault zone. The middle volcaniclastic member of the Picuris Formation crops out in the western map area, generally west of Arroyo Miranda. It is extensively faulted in both the Miranda and La Serna fault zones.

Santa Fe Group. Although the Santa Fe Group is not exposed in the study area, it certainly exists in the subsurface of the northern part of the map area. The exact nature of the Santa Fe Group is unknown, although borehole data indicate that relatively thin Quaternary deposits are underlain by thick Tertiary sand and gravel in the basin. Geologists who have examined cuttings from deep exploration boreholes in the Taos area have picked out the Chamita-Ojo Caliente contact, and the Ojo Caliente-Chama-El Rito contact locally in the subsurface. At present, due to the heterogeneity of the Santa Fe Group, and the paucity of petrographic analysis of the cuttings, we believe that within the map area the data are insufficient for constructing isopach or structure contour maps on any of the Santa Fe Group sedimentary subdivisions described below.

Servilleta Formation basalts exist in the subsurface in the northern part of the map area. We have used available well data to constrain the extent of Servilleta basalt in the subsurface, and are also attempting to fingerprint basalt flows encountered in deep boreholes using geochemistry and geochronology.

As rift extension progressed, and normal faulting along the Sangre de Cristo fault offset the Taos Range from the San Luis basin, the volcaniclastic and Precambrian-clast dominated Santa Fe Group began to accumulate in the broad rift basin. The Tesuque Formation (Miocene to Pliocene) of the Santa Fe Group, was originally defined near Santa Fe by Baldwin (1956). In the Picuris Range area, Miller et al. (1963) described this sequence as buff-colored, poorly sorted, weakly consolidated, sand, silt, gravel, volcanic ash, clay, and breccia that ranges in thickness from 500 to 3500(?) ft (150 to 1065(?) m). Much of this unit was derived locally from Paleozoic and Precambrian rocks, and along the flanks of the Picuris Mountains sits unconformably on Precambrian basement. Rock types typically vary considerably along strike.

In the Taos/Pilar area, the oldest Tesuque Formation unit is the **Chama-El Rito Member**, composed predominantly of volcanic-rich, non-fossiliferous sandstone and conglomerate, with minor mudrock interbeds. Conglomerates are generally purplish to gray due to the abundance of pebble-size, intermediate composition, Tertiary volcanic clasts. Sandstones are pinkish-gray to buff, poorly to moderately sorted, with highly variable grain size. Sandstones are transitional between arkoses and volcanic arenites. White beds of calcareous, pyroclastic volcanic ash, less than 2 m thick, are found locally. Fluvial and alluvial sedimentary structures are common. The Chama-El Rito Member, thought to be 18-14 Ma, represents braided stream deposits on a distal alluvial fan derived from a volcanic terrain to the northeast (Steinpress, 1980). The Chama-El Rito Member is locally exposed along the Picuris Mountains piedmont, and we have inferred it in the subsurface in the study area. Thickness in the Dixon area was estimated to be 480 m (1570 ft) (Steinpress, 1980).

The Chama-El Rito Member is conformably below, and interfingers with, the **Ojo Caliente Sandstone Member** of the Tesuque Formation west of the study area, along Rito Cieneguilla, near Pilar (Leininger, 1982; Kelson and Bauer, 1998). The Ojo Caliente is a buff to white, well-sorted eolian sandstone, consisting mostly of fine sand. Tabular crossbeds are common, with some sets over 4 m in height. Transport was from southwest to northeast, approximately 13-12 Ma (Steinpress, 1980). The Ojo Caliente is not exposed in the study area, but probably exists in the subsurface. If so, its lateral extent and thickness are generally unknown, but estimated to range from 30 to 250 m (100 to 820 ft). Based on lithologic interpretations from well cuttings and downhole geophysics, the Town of Taos exploration well along the Rio Pueblo in the northwestern corner of the study area (Well RP-2000, TW-112) penetrated what appears to be a 650-ft interval of primarily Ojo Caliente sands (Drakos and Lazarus, 1998).

During rifting in late Miocene time, high-angle faulting produced deep, narrow, fault-bounded basins that filled with great thicknesses of clastic sediments and volcanic rocks. In the Taos/Pilar area, the clastic sediments are named the **Chamita Formation** of the Tesuque Formation (the name Cieneguilla member has been abandoned), and the volcanic unit is named the Servilleta Formation. To the north of Taos, some workers have used an informal name, the **Lama Formation**, to describe the Tertiary clastic sediments that lie above the upper Servilleta basalt. In light of the fact that alluvial sedimentation was continuous before, during, and after basalt eruptions, and that the eruptions were essentially instantaneous compared to the time involved in sedimentation, we will use the Chamita Formation designation for all of these Pliocene sediments.

The **Chamita Formation** (Miocene and Pliocene) is well exposed in the Pilar area, where it ranges from a lower section of buff-colored, moderate to poorly sorted sands with clasts of intermediate volcanic rock, quartzite, and other metamorphic rocks, to a middle section with fewer volcanic clasts and more metamorphic clasts, to an upper section that is devoid of volcanic clasts. Overall, the unit coarsens upwards. On Pilar Mesa, dips decrease from 30°NW at the base to horizontal at the top, with an internal angular unconformity of about 15° near the top of the exposure. Its contact with the Ojo Caliente Sandstone is interfingering. The upper part of the unit represents an axial drainage off the uplifted Picuris Mountains block at about 8-5 Ma (Ingersoll and others, 1990). Thickness of the Chamita Formation is highly variable and difficult to estimate at any given location. It is also extremely difficult to distinguish the Chamita Formation from overlying Quaternary alluvial deposits, a fact which poses a problem when interpreting lithologies and formational contacts based solely on well cuttings. Thickness has been estimated to range from 100 to 230 m (330 to 750 ft) in the Pilar area (Steinpress, 1980). However, in the Town of Taos exploration well along the Rio Pueblo (Well RP-2000, TW-112), thickness of the Chamita Formation below the lower Servilleta basalt was estimated to be 930 ft (Drakos and Lazarus, 1998).

Nearly flat-lying basalts of the Pliocene **Servilleta Formation** cap the Taos plateau over much of the southern San Luis basin. The basalt is a dark-gray, diktytaxitic olivine tholeiite that erupted as thin, fluid, widespread, pahoehoe basalt flows. Individual flows, which are up to 12 m thick, are grouped into packages of from one to ten flows, and separated by 0.3- to 4.5-m-thick sedimentary intervals (Leininger, 1982). Dungan and others (1984) identified three basalt groups at the Gorge Bridge, a classification that has been adopted by most workers. A lower basalt package consists of two sets of flows totaling 51 m, that locally are separated by up to 4 m of Chamita Formation sediments. A middle basalt of 36 m is separated by a relatively thick, 30-m sedimentary interval from an upper basalt sequence of 30 m. However, the relative thicknesses of the various basalt packages, individual flows, and intervening sediments are quite variable. Limited exposure of the basal basalt in the gorge suggests that flows erupted onto a nearly flat erosional surface of the Chamita Formation. Five central vents to the north are the sources of the flows (Lipman and Mehnert, 1979), which dip gently, thin, and pinch out to the east and southeast. A recent study of isotopic ages of the volcanic rocks of the Taos plateau has shown a range in ages of the Servilleta Formation basalts from 4.81±0.04 to 3.12±0.13 Ma at the Gorge Bridge, and from 4.33±0.02 to 2.93±0.14 Ma at the Dunn Bridge (Appelt, 1998).

The Servilleta basalts have been encountered in many test and exploration wells near Taos, and the eastward lateral extent of at least the uppermost basalt flows can be approximated in map view (Plate 1). The ability of the basalt to transmit water depends upon the extent of fracturing and/or the presence of cooling joints, characteristics that vary amongst individual flows as well as spatially within a single flow. Where the lavas are not fractured or jointed, they are relatively impermeable. The limited data currently available indicate that generally the basalts do transmit water, sometimes in large quantities, although individual flows behave locally as confining units (Winograd, 1959).

The intervening Chamita Formation sediments also vary significantly in their lithologic and hydrologic characteristics. A thick sequence of sandy, gravel fluvial sediments separating the upper and middle basalts, termed the Agua Azul aquifer (Drakos and Lazarus, 1998), is reported to have a transmissivity ranging from 280 to 700 ft^2/day (hydraulic conductivity of 8 to 26 ft/d) at the RP-2000 well (TW-112). In the Karavas 2 exploration well, the intervening fluvial sediments are dominantly sand, with an expected conductivity in the range 0.1 to 1 ft/d. In general, lithologic characteristics of interbedded Chamita Formation sediments range from lacustrine clays to axial fluvial sands and gravels. These sediments would be expected to exhibit hydraulic conductivities ranging from 100 to 10^{-4} ft/d. Owing to the spatially variable hydrogeologic characteristics of the basalts and intervening sediments, it is extremely difficult to characterize their different water-bearing capacities on a basin-wide or even regional scale.

4. Quaternary

Quaternary deposits in the Taos area generally are unconsolidated, make up the shallow aquifers, and provide areas for ground water recharge. The study area contains a variety of coalescent alluvial-fans, stream channel, and terrace deposits that range in age from early(?) Pleistocene to Holocene. In the western part of the study area, surficial deposits (high alluvial fans?) derived from the Picuris Mountains interfinger with alluvial terrace deposits along Rio Grande del Rancho near Talpa. The alluvial fans grade to the highest Servilleta Formation basalt along the southern rim of the Rio Pueblo de Taos gorge (Kelson, 1986). In the central and northern parts of the study area, near-surface Quaternary units consist of coarse-grained fluvial sediments deposited by major streams, and coarse- to fine-grained alluvial-fan sediments derived from smaller, mountain-front drainages. The sandy area contains fluvial and alluvial-fan deposits that range in age from early Pleistocene (1.6 to 0.7 Ma) to recent.

Fluvial sediments are present primarily along the Rio Grande del Rancho, Rio Chiquito, Rio Pueblo de Taos, and Rio Fernando valleys. These poorly sorted sands and gravels contain subrounded clasts of quartzite, slate, sandstone, schist, and granite, and are laterally continuous in a down-valley direction (Kelson, 1986). Soils developed on these deposits associated with older, higher stream terraces (i.e., the terrace beneath the village of Llano Quemado) contain well-developed (stage III to IV) calcic horizons that may impede near-surface infiltration of meteoric water. Younger terraces are associated with lesser amounts of soil development (stage I to II calcic horizons; Kelson, 1986). Because these deposits lack substantial soil development and are located near active watercourses, they allow substantial amounts of surface water to infiltrate into the ground water system. Continuous zones of saturation 15 to 40 ft thick have been identified along the major water courses in the valley (Spiegel and Couse, 1969), and have been shown to be in direct hydraulic communication with the underlying Quaternary alluvial deposits or Santa Fe Group sediments.

Alluvial-fan deposits in the central and northern parts of the study area are derived mostly from smaller mountain-front drainages developed in Pennsylvanian sandstone and shale. In general, these deposits are coarse-grained sands and gravels near the mountain front, and are finer-grained with distance to the north or west. The alluvial-fan deposits likely are laterally discontinuous and moderately heterogeneous. Older fan deposits are associated with well-developed soils (stage III to IV calcic soils), whereas younger deposits contain moderately developed soils (stage I to II calcic horizons) or lesser-developed soils. The younger fans in many places bury older fan deposits, such that subsurface conditions may vary considerably across the mountain-front piedmont. Because of this variability, ground-water flow paths may be complex along the Sangre de Cristo mountain front.

North of Rio Pueblo de Taos, in the northwestern corner of the study area, the Servilleta basalt is overlain unconformably by fine-grained deposits that likely are: 1) the distal parts of older alluvial fans shed from the Sangre de Cristo Mountains; and/or 2) derived from the ancestral Rio Grande (Kelson, 1986). These deposits are poorly exposed, but based on stratigraphic position, are probably middle Pleistocene in age and may have well-developed soils beneath stable ground surfaces.

IV. HYDROGEOLOGY

Given the spatially complex distribution of coalescing Quaternary and Tertiary alluvial and volcanic units along and adjacent to the basin margin, and the combined influence of complex faulting, ground-water flow paths along the southern edge of the Taos Valley are also expected to be quite complex. Evaluating ground-water flow at the basin margin is an important step in determining what recharge mechanisms are active along the margin and at what geographic locations. These data and interpretations are important factors in supporting more quantitative efforts to model ground-water flow in the basin. Piezometric surface maps, when interpreted in a geologic framework, are important hydrogeologic tools, and help identify and evaluate: (1) ground-water flow paths; (2) geologic controls on ground-water flow (structural, stratigraphic, or depositional); and (3) areas receiving or lacking active recharge. A piezometric surface map was developed for the margin of the southern Taos Valley extending from Talpa northeast to Cañon, based on the domestic well inventory presented in Appendix 2. Wells used in creating the map are completed in Pennsylvanian bedrock, Tertiary Picuris Formation, and Tertiary/Quaternary basin fill alluvium. The piezometric contours, developed separately for mountain bedrock and alluvial basin aquifers, are shown on a 1:12,000 geologic base map on Plate 2. A discussion of the piezometric map and basic interpretations are presented below.

A. Mountain Bedrock Aquifers

The piezometric surface map for the mountain bedrock aquifer(s), shown in red contours on Plate 2, is based on 39 wells completed in Pennsylvanian shale, sandstone, and limestone, as well as Tertiary Picuris Formation. The wells range from 118 to 500 ft in depth, and are found from the foothills south of the Embudo fault zone northward to the farthest basinward expression of the fault zone. Approximately half of these wells exhibit artesian or semi-artesian conditions.

Hydraulic gradient in the bedrock aquifers generally follows topography, sloping downward from the mountains toward the basin. Ground-water flow direction is NW at a moderate to high gradient of about 0.1 to 0.7. The hydraulic gradient along the mountain front between the Rio Chiquito and the Rio Fernando is relatively uniform, of moderate grade (0.25 to 0.50), and does not appear to vary significantly with well depth. The most dramatic gradient anomaly occurs along the Rio Grande del Rancho, between Arroyo Miranda and Rio Chiquito where the hydraulic gradient flattens to approximately 0.1. This lower gradient indicates a zone of relatively high hydraulic conductivity and increased ground-water flow in the region bounded by the Miranda and Rio Grande del Rancho faults. This increase in ground-water flow is an expected response to pervasive fault-related fracturing in the well-indurated Pennsylvanian sandstones and limestones and crystalline Proterozoic granite. Geologic mapping noted that fractures near these faults were ubiquitous and open, with only minor carbonate cement present in fractures. Hydrostatic head conditions also seem to prevail in this region, based on apparently uniform hydraulic heads over the upper 360 ft of aquifer in wells TW-1, TW-93, and TW-110.

The Miranda fault exerts significant control on ground-water flow at the mouth of Miranda Canyon, probably due both to (fault related) increased hydraulic conductivity in the Proterozoic granite, and to relatively low conductivity in the abutting portion of the Tertiary Picuris Formation. Piezometric contours are deflected parallel to the fault and indicate that ground-water flows WNW through the Tertiary Picuris Formation at a relatively steep gradient of 0.7. Evidence also exists for a vertical component of flow near the fault, based on a vertically upward gradient of approximately 0.15 between wells TW-26 and TW-73. Further, the discharge of thermal water at Ponce de Leon springs is indicative of both very deep, regional circulation of ground water as well as a vertically upward gradient near Miranda and Cuchilla de Ojo faults. The Picuris Formation exerts significant control on ground-water flow in the Talpa area. Variegated siltstones and claystones present in the lower Picuris typically form a relatively impermeable, confining layer over the basal quartz conglomerate, which can produce significant quantities of water (e.g. well TW-67). In parts of the Rio Grande del Rancho floodplain, some wells go down over 400 ft to get good production from the basal Picuris Formation.

B. Basin Alluvial Aquifer

The piezometric surface map for the basin alluvial aquifer, shown in blue contours on Plate 2, is constructed from data in 38 wells completed in Quaternary and Tertiary alluvial material. With very few exceptions, no distinction is made regarding formation or unit of completion. The wells on which piezometric contours are based range from 82 to 1020 ft in depth, but most are less than 440 ft. The wells are primarily located along the basin margin in the Talpa, Weimer Road, and Cañon areas, with a few wells located outboard from the margin toward the so-called basalt line. Slightly less than half of these wells exhibit artesian or semi-artesian conditions.

The first notable feature of basin-margin water levels is that hydraulic head appears to vary significantly with depth. Based on these limited data, it can generally be noted that wells with mid-screen elevations less than 6,800 ft (wells TW-6, TW-71, TW-83, TW-100, TW-104, and TW-105) exhibit lower hydraulic heads than nearby wells completed over 6,800 ft, indicating a vertically downward gradient in the shallow margin aquifer. This head drop has no readily identifiable lithologic or geologic control, but is observed along the margin between Talpa and Weimer Road, and in the basin east of Ranchos de Taos. There are insufficient data to evaluate the vertical gradient near Cañon. The downward flow component is, however, consistent with a regional pattern of active ground-water recharge beginning at the basin margin and extending basinward for an undefined distance. Only those wells with mid-screen elevations greater than 6800 ft were utilized in constructing the piezometric contours for the alluvial aquifer depicted on Plate 2.

The second notable feature reflected by the piezometric map is the existence of a slightly reversed gradient at the basin margin, that is necessarily accompanied by a piezometric high midway between the Embudo fault zone and the basalt line. The piezometric high, or water table mound, is defined by water levels in wells TW-94, TW-5, and TW-114. The reverse gradient indicates that, at shallow depths along the basin margin, ground water flows south and southeast, back toward the mountains and in a direction opposing the topographic gradient. This reversed gradient does not appear to be just a local phenomenon, rather it is defined by water levels in three, widely distributed wells groups: (1) wells TW-88, TW-87, and TW-84 in the Weimer Road area; (2) wells TW-94, TW-5, TW-14 and TW-72 near Talpa; and (3) wells TW-57, TW-11 and TW-13 north of Weimer Road. This reversed gradient is also suggested by water levels in the extreme western portion of the study area (wells TW-111, TW-109, TW-7, and TW-63 and cross-section B-B'); however, varying depths of completion for these wells preclude a definitive gradient interpretation in this area. The gradient reversal is not observed in deeper alluvial wells (those completed at elevations less than 6800 ft). Anomalously high water levels exist in alluvial wells within the Embudo fault zone (wells TW-4, TW-70, and TW-74), and could reflect local perched conditions within thin Quaternary fan deposits.

Previous work by Spiegel and Couse (1969) produced a piezometric map from data collected in 1957 and 1964-1968, from basin wells in this area, that defined a uniform, NW-trending hydraulic gradient extending from the mountain front into the basin. However, this map contained no data along the basin margin, and made no consideration of depth of completion of the wells, rather contoured water levels from both shallow and deep alluvial wells. This previous map did reflect elevated water levels at locations coincident with the water table mound illustrated on Plate 2. The piezometric high defined in this study is based on fairly limited data, and thus it is uncertain as to whether the water table mound actually extends continuously along the basin margin, or whether it is a localized feature associated with mountain front drainages and the infiltration of stream-derived recharge. It could be that the actual piezometric surface reflects features of both Plate 2 and the map of Spiegel and Couse (1969), wherein the regional basin margin gradient is a NW-trending, mountain-front-to-basin, gradient, punctuated by local water table mounds created by infiltration of stream-derived recharge. A higher resolution water table map extending from the basin margin to the basalt line would be required in order to resolve the question.

C. Water Quality Along the Basin Margin

Although an in-depth evaluation of water quality characteristics of the aquifers was not within the scope of this study, general observations of water quality were made based on information received from well drillers and owners. These observations are of general interest, and provide added support for some of the conceptual hydrogeologic interpretations discussed below. These general observations are as follows:

- Elevated iron (Fe) concentrations are prevalent in deep alluvial wells along the margin (e.g. TW-83).
- Elevated sulfur (S) concentrations and overall poor water quality are common in wells completed in Pennsylvanian shales (e.g., TW-85 and TW-41).
- A trend of warm water wells exists in the Weimer Road area defined by TW-13 (74°F), TW-88 (62°F), and TW-102 (52°F), as well as intervening wells, and appears to be coincident with a major fault strand of the Embudo fault zone.

D. Geologic Controls on Ground-Water Flow

By developing and interpreting a water level or piezometric map within a geologic framework, geologic controls on ground-water flow can be identified. The ground-water study by Spiegel and Couse (1969) interpreted previous water level data to infer the existence of five areas of high transmissivity within the Santa Fe Group sediments, four of which occur in or adjacent to our study area (see Plate 2). Two high transmissivity zones are located in the basin generally along the Rio Grande del Rancho (zones A and B of Spiegel and Couse, 1969), one of which (zone A) is coincident with the water table mound depicted on Plate 2. Two additional high transmissivity zones (zones C and D) are located generally along, but slightly north of the current trend of the Rio Fernando. Spiegel and Couse (1969) suggested these areas were due to the local occurrence of coarser or better-sorted sediments in certain layers of the upper alluvial facies of the Santa Fe Group. We agree, but additionally propose that zones A and B represent a Quaternary/Tertiary axial stream facies, probably present throughout the entire Santa Fe Group, that was deposited by an ancestral drainage associated with the Miranda graben. The Miranda graben, a Laramide structure within the Picuris-Pecos fault system, was certainly an active feature during and since the Tertiary and throughout the tectonic development of the Taos graben. This ancestral drainage has likely provided a significant source of axial stream sediments to the basin since Tertiary time. Whether a similar history is presumable for the Rio Fernando drainage is not as certain. Significant east-west trending faults have been mapped in Pennsylvanian sediments in the Rio Fernando canyon, but there are insufficient data on which to infer a history of movement on the faults. The mere existence of high transmissivity zones C and D coincident with the drainage is itself suggestive that axial stream deposits derived from an ancestral Rio Fernando exist within the Santa Fe Group sediments.

In addition to influencing facies distribution in the developing Taos graben, the basin-margin faults also control current ground-water movement along and across the basin margin. The Embudo fault zone, a complex margin fault consisting of a series of fault strands that step out into the basin, cuts Proterozoic through Quaternary units (see cross-section B-B’) across a zone 2 km wide. The major fault strands have been noted to include broad, clay-rich, gouge zones, particularly in Tertiary rocks, and to anastomose locally around pods of undeformed rock, both features that are likely to reduce permeability perpendicular to the fault. In general, water level data along the basin margin (Plate 2) suggests that the Embudo fault zone impedes but does not prevent the flow of ground water across the fault and into the basin. This is supported by the existence of small springs at several locations immediately upgradient of major strands of the Embudo, as well as the occurrence of significant water-level declines across major fault strands and dry holes at anomalous depths down-gradient of major fault strands (e.g., TW-106 and TW-107). One well, TW-85, observed to be completed at considerable depth (650 ft) within a major strand of the Embudo fault zone, is reported to be an extremely poor producing well. Relatively restricted ground-water flow across the Embudo fault zone is consistent with the existence of a reversed hydraulic gradient at the basin margin; conversely, elevated iron concentrations and poor water quality in alluvial wells at the basin margin is also indicative that a subsurface pathway does exist to move poor quality ground water from the Pennsylvanian sediments, across the fault, and into the basin. Hence, it seems the process is one controlled by relative rates of recharge via different mechanisms.

The large north-south Laramide faults associated with the Picuris-Pecos fault system and the Miranda graben also influence the movement of ground water across the basin margin. In particular, the Miranda fault, the Cuchilla del Ojo fault, and the Rio Grande del Rancho fault, together form an extensive, pervasive fault-related fracture network that increases bedrock permeability and aquifer transmissivity. Water level data (Plate 2) indicate the presence of a zone of anomalously low hydraulic gradient and increased transmissivity encompassing the area between the Miranda fault and the Rio Grande del Rancho fault, and extending across the Embudo fault zone. Because water level data west of the Miranda fault are limited, no inference can be made regarding a continuation of this high transmissivity zone to the west and toward the Picuris-Pecos fault. Based on available data, the area immediately east of the Miranda fault is the only basin-margin location within the study area where there appears to be a significant component of ground-water flow across the Embudo fault zone.

Although data within the basin are insufficient to precisely define how and where these large north-south faults cross the basin, their presence in the basement of the Taos graben can not be questioned. The influence these faults have on basin structure and the geometry of the alluvial aquifers in the Taos Valley is discussed in the context of a basin-scale geologic model presented below in section V.

E. Conceptual Model of Mountain Front Recharge

In the previous sections concerning the regions aquifers, we have presented much discussion on the subject of recharge. However, because the topic is critical to current and future efforts to quantify ground-water flow, availability and impacts of development, a brief summary of the findings of this study regarding recharge to the alluvial basin aquifer is also presented here. The recharge processes evaluated in this study have focused on mountain front processes that may be active along the basin margin, specifically subsurface inflow of ground water from the mountains, mountain-stream-channel recharge, and arroyo-channel recharge. The method used to evaluate which recharge mechanisms may be active in specific geographic areas integrates geologic data, hydrologic data, and to a limited extent, qualitative hydrogeochemical data.

The importance of mountain-stream-channel recharge as a significant recharge component to the alluvial aquifer in the Taos Valley has been recognized since the earliest ground-water studies of the area (Bliss, 1928; Winograd, 1959; Spiegel, 1962; Spiegel and Couse, 1969). It is clear that the major perennial streams in the study area, Arroyo Miranda, the Rio Grande del Rancho, the Rio Chiquito, and the Rio Fernando, all contribute a significant volume of recharge to the shallow alluvial aquifer after they cross the basin margin fault system(s) (Embudo fault zone or Sangre de Cristo fault) and flow across the coarse, proximal, alluvial fan deposits. Hydraulic connection and interaction between the stream-course aquifers and the underlying/adjacent Santa Fe Group aquifer has also been shown in previous studies (e.g., Spiegel and Couse, 1969; Cooper, 1972; Drakos and Lazarus, 1998). An additional finding of this study is the significant potential for the major fault-controlled stream systems such as the Rio Grande del Rancho to affect the distribution of highly permeable axial stream deposits throughout the entire Santa Fe Group formation, and thus provide a mechanism and window for mountain-stream-channel recharge to contribute not only to the shallow alluvial aquifer, but also to the deep underlying system. Arroyo-channel recharge is also an active recharge mechanism to the shallow aquifer along the basin margin, but on a significantly smaller volumetric scale than mountain-stream-channel recharge.

The importance of subsurface inflow as a significant recharge mechanism in the Taos Valley has not been addressed in any previous work. Indeed, most hydrogeologists have probably assumed that subsurface inflow across the margin faults is negligible, and for most of the basin margin this assumption is likely a reasonable one. However, considerable geologic and limited hydrologic data indicate that subsurface inflow may be a very significant component of recharge at certain geographic locations. In this study area, the region between the Miranda fault and the Rio Grande del Rancho fault is shown to be such an area.

In summary, we present a simple conceptual model of mountain front recharge along the basin margin between Talpa and Cañon. The area between the Miranda fault and the Rio Grande del Rancho fault is the most significant recharge window along the portion of the basin margin evaluated in this study. Both mountain-stream-channel recharge and subsurface inflow are highly active mechanisms in this area, and together must contribute volumetrically significant amounts of ground-water recharge to the shallow alluvial aquifer and potentially to the deeper alluvial system in the Taos Valley. The contribution this recharge provides to the Taos Valley aquifers is potentially augmented by the presence of highly transmissive axial stream deposits at depth throughout the Santa Fe Group sediments at this location. Data are insufficient to evaluate recharge along the margin west of the Miranda fault; however, the presence of thick sequences of lower Picuris formation throughout Arroyo Miranda may certainly limit subsurface inflow in that area, and mountain-stream-channel recharge is an active mechanism only along Alamo Arroyo. The basin margin between the Rio Grande del Rancho and the Rio Fernando lacks an active recharge mechanism that can provide significant volumes of ground water to the basin, as both mountain-stream-channel recharge and subsurface inflow are negligible in this area. Arroyo-channel recharge, the only active mechanism here, generally contributes relatively small volumes of recharge. The Rio Fernando, like the Rio Grande del Rancho, is also a significant source of mountain-stream-channel recharge, and may potentially contribute some subsurface flow. Additional geologic and/or geophysical data are required to more fully evaluate the east-west faults in the Rio Fernando canyon and assess their potential for providing a significant pathway for subsurface flow across the margin.

V. PRELIMINARY BASIN-SCALE GEOLOGIC MODEL

Our basin-scale geologic model is based on a 1:24,000 tectonic map that we compiled from the following data sources:

1) Our new 1:12,000 geologic maps and cross sections.
2) The Taos SW 7.5-min quadrangle geologic map of Bauer and Kelson (1997).
3) Selected fault data from Machette and Personius (1982) 1:250,000 map, Kelson (1986), and Kelson and others (1997).
4) Residual gravity data of Cordell and Keller (1984).
5) Residual total-magnetic intensity map of Cordell and Keller (1984).
6) Geomorphologic data from Dungan and others (1984).
7) Public domain well records from the NMOSE files.
8) Select Town of Taos exploration well records.
9) Select Pueblo of Taos/BIA well records.
10) Shallow seismic reflection surveys by C. Reynolds for BIA, dated 5/27/86 and 5/18/92.
11) Locations of springs from USGS topographic maps, Garrabrant (1993), Johnson (1998), and our analysis of aerial photography.
12) Geologic cross sections from Glorieta Geoscience and John Sorrell (formerly of the BIA).
13) A variety of published papers and M.S. theses.

The tectonic map represents a first attempt at integrating all of the geologic, geophysical, and subsurface data that are available (Plate 4). A comprehensive evaluation of these data sources and the details of the tectonic model are beyond the scope of this report.

The model is limited by some data sources. The major limitation is that no detailed geologic maps exist adjacent to our field area. In addition, parts of the gravity data of Cordell and Keller (1984) may be insufficient to resolve moderately sized rift structures in the Taos area. For example, the Town Yard well suggests the presence of the buried Town Yard bench, which is not expressed in the regional gravity data. In addition, if extensive Paleozoic and early Tertiary rocks exist in the subsurface beneath the Taos valley, gravity models probably need to be recalibrated because published depth-to-basement estimates could be incorrect. Nevertheless, Plates 4 & 5 show the most up-to-date tectonic model using all the available data.

A. Taos Graben

The Taos graben, which was first recognized by Cordell (1978) from gravity data, is the major structural feature in the Taos area, and probably is the key to deciphering the great variety of surficial geologic and physiographic features in the region. At the latitude of Taos, the north-south graben is approximately 13 km (8 mi) wide, making the main rift graben considerably narrower than the topographic valley (about 32 km, 20 mi wide). The deepest part of the graben is just west of Taos Pueblo, where the depth to Precambrian basement rocks is estimated at over 5000 m (16,400 ft) from gravity data (Keller and others, 1984).

The western edge of the graben is a buried fault zone (herein named the Gorge fault zone) that appears to underlie the Rio Grande gorge. Tectonic surface expression of the Gorge fault zone in the area is scarce. The Dunn Bridge fault, which is exposed in the gorge near the Dunn Bridge, a normal, east-down, north-striking, 35 m scarp that has formed in the last 3.5 Ma (Dungan and others, 1984). Recent mapping in the Carson quadrangle by Kelson and Bauer (1998) identified an east-facing fault scarp that branches from the Embudo fault near Pilar, and extends northward towards the Dunn Bridge fault. A large number of springs, including Manby hot springs, exist along the Rio Grande between Taos Junction bridge and near the Red River. It is likely that at least the hot springs owe their existence to the buried Gorge fault zone.

The position of the Rio Grande and its gorge probably is related to the existence of the Gorge fault zone and the western edge of the Taos graben. Dungan and others (1984) concluded that the position of the river is "controlled by a combination of overall east-tilting of the plateau, westward prograding alluvial fans, and the local control exerted by the faults, which in turn are surface manifestations of the deep Taos graben". The gentle east tilt of the plateau likely forced the ancestral Rio Grande eastward, while the prograding fans probably constrained the amount of eastward migration. Possibly, the Rio Grande incised above the Gorge fault due to the existence of a now-eroded, north-trending fracture zone in the basalts above the fault zone.

The Taos graben was mostly formed by the time the lower Servilleta basalt erupted about 4.5 Ma. On the Taos Plateau, the Rio Grande was superposed on the plateau after eruption of the youngest Servilleta basalts (ca. 3 Ma), and began to rapidly entrench upon integration of the river system at approximately 0.5 Ma (Wells and others, 1987). Although most of the high-angle faults on the plateau did not cause thickening or thinning of volcanic flows across the faults, evidence exists for active rift faulting during the time that the Servilleta basalts were erupted and the interlayered Chamita sediments were accumulating (Peterson, 1981; Dungan and others, 1984). A notable example is found at the Dunn Bridge fault where the sedimentary interval between the middle and upper basalts increases 17 m (56 ft) across the fault.

The eastern edge of the Taos graben correlates with mapped and inferred structures of the Sangre de Cristo fault zone. Gravity data as interpreted by Reynolds (1992), showed a complex eastern fault zone that generally steps down into the graben. Reynolds (1986, 1992) also performed shallow seismic reflection surveys over parts of Taos Pueblo, interpreting a complex system of buried faults along the Cañon section of the fault zone, including some small-scale horst and graben geometries. We have not mapped in any of the areas covered by the Reynolds surveys, but we believe that evidence exists for a southward extension of such structures into our map area. In 1996, the Town of Taos drilled an exploration water well at the Town Yard, southwest of Taos (Plate 1). At about 600 ft, a 70-ft-thick basalt was encountered, and at 720 ft Pennsylvanian sedimentary strata were encountered. Drilling ceased after penetrating 300 ft of the Pennsylvanian section. Just to the northeast of the Town Yard well is a spring that is shown on the USGS Taos quadrangle. The existence of shallow bedrock and the spring is consistent with a large, NNE-trending structural bedrock high (herein called the Town Yard bench) present in the subsurface. The bench corresponds with a strong gravity gradient, and projects northward along the western edge of Buffalo Pasture wetland area of Taos Pueblo. The western boundary fault of the bench also projects southward into the Picuris-Pecos fault system mapped south of the Embudo fault zone. We have not found any surface expression of the western boundary fault (herein named the Town Yard fault) of the Town Yard bench within our map area. We suspect that this buried structure has an impact on ground water flow in the Taos area, and may represent a reactivated part of the Miranda fault zone to the south. We do not know the exact configuration of the structural bench, and have shown a speculative location on the maps (Plate 4).

The Taos graben appears to be shallower and narrower north of Arroyo Hondo. These complexities might be related to the western part of the Questa caldera, which now is buried within the rift in the Questa area. To the south, the Taos graben terminates against the Embudo fault zone in some unknown manner. The gravity map shows that the gravity gradient along the southern extension of the Gorge fault zone shallows such that there is no clear intersection of the graben and the Embudo fault zone. Bauer and Kelson (1997) and Kelson and Bauer (1998) showed an unnamed east-down fault that may represent the southernmost extension of the Gorge fault. This fault intersects the Embudo fault on Pilar mesa, coincident with a change in strike of the Embudo fault from E-W to NE-SW (see Kelson and others, 1997). Part of the eastern intersection is exposed where we have mapped the Cañon section joining the Embudo fault near Talpa. However, the gravity data indicate that the master rift-boundary faults probably are buried beneath Taos, and we have no field control on their southern terminations. Reynolds (1992) depicted the borders of the Taos graben as deflected westward into the Embudo fault zone. However, gravity data tend to smooth angular features. Based on surface exposures near Talpa, we suspect that the buried bedrock (Tertiary and older) north of Talpa is broken into a checkerboard pattern of fault blocks due to the superposition of north- and east-striking fault systems. Such a pattern may have profound implications for ground water flow.

A variety of other surficial geologic and geomorphic features appear to be associated with the Taos graben. These include Los Cordovas faults, the Gorge arch and associated flexures, stream asymmetries, and certain linear drainages.

Los Cordovas faults are located above the deepest part of the Taos graben. The faults are rather uniformly spaced, barely diverge from a north-south trend, are nearly all west-down, and appear to terminate to the north and south. Lambert (1966) noted that they are directly on trend with both the Picuris-Pecos fault to the south, and the Sangre de Cristo fault to the north, but failed to speculate on a possible connection. As stated earlier, we believe that the Picuris-Pecos fault system exists in the subsurface of the Taos graben. We do not know their locations, but we agree with Lambert that Los Cordovas faults could be related to them. The fact that the Los Cordovas faults are short, west-down, and are located over the deepest part of the suggests that they could be antithetic, west-dipping faults that intersect the Taos graben at depth. On the cross sections, we have chosen to speculatively show the major strands of the Picuris-Pecos fault system as major, Laramide, rift-reactivated structures that shallow into the Pleistocene Los Cordovas faults.

A number of very gentle, broad flexures (Gorge arch and other folds on Plate 4) have been identified in the Taos area (Muehlberger, 1979; Peterson, 1981; Dungan and others, 1984; Personius and Machette, 1984). These interpretations were based on drainage patterns and stream asymmetries on the Taos plateau. Dip changes in the basalt horizons are imperceptible in the field. In the eastern Taos Plateau, Peterson (1981) identified seven domains of similarly oriented asymmetrical valleys, and suggested that the warping occurred after emplacement of the Servilleta basalts. Interestingly, the two primary flexures, the Gorge arch and the syncline along the Rio Pueblo de Taos, are parallel to the Embudo fault zone, and bracket the deepest part of the Taos graben and Los Cordovas fault. We suspect that the flexures are a surface manifestation of the complex subsurface fault geometry, but because our subsurface and kinematic data are inadequate, any coherent conceptual model is poorly constrained.

B. Embudo and Sangre de Cristo Fault Zones

Previous workers have suggested that the Embudo fault zone is a relatively young rift feature that corresponds with the initial uplift of the Picuris Mountains in the late Miocene (Manley, 1978; Ingersoll and others, 1990). Our mapping shows that there is no distinct boundary between the Embudo fault zone and the Cañon section of the Sangre de Cristo fault zone. The Embudo zone swings smoothly northward in the Talpa area to merge with the Cañon section. The most reasonable explanation is that the Embudo and the Cañon section of the Sangre de Cristo faults are the same age. Kelson and others (1997) suggested that the Embudo and Sangre de Cristo faults both exhibit evidence of Holocene activity. Thus, there are three ways to view the kinematic history: 1) the Embudo fault (and therefore the uplift of the Picuris Mountains) is older than late Miocene; 2) at least parts of the Sangre de Cristo fault zone are also young; or 3) some combination of numbers 1 and 2. Our current working hypothesis is that the crescent-shaped Taos valley embayment, defined by the Cañon section on the east and the east edge of the Taos graben on the west, formed in partnership with the Embudo transfer zone, in early Miocene time. If so, the pre-early Miocene eastern edge of the rift was defined, from north to south, by the Sangre de Cristo fault zone north of the Rio Hondo, the buried eastern edge of the Taos graben (i.e., Town Yard fault), and the Picuris-Pecos fault system of the Miranda graben.

C. Servilleta Basalts

The Servilleta basalt strata have a profound effect on ground water flow (Winograd, 1959; Drakos and Lazarus, 1998). Using existing borehole data, we have attempted to define the outline of basalt flows in the subsurface (Plates 1 and 4). In the map area, boreholes provide enough information to constrain at least the youngest basalt unit. Not surprisingly, the basalt line closely parallels the edge of the basin and the fault zones. Surprisingly, at least the youngest basalts exist in the subsurface as far east as the center of Taos. Not enough deep boreholes exist to evaluate the extent of any older flows in the map area.

We have chosen not to interpolate basalt flow geometry between boreholes on all of the cross sections. The thicknesses of basalt intervals and locations of sedimentary interbeds are highly variable over the Servilleta volcanic field. This is best illustrated by the basalt stratigraphy in the Rio Grande gorge and comparative measured sections in the gorge and tributary canyons (figures 5 and 7 in Dungan and others, 1984). The main Servilleta stratigraphy of lower, middle, and upper basalt members appears to hold up over much of the Taos Plateau, and we are performing geochemical analyses of borehole cuttings in order to evaluate basalt stratigraphy in the Taos Valley.

In his 1989 Taos Pueblo geological/geophysical review, C. Reynolds stated that the thickest basalts were located on the horst/bench to the west of the Taos graben. We are not sure how he determined thicknesses. Intuitively, we would expect that lavas travelling southeastward from their eruptive vents would tend to pool in the low areas, such as over the Taos graben. The fact that some of the basalts flowed as far as Taos means that they must have pooled in the valley in order to flow "uphill" to onlap the eastern alluvial fans.

D. Picuris-Pecos Fault System

The five N-S fault zones of the Picuris-Pecos fault system in the southern map area form a 5-mile-wide zone of high strain in rocks that range in age from Early Proterozoic to less than about 18 Ma. Based on our preliminary mapping, there is no evidence for similar fault zones to the immediate east and west. This concentrated zone of high-angle faulting has probably had a long history of reactivation as both strike-slip and dip-slip systems. We postulate that the faults that juxtapose young rocks (e.g., Picuris Formation) might look like the Picuris-Pecos fault (which juxtaposes Proterozoic rocks) at deeper structural levels. Because the older members of the Picuris Formation are restricted to the fault zone, we suggest that the fault zone defined an Eocene(?) to early Miocene graben (Miranda graben) that served as a locus of deposition for volcaniclastic sediments shed from the north. At least parts of the graben have remained low during the Neogene, preserving these unusual rocks. One consequence of this theory is that at least parts of the Picuris Formation are restricted to the graben and its buried expression under the Taos valley.

It is likely that the Rio Grande rift used this crustal flaw during early rifting. The faults that cut the youngest rocks (ca. 18 Ma Picuris Formation) are strike-slip, and may represent pre-Embudo transfer zone rift kinematics. At that time, the eastern edge of the San Luis basin continued north along the Sangre de Cristo Mountain front. At some later time (mid-Miocene?), the Embudo fault zone and the Cañon section formed, and this section of the Picuris-Pecos fault system has been inactive ever since.

The cross sections (Plates 1 &3) show these older N-S faults as deep pre-cursors to the major Los Cordovas fault strands. Such a correlation is speculative, but reasonable, as the N-S faults project northwards into the similarly spaced and oriented southernmost Los Cordovas faults that are exposed along the Rio Pueblo de Taos.

Only a few hot springs exist in the Taos area. Ponce de Leon springs are located at the intersection of the Miranda and McGaffey faults, in Proterozoic granite and pegmatite. The water is approximately 91°F, and flows at about 300 gpm, and probably represents a deep convective system. If so, the Miranda fault is a deep-seated structure, and perhaps represents the fossilized southern extension of the Town Yard fault.

E. Unconfirmed East-Striking Fault System

There is some suggestion of a significant east-west fault system in the Taos area. The linearity of the Rio Fernando, Rio Pueblo, and upper Rio Lucero may be due to east-striking faults. Although we have not mapped the bedrock north of the southern Taos Pueblo boundary, our reconnaissance work in Pennsylvanian rocks along the Rio Fernando found near-vertical, east-striking, strike-slip faults (see Plate 1). Other workers have found high-angle, east-striking faults in the Sangre de Cristo Mountains east of the pueblo. The north boundary of the Taos Pueblo buffalo fields is an east-trending vegetative lineament that contains many small springs and seeps (Plate 4), and may represent a shallowly buried fault. In addition, based on shallow seismic reflection surveys, Reynolds (1989, 1992) postulated buried east-striking faults in the Taos Pueblo that appeared to be crosscut by north-striking rift-style faults. If such a set of east-striking faults exists, they probably influence recharge in the mountain/piedmont zones of the Taos Range, and affect ground water flow in the Taos valley.

VI. RECOMMENDATIONS AND DATA NEEDS

We view this investigation as an initial step in deciphering the geology and hydrogeology of the Taos area. We believe that any investigation of ground water resources should be solidly based in the best, most detailed, geologic maps available. In an area as structurally and stratigraphically complex as Taos, where basinal structures and bedrock are covered, the chronology of deposition and deformation must be understood. Our approach has been to produce detailed geologic maps, and then incorporate all other data sources into a geologic model that allows one to predict the subsurface environment, and therefore better assess the behavior of ground water. However, we have been limited by a variety of inadequate data sources, mostly related to subsurface geology and hydrogeology.

This section presents a list of recommendations for additional data collection for both our study area and for the Taos valley in general. Ultimately, such studies will permit a better evaluation and quantification of ground water availability in the Taos valley.

A. Specific Data Needs In Our Study Area

1. Town Yard structural bench. We have tentatively identified a large north-trending structural bench (the Town Yard bench) that probably extends from the Ranchos de Taos area northward to the Buffalo Pasture area of Taos Pueblo. The bench is a major basement high that affects ground water availability. To date, the only direct evidence of its existence is through a Town of Taos water well that encountered bedrock at a shallow depth. We do not know whether the bench steps up to the mountains, or whether it represents a horst with a deep sub-basin between it and the mountains. We believe that much could be learned about this structure through a simple, quick, inexpensive gravity survey. Such a survey would involve approximately two months of data collection and a month of follow-up computer processing and modeling. If properly done, such a survey would provide excellent controls on subsurface faulting and thickness of basin fill. If the bench can be successfully mapped by geophysics, exploration boreholes and water supply wells could then be optimally located.

2. Water well inventory. We have found that trying to incorporate borehole data into our study is a frustrating and hugely time-consuming task, oftentimes with dubious results. When well records can actually be located, they are commonly inadequate. Although the Taos area is the focus of a lengthy and expensive adjudication process, there apparently exists no database of boreholes. Well records for the deep exploration wells and municipal wells can not be easily found, in spite of the fact that they provide the best information available for solving hydrogeologic problems. Similarly, many shallow domestic wells are not on file at the Office of the State Engineer, and most of the available logs are improperly located and logged by the driller. Clearly, a digital database of all available data is a necessity. Such a database should contain the essential data, such as well number, location (including UTM coordinates), driller, date of completion, depth of completion, water level, etc. Ideally, the database would eventually be tied into topographic maps through a GIS system. Such a system could easily be expanded in the future to include other parameters, such as water chemistry, water quality, etc.

3. Geologic mapping. Our field mapping was limited to the upper piedmont slope, along the basin/mountain interface. Within our study area, detailed mapping should be done in the basin and along the mountain front. Such mapping will provide valuable information concerning the nature of Los Cordovas faults, the Servilleta basalts, the tectonic geomorphology of the valley, basement fault geometries, and Pennsylvanian stratigraphy. All of which would help to better constrain the geologic and hydrogeologic models.

B. General Data Needs For The Taos Valley Area

1. General geologic needs

Geologic mapping of the rest of the Taos valley. Ultimately, the remainder of the Taos area, including the Arroyo Seco and Arroyo Hondo areas, should be mapped in detail. Until such mapping is completed, attempts to model the geometry and hydrogeology of the basin will be limited by incomplete data.

Fault analysis. We did not attempt a kinematic analysis of the various generations of faults in bedrock units. Such work would help to determine when and how faulting occurred. This in turn, would help us to better evaluate the geologic history and to better visualize the 3-D architecture of the basin.

2. Geophysical

Geophysical surveys. In our map area, and over most of the Taos valley, the only geophysical data available are regional gravity and magnetic surveys. More focused studies using gravity, high-resolution aeromagnetics, seismics, and other techniques could help resolve subsurface structure and stratigraphy. In addition, the type of deep geothermal well logging that Dr. Marshall Reiter (NMBMMR) is currently doing in the Albuquerque basin would add useful insights into the communication and interaction between the shallow and deep aquifer systems.

3. Hydrologic

Ground water chemistry and age determination. Very little geochemical data exist for the Taos-area aquifers. Existing data are totally insufficient to support a thorough evaluation of water quality or ground-water residence times in the shallow or deep alluvial aquifers. The limited geochemical data that do exist indicate that water quality diminishes with depth and that the deep and shallow aquifer systems have unique geochemical signatures (Drakos and Lazarus, 1998). Thus, geochemical data will provide important insight for characterizing the ground-water flow system. Water quality and geochemical data should be gathered in a widely spaced network of existing shallow and deep alluvial wells completed throughout the Santa Fe Group and stream-course aquifers. Analyses should include general chemistry, trace element chemistry, stable isotope chemistry ($^{2}H/^{1}H$ and $^{18}O/^{16}O$), and age determination sampling that should include at a minimum ^{3}H and ^{14}C, and if possible, CFCs.

Evaluation of stream losses and gains. Several ground-water studies have shown that the perennial streams in the Taos Valley are hydraulically connected to shallow stream-course and Santa Fe Group aquifers, and mountain-stream-channel and arroyo-channel recharge are known to be important mechanisms of mountain-front recharge to the ground-water systems. On the other hand, surface water data indicate that certain reaches of the Rio Pueblo de Taos as well as other major perennial streams (Red River, Rio Hondo, Rio Grande) gain flow due to ground-water accretion. An evaluation of stream/aquifer interaction is necessary to understand both the ground-water and surface-water systems, and to quantify ground-water and surface-water availability. Identification of critical stream reaches that are subject to infiltration or accretion will improve water balance estimates and help validate ground-water model results. This evaluation should include the following elements:

(a) First, estimate stream gains and losses between intervening gage stations by analyzing existing **daily** discharge data. Estimates derived from daily discharge data will be more accurate and informative than previous estimates derived from annual discharge data, and will help guide identification of critical stream reaches requiring additional study.

(b) Second, conduct seepage runs at various low to intermediate discharges along critical reaches of the Rio Pueblo and its tributaries. Seepage runs, which consist of measuring discharge at intervals along a channel reach during a period of low or base flow, will identify if and where significant channel losses or gains occur, and will quantify surface-water/ground-water exchanges. Discharge measurements should be accompanied by measurements of specific conductance and temperature to extend usefulness of the data and confidence in interpretations. Because seepage runs can give different results at different times, seasonal or even monthly measurements should be taken over the course of a year.

Exploration wells. The future installation of deep exploration wells should: first, be directed by geologic criteria derived from previous geologic studies; and second, be accompanied by detailed geologic and geophysical logging, and petrographic analysis of samples by geologists familiar with the stratigraphy and rock formations of the area. In addition, core samples should be collected for laboratory analysis of additional hydraulic parameters to include porosity, grain size analysis, and saturated hydraulic conductivity.

Borehole measurements for vertically-distributed hydraulic conductivity. The most important hydraulic parameter required to support three-dimensional (or quasi three-dimensional) ground-water flow models is the hydraulic conductivity distribution. Traditional pumping tests provide estimates of vertically-averaged hydraulic conductivity. However, the three-dimensional or quasi three-dimensional models that are required for basin-scale ground-water flow modeling require vertically-distributed hydraulic conductivity, or in other words, the horizontal hydraulic conductivity as a function of vertical position. This is particularly important for simulating ground-water flow in layered sedimentary aquifers such as the shallow alluvial aquifer in the Taos area. The ability of a ground-water model to confidently predict impacts to the Rio Grande from pumping shallow or intermediate-depth wells on the piedmont would be greatly improved with good vertically-distributed conductivity data. Future aquifer characterization efforts in the Taos area should include applying one of the simple, inexpensive, borehole methods for making vertically-distributed measurements of hydraulic conductivity in new and existing wells. The most practical methodologies (Molz and others, 1990) are flowmeter tests (Hess, 1986; Morin and others, 1988; Molz and others, 1989) and multi-level slug tests (Zlotnik and McGuire, 1998). New technologies are emerging all the time in response to the need for this type of data.

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VIII. REFERENCES CITED

Aldrich, M.J., Jr., 1986, Tectonics of the Jemez lineament in the Jemez Mountains and Rio Grande rift: Journal of Geophysical Research, v. 91, no. B2, p. 1753-1762.

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

Aoki, K., 1967, Petrography and petrochemistry of latest Pliocene olivine-tholeiites of the Taos area, northern New Mexico, U.S.A.: Contributions to Mineralogy and Petrology, v. 14, p. 191-203.

Appelt, R. , 1998

Armstrong, A.K. and Mamet, B.L., 1979, The Mississippian system of north-central New Mexico: New Mexico Geological Society Guidebook 30, p. 201-207.

Armstrong, A.K. and Mamet, B.L., 1990, Stratigraphy, facies, and paleotectonics of the Mississippian system, Sangre de Cristo Mountains, New Mexico and Colorado and adjacent areas: New Mexico Geological Society Guidebook 41, p. 241-249.

Baldwin, B., 1956, The Santa Fe group of north-central New Mexico: New Mexico Geological Society Guidebook 7, p. 115-121.

Baltz, E.H., 1978, Resume of Rio Grande depression in north-central New Mexico; in J.W. Hawley, ed., Guidebook to Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 210-228.

Bauer, P.W., 1988, Precambrian geology of the Picuris Range, north-central New Mexico [Ph.D. Dissertation]: New Mexico Bureau of Mines and Mineral Resources, Open-File Report OF-325, 260 p.

Bauer, P.W., 1993, Proterozoic tectonic evolution of the Picuris Mountains, northern New Mexico: Journal of Geology

Bauer, P.W. and Helper, M., 1994, Geology of the Carson 7.5-minute quadrangle, Taos County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map GM-71, scale 1:24,000.

Bauer, P.W. and Kelson, K., 1997, Geology of the Taos SW 7.5-minute quadrangle, Taos County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-File Digital Geologic Map OF-DM 12, scale 1:12,000.

Bauer, P.W. and Kelson, K., in prep., Geology of the Ranchos de Taos 7.5-minute quadrangle, Taos County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-File Digital Geologic Map OF-DM 33, scale 1:12,000.

Bauer, P.W. and Ralser, s., 1995, The Picuris-Pecos fault – Repeatedly reactivated, from Proterozoic(?) to Neogene; New Mexico Geological Society Guidebook 46, p.

Bliss, J.H., 1928, Seepage study on Rio Grande between State line bridge, Colorado, and Embudo, New Mexico, and between Alamosa, Colorado, and Embudo, New Mexico: New Mexico State Engineer, Ninth Bienn. Report, 1928-1930, July 1928, p. 27-40.

Casey, J.M., 1980, Depositional systems and basin evolution of the Late Paleozoic Taos trough, northern New Mexico [Ph.D. dissertation]: Austin, University of Texas, 236 p.

Casey J.M. and Scott, A.J., 1979, Pennsylvanian coarse-grained fan deltas associated with the Uncompahgre uplift, Talpa, New Mexico: New Mexico Geological Society Guidebook 30, p. 211-217.

Cather, S.M., 1992, Suggested revisions to the Tertiary tectonic history of north-central New Mexico; New Mexico Geological Society, Guidebook 43, p. 109-122.

Chapin, C.E., 1979, Evolution of the Rio Grande rift-a summary: in Riecker, R.W., ed., Rio Grande rift-tectonics and magmatism: American Geophysical Union, Washington, D.C., p. 1-5.

Chapin, C.E. and Cather, S.M., 1994, Tectonic setting of the axial basins of the northern and central Rio Grande rift, in Keller, G.R. and Cather, S.M. (eds.), Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting, Geological Society of America Special Paper 291, p. 5-25.

Chapin, R.S, 1981, Geology of the Fort Burgwin Ridge, Taos County, New Mexico: M.S. thesis, University of Texas at Austin, 151 p.

Condie, K. C. (1980). Precambrian rocks of Red River–Wheeler Peak area, New Mexico. New Mexico Bureau of Mines and Mineral Resources Geologic Map 50, scale 1:48,000.

Coons, L. M., and Kelly, T. E., 1984, Regional hydrogeology and the effect of structural control on the flow of groundwater in the Rio Grande Trough, northern New Mexico. New Mexico Geological Society, 35th Field Conference, New Mexico Bureau of Mines and Mineral Resources, p. 241–244.

Cooper, J.B., 1972, Letter Memorandum from James B. Cooper, U. S. Geological Survey, to R. W. Fife, U. S. Bureau of Reclamation, re well data and production characteristics of San Juan-Chama exploration wells, May 22, 1972, 8 pp.

Cordell, L., 1978, Regional geophysical setting of the Rio Grande rift: Geological Society of America Bulletin 89, p. 1073-1090.

Cordell, L. and Keller, G.R., 1984, Regional structural trends inferred from gravity and aeromagnetic data in the New Mexico-Colorado border region: New Mexico Geological Society Guidebook 35, p. 21-23.

Czamanski, G.K., Foland, K.A., Kubacher, F.A. and Allen, J.C., 1990, The 40Ar/39Ar chronology of caldera formation, intrusive activity and Mo-ore deposition near Questa, New Mexico: New Mexico Geological Society Guidebook 41, p. 355-358.

Drakos, P. and Lazarus, J., 1998, Hydrogeologic characterization, surface water-ground water interaction, and water quality in the southern San Luis basin in the vicinity of Taos, New Mexico,

Dungan, M.A., Muehlberger, W.R., Leininger, L., Peterson, C., McMillan, N.J., Gunn, G., Lindstrom, M., and Haskin, L., 1984, Volcanic and sedimentary stratigraphy of the Rio Grande Gorge and the Late Cenozoic geologic evolution of the southern San Luis Valley: New Mexico Geological Society Guidebook 35, p. 157-170.

Garrabrant, L.A., 1993, Water resources of Taos County, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 93-4107, 86 p.

Hearne, G. A. (1975). Letter evaluating the impact of ground water withdrawals on the water levels and the flow in the streams. Letter from Hearne of the USGS to Warren Weber of the USBR, 3/4/75.

Hearne, G. A., and Dewey, J. D. (1988). Hydrologic analysis of the Rio Grande basin north of Embudo, New Mexico, Colorado and New Mexico. U.S. Geological Survey Water-Resources Investigations Report 86–4113, 244 p.

Hess, A.E., 1986, Identifying hydraulically conductive fractures with a slow-velocity borehole flowmeter: Canadian Geotechnical Journal 23, p. 69-78.

Ingersoll, R.V., Cavazza, W., Baldridge, W.S., and Shafiqullah, M., 1990, Cenozoic sedimentation and paleotectonics of north-central New Mexico: Implications for initiation and evolution of the Rio Grande rift: Geological Society of America Bulletin v. 102, p. 1280-1296.

Keller, G.R., Cordell, L., Davis, G.S. and others, 1984, A geophysical study of the San Luis Basin: New Mexico Geological Society Guidebook 35, p. 51-58.

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

Kelson, K.I., 1986, Long-term tributary adjustments to base-level lowering in northern Rio Grande rift, New Mexico: M.S. thesis, University of New Mexico, 210 p.

Kelson, K.I. and Wells, S.G., 1987, Present-day fluvial hydrology and long-term tributary adjustments, northern New Mexico: In Quaternary tectonics, landform evolution, soil chronologies and glacial deposits—Northern Rio Grande rift of New Mexico, Friends of the Pleistocene-Rocky Mountain Cell Guidebook, p. 95-109.

Kelson, K.I., Unruh, J.R. and Bott, J.D.J., 1996, Evidence for active rift extension along the Embudo fault, Rio Grande Rift, northern New Mexico [abs.]: Geological Society of America Abstracts with Program, v. 28, no. 7, p. A377.

Kelson, K.I., Unruh, J.R., and Bott, J.D.J., 1997, Field Characterization, Kinematic Analysis, and initial Paleoseismic assessment of the Embudo fault, northern New Mexico: Final Technical Report to the U.S. Geological Survey from William Lettis and Associates, Inc., 48 p.

Kelson, K.I. and Bauer, P.W., 1998, Geology of the Carson 7.5-minute quadrangle, Taos County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-File Digital Geologic Map OF DM-22, scale 1:12,000.

Lambert, P.W., 1966, Notes of the late Cenozoic geology of the Taos-Questa area, New Mexico: New Mexico Geological Society Guidebook 17, p. 43-50.

Leininger, R.L., 1982, Cenozoic evolution of the southernmost Taos plateau, New Mexico: M.S. thesis, University of Texas at Austin, 110 p.

Lipman, P.W. and Mehnert, H.H., 1979, The Taos Plateau volcanic field, northern Rio Grande rift, New Mexico: in Riecker, R.C., ed., Rio Grande rift – Tectonics and magmatism: American Geophysical Union, Washington D.C., p. 289-311.

Lipman, P.W. and Reed, J.C., Jr., 1989, Geologic map of the Latir volcanic field and adjacent areas: U.S. Geological Survey Miscellaneous Investigations Map I-1907, scale 1:48,000.

Machette, M.N. and Personius, S.F., 1984, Quaternary and Pliocene faults in the eastern part of the Aztec quadrangle and the western part of the Raton quadrangle, northern New Mexico: U.S. Geological Survey Map MF-1465-B, scale 1:250,000.

Machette, M.N., Personius, S.F., Kelson, K.I., and Seager, W.R., 1996, New digital map and computer database of Quaternary faults and folds in New Mexico [abs.]: Geological Society of America Abstracts with Program, v. 28, no. 7, p. A377.

Machette, M.N., Personius, S.F., Kelson, K.I., Haller, K.M., and Dart, R.L., 1998, Map and data for Quaternary faults in New Mexico: U.S. Geological Survey Open-File report 98-521, 443 p.

Manley, K., 1976, The late Cenozoic history of the Española Basin, New Mexico [Ph.D. thesis]: University of Colorado, 171 p.

Manley, K., 1978, Cenozoic geology of the Espanola basin: New Mexico Bureau of Mines and Mineral Resources, Circular 163, p. 201-210.

Manley, K., 1979, Stratigraphy and structure of the Espanola basin, Rio Grande rift, New Mexico, in Riecker, R.E., ed., Rio Grande rift: tectonics and magmatism: American Geophysical Union, Washington, p. 71-86.

Manley, K., 1984, Brief summary of the Tertiary geologic history of the Rio Grande rift in northern New Mexico: New Mexico Geological Society, Guidebook 35, p. 63-66.

Menges, C.M., 1988, The tectonic geomorphology of mountain front landforms in the northern Rio Grande rift, New Mexico: Ph.D. dissertation, University of New Mexico, 140 p.

Menges, C.M., 1990, Late Cenozoic rift tectonics and mountain-front landforms of the Sangre de Cristo Mountains near Taos, northern New Mexico: New Mexico Geological Society Ghidebook 41, p. 113-122.

Miller, J.P., Montgomery, A., and Sutherland, P.K., 1963, Geology of part of the Sangre de Cristo Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 11, 106 p.

Molz, F.J., Guven, O., and Melville, J.G., 1990, A new approach and methodologies for characterizing the hydrogeologic properties of aquifers. EPA Project Summary, EPA/600/S2-90/002. Robert S. Kerr Environmental Research Laboratory, 7 p.

Molz F.J., Morin, R.H., Hess, A.E., Melville, J.G., and Guven, O., 1989, The impeller meter for measuring aquifer permeability variations: evaluation and comparison with other tests: Water Resources Research, 25, p. 1677-1683.

Montgomery, A., 1953, Precambrian geology of the Picuris Range, north-central New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 30, 89 p.

Montgomery, A., 1963, Precambrian geology, in Miller, J.P., Montgomery, A., and Sutherland, P.K., Geology of part of the Sangre de Cristo Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 11, p. 7-21.

Morin, R.H., Hess, A.E., and Paillet, F.L., 1988, Determining the distribution of hydraulic conductivity in a fractured limestone aquifer by simultaneous injection and geophysical logging: Ground Water 26, p. 586-595.

Muehlberger, W.R., 1979, The Embudo fault between Pilar and Arroyo Hondo, New Mexico: an active intracontinental transform fault: New Mexico Geological Society, Guidebook 30, p. 77-82.

Morgan, P. and Golombek, M., 1984, Factors controlling the phases and styles of extension in the northern Rio Grande rift: New Mexico Geological Society Guidebook 35, p. 13-20.

Personius, S.F. and Machette, M.N., 1984, Quaternary faulting in the Taos Plateau region, northern New Mexico: New Mexico Geological Society Guidebook 30, p. 83-90.

Peterson, C.M., 1981, Late Cenozoic stratigraphy and structure of the Taos Plateau, northern New Mexico: M.S. thesis, University of Texas at Austin, 57 p.

Rehder, T.R., 1986, Stratigraphy, sedimentology, and petrography of the Picuris Formation in Ranchos de Taos and Tres Ritos quadrangles, north-central New Mexico: M.S. thesis, Southern Methodist University, 110 p.

Read, C.B. and Wood, G.H., Jr., 1947, Distribution and correlation of Pennsylvanian rocks in late Proterozoic sedimentary basins on northern New Mexico: Journal of Geology, v. 55, p. 220-236.

Reynolds, C.B., 1986, Shallow seismic reflection survey, Taos Pueblo, Taos County, New Mexico: Charles B. Reynolds and Associates report to the BIA, May 27, 10 p.

Reynolds, C.B., 1989, Geological/geophysical review, Taos Pueblo area, Taos County, New Mexico: Charles B. Reynolds and Associates report to the BIA, August 10, 8 p.

Reynolds, C.B., 1992, Shallow seismic reflection survey, northern Taos Pueblo area, Taos County, New Mexico: Charles B. Reynolds and Associates report to the BIA, May 18, 9 p.

Soegaard, K. and Caldwell, K.R., 1990, Depositional history and tectonic significance of alluvial sedimentation in the Permo-Pennsylvanian Sangre de Cristo Formation, Taos trough, New Mexico: New Mexico Geological Society Guidebook 41, p. 277-289.

Spiegel, Zane (1962). Hydraulics of certain stream-connected aquifer systems. New Mexico State Engineer Special Report, 102 p.

Spiegel, Zane, and Couse, I. W. (1969). Availability of ground water for supplemental irrigation and municipal-industrial uses in the Taos Unit of the U.S. Bureau of Reclamation San Juan–Chama Project, Taos County, New Mexico. New Mexico State Engineer, Open-File Report, 22p.

Steinpress, M.G., 1980, Neogene stratigraphy and structure of the Dixon area, Espanola basin, north-central New Mexico [M.S. thesis]: University of New Mexico, Albuquerque, 127 p.

Summers, W.K., 1976, Catalog of thermal waters in New Mexico: New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 4, 80 p.

Turney, Sayre and Turney (1982). A study on the feasibility of development and construction of a San Juan-Chama diversion water system for the town of Taos, New Mexico. Turney, Sayre and Turney Engineers, Santa Fe, New Mexico.

Wells, S.G., Kelson, K.I. and Menges, C.M., 1987, Quaternary evolution of fluvial systems in the northern Rio Grande rift, New Mexico and Colorado: Implications for entrenchment and integration of drainage systems: In Quaternary tectonics, landform evolution, soil chronologies and glacial deposits—Northern Rio Grande rift of New Mexico, Friends of the Pleistocene-Rocky Mountain Cell Guidebook, p. 95-109.

Wilson, L., Anderson, S. T., Classan, A. et al. (1980). Future water issues, Taos County, New Mexico. Lee Wilson and Associates, Inc., Consultant report prepared for the Taos County Board of Commissioners, variously paginated.

Wilson, L., Anderson, S. T., Jenkins, D., and Lovato, P. (1978). Water availability and water quality Taos County, New Mexico. Lee Wilson and Associates, Inc., Consultant report prepared for the Taos County Board of Commissioners, variously paginated.

Winograd, I. J. (1959). Ground-water conditions and geology of Sunshine Valley and western Taos County, New Mexico. New Mexico State Engineer Office, Technical Report 12, 70 p.

Zlotnik, V.A. and McGuire, V.L., 1998, Multilevel slug tests in highly permeable formations: 1: modification of the Springer-Gelhar (SG) model: Journal of Hydrology 204, p. 271-282.

APPENDIX 1 - OTHER SELECTED REFERENCES FOR THE TAOS AREA

Aerial Photographs (1982). National High-Altitude Program 2. National High-Altitude Program 2. Color Infrared, Roll 335, Frames 119–124. June 4, 1982.

Aerial Photographs (1981). National High-Altitude Program 81. Color Infrared, Roll 365, Frames 16–18. September 29, 1982.

Akin, P. D., and Borton, R. L. (1971). General geology and ground-water conditions in the Tres Piedras area, Taos and Rio Arriba Counties, New Mexico. New Mexico State Engineer Open-File Report, 7 p.

Anonymous. (1958). Ground-water investigation at Arroyo Seco, Taos County, New Mexico. Consultant report to W. F. Turney and Associates, 2 p.

Anonymous (1960). Ground-water investigation at Arroyo Seco, Taos County, New Mexico. Consultant report to W. F. Turney and Associates, 1 p.

Applied Earth Sciences (1989). Taos Exxon station aquifer test data and analysis, 1989. Applied Earth Sciences, Houston, Texas.

Baldridge, W. S., Dickerson, P. W., Riecker, R. E., and Zidek, J., eds. (1984). Guidebook to Rio Grande rift, northern New Mexico. New Mexico Geological Society, 35th Field Conference, 380 p.

Baltz, E. H. (1965). Stratigraphy and history of Raton Basin and notes on San Luis Basin, Colorado–New Mexico. American Association of Petroleum geologists Bulletin, v. 49, p. 2041–2075.

Baltz, E. H. (1978). Resume of Rio Grande depression in north-central New Mexico. **In** Guidebook to Rio Grande rift in New Mexico and Colorado. New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 210–227.

Bauer, P. W., Love, J. C., Schilling, J. H., and Taggart, J. E., Jr. (1991). The enchanted circle-loop drives from Taos. New Mexico Bureau of Mines and Mineral Resources Trips to the Geologic Past, no. 2, 137 p.

Bauer, P. W., Lucas, S. G., Mawer, C. K., and McIntosh, W. C., eds. (1990). Tectonic development of the southern Sangre de Cristo Mountains, New Mexico. New Mexico Geological Society, 41st Field Conference, 450 p.

Boyd, J. S. (1963). Ground-water investigation, Tres Pedras vicinity, Taos and Rio Arriba Counties, New Mexico. U.S. Forest Service Open-File Report, 4 p.

Brimhall, R. M., and Titus, F. B. (1967). Hydrologic reconnaissance and recommendations for ground-water development on the D. H. Lawrence Ranch, Taos County, New Mexico. New Mexico Institute of Mining and Technology Open-File Report, 24 p.

Bryan, Kirk (1928). Preliminary report on the geology of the Rio Grande Canyon as affecting the increase in flow of the Rio Grande south of the New Mexico–Colorado boundary. New Mexico State Engineer 9th Biennial Report, 1928–1930, p. 107–120.

Bureau of Reclamation (1955). San Juan–Chama Project: Appendix D–Hydrology. Bureau of Reclamation, Amarillo Regional Office, Texas.

Bureau of Reclamation (1971). Definite plan report, San Juan–Chama Project, Indian Camp System—Taos Unit, New Mexico. Bureau of Reclamation, Amarillo Regional Office, Texas.

Bureau of Reclamation (1976). New Mexico water resources—Assessment for planning purposes. Bureau of Reclamation, U.S. Department of Interior, in cooperation with the state of New Mexico.

Chapin, C. E. (1988). Axial basins of the northern and central Rio Grande rift. **In** Sedimentary cover—Northern American Craton, Basins of the Rocky Mountain region, U.S.A. Geological Society of America—Decade of North American Geology, v. D-2, p. 167–170.

Chapin, T. S. (1981). Geology of Fort Burgwin Ridge, Taos County, New Mexico. University of Texas, Austin, TX. Unpublished M.A. thesis, 151 p.

Chudnoff, M. (1992). Analysis of transfer of ground-water rights from To-O-The-Word Farms to the vicinity of Taos airport. State Engineer Office Memorandum, 3/18/92.

Clark, K. F. (1968). Structural controls in the Red River district, New Mexico. Economic Geology, v. 63, p. 553–566.

Clark, K. F., and Read, C. B. (1972). Geology and ore deposits of Eagle Nest area, New Mexico. New Mexico Bureau of Mines and Mineral Resources Bulletin 94, 162 p.

Condie, K. C. (1980). Precambrian rocks of Red River–Wheeler Peak area, New Mexico. New Mexico Bureau of Mines and Mineral Resources Geologic Map 50, scale 1:48,000.

Coons, L. M., and Kelly, T. E. (1984). Regional hydrogeology and the effect of structural control on the flow of groundwater in the Rio Grande Trough, northern New Mexico. New Mexico Geological Society, 35th Field Conference, New Mexico Bureau of Mines and Mineral Resources, p. 241–244.

Corps of Engineers (1975). Report on hydrologic investigations—flood plain information study—Rio Fernando de Taos, Taos and Taos County, New Mexico. Corps of Engineers, Albuquerque District, Albuquerque, New Mexico.

Couzens, J. K. (1974a). Historical water supply available to irrigation users diverting from the Rio Lucero tributary to the Rio Pueblo de Taos. State Engineer Office Memorandum, 4/2/74.

Couzens, J. K. (1974b). Historical water supply available to irrigation users diverting from the Arroyo Seco of the Rio Pueblo de Taos. State Engineer Office Memorandum, 4/2/74.

Crouch, T. M. (1985). Potentiometric surface, 1980, and water-level changes, 1969–80, in the unconfined valley-fill aquifers of the San Luis Basin, Colorado and New Mexico. U.S. geological Survey Hydrologic Investigations Atlas HA-683, 2 sheets, scale 1:250,000.

Crowl, C. D., and Winslow, K. C. (1974). Supplement to hydrological report for the Mission Hills Subdivision, Taos County, New Mexico. Rio Grande Surveying Service consultant rpt., 10 p.

Dane, C. H., and Bachman, G. O. (1965). Geologic map of New Mexico. U.S. Geological Survey, 2 sheets, scale 1:500,000.

Darnell, P. S. (1987). Application for Permit to Appropriate the Underground water of the state of New Mexico. File: RG-40450-S-2, State Engineer Office Memorandum, 11/13/87.

Dinwiddie, G. A. (1964). Municipal water supplies and uses, northeastern New Mexico. New Mexico State Engineer Technical Report 29B, 64 p.

Dinwiddie, G. A., Mourant, W. A., and Basler, J. A. (1966). Municipal water supplies and uses, northwestern New Mexico. New Mexico State Engineer Office, Technical Report 29C, 197 p.

Dungan, M. A. et al. (1984). Volcanic and sedimentary stratigraphy of the Rio Grande Gorge and the late Cenozoic evolution of the southern San Luis Valley. New Mexico Geological Society Guidebook, 35th Field Conference, p. 157–170.

Dungan, M. A., Thompson, R. A., and Stormer, J. S. (1989). Excursion 18B—Rio Grande rift volcanism—Northern Jemez zone, New Mexico. **In** Field excursions to volcanic terrains in the western United States, Volume I—Southern Rocky Mountain region. New Mexico Bureau of Mines and Mineral Resources Memoir 46, p. 435–486.

Earth Environmental Consultants, Inc. (1978). Geohydrological conditions in the area of the Quail Run Subdivision, Addendum #1 and Addendum #2.

Faith, S. E. (1974). An equilibrium distribution of trace elements in a natural stream environment: the Red River near Questa, New Mexico. New Mexico Bureau of Mines and Mineral Resources Open-File Report 50, 54 p.

Fenneman, N. M. (1931). Physiography of the western United States. McGraw-Hill, New York, New York. 534 p.

Gabin, V. L., and Lesperance, L. E. (1977). New Mexico climatological data, precipitation, temperature, evaporation and wind, monthly and annual means, 1850–1975. W. K. Summers and Associates, 436 p.

Garn, H. S. (1984). Spatial and temporal variations in water quality of the Rio Grande–Red River Wild and Scenic River, Taos County, New Mexico. **In** Selected papers on water quality and pollution in New Mexico. New Mexico Bureau of Mines and Mineral Resources, Hydrologic Report 7, p.49–59.

Garn, H. S. (1985). Point and nonpoint source trace elements in a wild and scenic river of northern New Mexico. Journal of Soil and Water Conservation, v. 40, no. 5, p. 458–462.

Garn, H. S. (1986). Quantification of instream flow needs of a wild and scenic river for water rights litigation. American Water Resources Association, Water Resources Bulletin, v. 22, no. 5, p. 745–751.

Garn, H. S., and Thomson, B. N. (1985). Analysis of cyanide data on the Red River, New Mexico. **In** Proceedings from Conference on Cyanide and the Environment, Fort Collins, CO, p. 161–174.

Geohydrology Associates (December 1983). Ground-water inventory of Indian trust lands, pueblos of Taos, San Juan and Santa Clara, New Mexico.

Glorieta Geoscience, Inc. (1991). Geohydrology of the Pinones de Taos, Taos County, New Mexico. Glorieta Geoscience, Inc., Santa Fe, New Mexico.

Gruner, J. W. (1920). Geologic reconnaissance of the southern part of the Taos Range, New Mexico. Journal of Geology, v. 28, no. 8.

Hacker, L. W., and Carleton, J. O. (1982). Soil survey of Taos County and parts of Rio Arriba and Mora Counties, New Mexico. Washington, D.C., U.S. Government Printing Office, 220 p.

Hagerman, C. de B. (1960). Ground-water report, Rancho Cerros de Taos (Taos County. Report to Kirby Cattle Company, 10 p.

Hagerman, C. de B. (1973). Water availability, Top of the World (Taos County). Consultant report to the Taos County Planning Commission.

Hagerman, C. de B. (1976). General geology and ground water conditions, Carson area, Taos County. Consultant report, 7 p.

Hawley, J. W., compiler (1978). Guidebook to Rio Grande rift in New Mexico and Colorado. New Mexico Bureau of Mines and Mineral Resources, Circular 163, 241 p.

Healy, F. G. (1927). Preliminary report of the feasibility of drilling for artesian water in western Taos and eastern Rio Arriba Counties, New Mexico. **In** Report on the Taos–Rio Arriba Counties investigations. New Mexico State Engineer Open-File Report, p. 133–136.

Hearne, G. A. (1975a). Letter evaluating the impact of ground water withdrawals on the water levels and the flow in the streams. Letter from Hearne of the USGS to Warren Weber of the USBR, 3/4/75.

Hearne, G. A. (1975b). Letter on the effects of pumping ground water along the Arroyo Seco. Letter from Hearne of the USGS to Warren Weber of the USBR, 4/8/75.

Hearne, G. A., and Dewey, J. D. (1988). Hydrologic analysis of the Rio Grande basin north of Embudo, New Mexico, Colorado and New Mexico. U.S. Geological Survey Water-Resources Investigations Report 86–4113, 244 p.

Heffern, E. L. (1990). A geologic overview of the Wild Rivers Recreation Area, New Mexico. **In** Bauer et al., eds. Tectonic development of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society, 41st Field Conference, p. 229–236.

Hem, J. D. (1985). Study and interpretation of the chemical characteristics of natural water 3rd ed.). U.S. Geological Survey Water-Supply Paper 2254, 264 p.

Herkenhoff, Gordon & Associates, Inc. (1981). Red River diversion feasibility report. Prepared for Northeast New Mexico Municipal Authority, funded by Interstate Stream Commission.

Herkenhoff, Gordon & Associates, Inc. (1983). Supplemental Red River diversion feasibility report. Prepared for Northeast New Mexico Municipal Authority, funded by the Interstate Stream Commission.

HKM Associates (September 1992). Summary BIA water claims report. Prepared for the Taos Pueblo, HKM Associates, Billings, Montana.

Hunt, C. B. (1977). Surficial geology of northeast New Mexico. New Mexico Bureau of Mines and Mineral Resources Geologic Map 40, 2 sheets.

Jacobi, G. Z. (1981). Effects of organic pollution on benthic macroinvertebrates in the Rio Hondo, Taos County, New Mexico. New Mexico Environmental Improvement Division, Water Pollution Control Bureau —82/1, 41 p.

Jacobi, G. Z. (1984a). Intensive survey of the Red River in the vicinity of the Red River and Questa wastewater treatment facilities and the Molycorp complex, Taos County, New Mexico, January 25–27, 1984. New Mexico Environmental Improvement Division, Surface Water Quality Bureau–84/1, 29 p.

Jacobi, G. Z. (1984b). Winter survey (VI) of the Rio Hondo, Taos County, New Mexico, March 8, 9, and 22, 1984. New Mexico Environmental Improvement Division, Surface Water Quality Bureau–84/3, 19 p.

Jacobi ,G. Z. (1986a). Water quality survey of the Red River, Taos County, New Mexico, April 15–17, 1985. New Mexico Environmental Improvement Division, Surface Water Quality Bureau–86/11, 63 p.

Jacobi, G. Z., and Smolka, L. R. (1986b). Water quality survey of the Rio Hondo before and during the ski season, November 19–20, 1984, and March 27–28, 1985. New Mexico Environmental Improvement Division, Surface Water Quality Bureau–86/3, 41 p.

Jacobi, G. Z., and Smolka, L. R. (1983). Intensive winter survey of the Rio Hondo, Taos County, New Mexico, March 29–31, 1982. New Mexico Environmental Improvement Division, Water Pollution Control Bureau–83/3, 44 p.

Jenkins, D. N. (1959). Ground-water conditions and geology of Sunshine Valley and western Taos County, New Mexico. New Mexico State Engineer Technical Report 12.

Jenkins, D. N. (1978). Geohydrologic investigation of the Turley Mill property, Taos County, New Mexico. Geohydrology Associates, Inc.

Jenkins, D. N. (1980). Geohydrology of the River View Acres near Arroyo Hondo, Taos County, New Mexico. Geohydrology Associates, Inc., consultant report to Varda Development Company.

Jenkins, D. N. (1982). Geohydrology of the Villas Encantadas area near Ranchos de Taos, Taos County, New Mexico. Consultant report to Stakeout Properties.

Jenkins, D. N. (1982). Geohydrology of the Deer Mesa Subdivision area near Valdez, Taos County. Water Futures, Albuquerque, New Mexico.

Jenkins, D. N. (1983). Geohydrology of the Taos Ridge Townhomes area, near Taos, Taos County, New Mexico. Geohydrology Associates, Inc.

Just, Evan. (1937). Geology and economic features of the pegmatites of Taos and Rio Arriba Counties, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Bulletin 13, 73 p.

Keller, G. R., Cordell, Lindrith, Davis, G. H., et al. (1984). A geophysical study of the San Luis Basin. **In** Baldridge et al., eds. Guidebook to Rio Grande rift, northern New Mexico: New Mexico Geological Society, 35th Field Conference, p. 51–58.

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

Kenelm, Winslow C. (1975). Los Taosenos Subdivision. Kenelm C. Winslow, registered professional engineer and land surveyor.

Kunkel, K. E. (1984). Temperatures and precipitation summaries for selected New Mexico locations. New Mexico Department of Agriculture, 190 p.

Lambert, P. W. (1966). Notes on the late Cenozoic geology of the Taos–Questa area, New Mexico. **In** New Mexico Geological Society Guidebook of Taos-Raton-Spanish Peaks Country, New Mexico and Colorado. New Mexico Geological Society, 17th Field Conference, p. 43–50.

Landsford, R. R., Dominguez, L., Gore, C. et al. (1991). Sources of irrigation water and irrigated and dry cropland acreages in New Mexico by county, 1988–90. Agricultural Experiment Station Technical Report 4. New Mexico State University, Las Cruces, New Mexico, 52 p.

Lansford, R. R., Mapel, C. L., Gerhardt, D. et al. (1988). Sources of irrigation and irrigated and dry cropland acreages in New Mexico by county, 1985–87. Agricultural Experiment Station Research Report 630. New Mexico State University, Las Cruces, New Mexico, 49 p.

Lansford, R. R., Sorensen, E. F., Creel, B. J., et al. (1978). Sources of irrigation and irrigated and dry cropland acreages in New Mexico by county, 1972–77. Agricultural Experiment Station Research Report 377. New Mexico State University, Las Cruces, New Mexico, 39 p.

Lazarus, J., and Faith, S. E. (1983). Geohydrologic reconnaissance of the ski and tennis ranch of Taos. Glorieta Geoscience, Santa Fe and Faith Engineering, Inc., Albuquerque, New Mexico.

Lazarus, J. (1989). Geohydrology of the Baird Joint Venture property, Taos County, New Mexico. Glorieta Geoscience, Inc., Santa Fe, New Mexico.

Lipman, P. W., and Mehnert, H. H. (1975). Late Cenozoic basaltic volcanism and development of the Rio Grande depression in the southern Rocky Mountains. Geological Society of America Memoir 144, p. 119–154.

Lipman, P. W., and Mehnert, H. H. (1979). The Taos Plateau volcanic field northern Rio Grande rift, New Mexico. **In** Rio Grande rift—Tectonics and magmatism: American Geophysical Union, Washington, D.C., p. 289–311.

Lipman, P. W., and Reed, J. C., Jr. (1989). Geologic map of the Latir volcanic field and adjacent areas. U.S. Geological Survey, Miscellaneous Investigations Map I-1907, scale 1: 48,000.

Long, P. E. (1976). Precambrian granitic rocks of the Dixon–Peñasco area, northern New Mexico—A study in contrasts. New Mexico Bureau of Mines and Mineral Resources, Open-File Report 71, 533 p.

Lynch, T. R., Popp, C. J., Jacobi, G. Z., and Robertson, James (1988). Assessing the sensitivity of high altitude New Mexico wilderness lakes to acidic precipitation and trace metal contamination. New Mexico Water Resources Research Institute Technical Completion Report, 177 p.

Maker, H. J., Folks, J. J., Anderson, J. U., and Link, V. G. (1974). Soil associations and land classification for irrigation, Taos County. Agricultural Experiment Station Research Report 268, New Mexico State University, Las Cruces, New Mexico, 44 p.

Manley, K. (1984). Brief summary of the Tertiary geologic history of the Rio Grande rift in northern New Mexico. **In** Guidebook to Rio Grande rift, northern New Mexico. New Mexico Geological Society, 35th Field Conference, p. 63–66.

McKinlay, P. F. (1956). Geology of Costilla and Latir Peak quadrangles, Taos County, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Bulletin 42, 32 p.

McKinlay, P. F. (1957). Geology of the Questa quadrangle, Taos County, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Bulletin 53, 23 p.

Meeks, T. O. (1952). Preliminary report on ground water in the Sunshine Valley area, Taos County, New Mexico. U.S. Soil Conservation Service Open-File Report, 6 p.

Menges, C. M. (1990). Late Cenozoic rift tectonics and mountain front landforms of the Sangre de Cristo Mountains near Taos, northern New Mexico. **In** New Mexico Geological Society Guidebook 41, p. 113–122.

Miller, J. P., Montgomery, Arthur, and Sutherland, P. K. (1963). Geology of part of the southern Sangre de Cristo Mountains, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Memoir 11, 106 p.

Moench, R. H., Grambling, J. A., and Robertson, J. M. (1988). Geologic map of the Pecos Wilderness, Santa Fe, San Miguel, Mora, Rio Arriba, and Taos Counties, New Mexico. U.S. Geological Survey, Miscellaneous Field Studies Map MF–1921B, scale 1:48,000.

Moench, R. H., and Lane, M. E. (1988). Mineral resource potential map of the Pecos Wilderness, Santa Fe, San Miguel, Mora, Rio Arriba, and Taos Counties, New Mexico. U.S. Geological Survey, Miscellaneous Field Studies Map MF–1921A, scale 1:48,000.

Montgomery, A. (1950). Geochemistry of tantalum in the Harding pegmatite, Taos County, New Mexico. American Mineralogist, v. 35, nos. 9 and 10.

Montgomery, A. (1953). Precambrian geology of the Picuris Range, north central New Mexico. Abstract of Bulletin 30 **in** New Mexico Geological Society, 7th Field Conference.

Muehlberger, W. R., and Muehlberger, S. (1982). Española-Chama-Taos—A climb through time. New Mexico Bureau of Mines and Mineral Resources, Scenic Trips to the Geologic Past, no. 13, 99 p.

New Mexico Department of Game and Fish. (1995). New Mexican Wildlife of Special Concern: Taos County. Biota Information System of New Mexico, New Mexico Department of Game and Fish, Conservation Services Division, electronic database retrieval.

New Mexico Energy and Minerals Department. (1986). Annual resources report. New Mexico Energy and Minerals Department, 123 p.

New Mexico Energy and Minerals Department. (1988). Annual resources report. New Mexico Energy and Minerals Department, 119 p.

New Mexico Energy, Minerals, and Natural Resources Department. (1991). Annual resources report. New Mexico Energy, Minerals, and Natural Resources Department, 65 p.

New Mexico Environmental Improvement Division. (1974a). New Mexico water supplies chemical data, major communities. New Mexico Environmental Improvement Division, Water Supply Regulation Section, 157 p.

New Mexico Environmental Improvement Division. (1974b). New Mexico water supplies chemical data, minor communities. New Mexico Environmental Improvement Division, Water Supply Regulation Section, 217 p.

New Mexico Environmental Improvement Division. (1980). Chemical quality of New Mexico community water supplies. New Mexico Environmental Improvement Division, Water Supply Section, 256 p.

New Mexico Environmental Improvement Division. (1981). Point source waste load allocation for the Twining Water and Sanitation District. New Mexico Environmental Improvement Division, Water Pollution Control Bureau, 43 p.

New Mexico Environmental Improvement Division. (1982). Point source waste load allocation for the town of Red River. New Mexico Environmental Improvement Division, Water Pollution Control Bureau, 39 p.

New Mexico Environmental Improvement Division. (1984). Directory of officials of community water supply system in New Mexico. New Mexico Environmental Improvement Division, Community Support Services Bureau, Water Supply Section-84/3, 203 p.

New Mexico Environmental Improvement Division. (1990). Intensive water quality stream surveys and lake water quality assessment surveys, 1989. New Mexico Environmental Improvement Division, Surface Water Quality Bureau, 199 p.

New Mexico Geological Society. (1956). Guidebook of Southeastern Sangre de Cristo Mountains, New Mexico. New Mexico Geological Society, Seventh Field Conference, 151 p.

New Mexico Geological Society. (1982). New Mexico highway geologic map. New Mexico Bureau of Mines and Mineral Resources, scale 1:1,000,000.

New Mexico Interstate Stream Commission and the New Mexico State Engineer Office. (1975). County profile (Taos County)—Water resources assessment for planning purposes. Santa Fe, New Mexico, 46 p.

New Mexico State Engineer Office. (1956a). Climatological summary, New Mexico, precipitation, 1849–1954. New Mexico State Engineer Office, Technical Report 6, 407 p.

New Mexico State Engineer Office. (1956b). Climatological summary, New Mexico, temperature, 1850–1954, frost, 1850–1954, evaporation, 1912–1954. New Mexico State Engineer Office, Technical Report 5, 277 p.

New Mexico State Engineer Office. (1979). Underground water. **In** Water Rights, Taos Adjudication Suit, Rio Hondo Section, v. 2, p. 29–63.

New Mexico State Engineer Office. (1980). Ground-water section, Cabresto section. **In** Red River water rights—Red River section, Cabresto section, Cerro section, Molybdenum Corp. of America (Taos County), U.S. District Court Case No. 7941. New Mexico State Engineer Office, p. 59–72.

New Mexico State Engineer Office. (1990). Annual report, State Engineer of New Mexico, 78th fiscal year, July 1, 1989, to June 30, 1990. New Mexico State Engineer Office, Santa Fe, New Mexico, 97 p.

New Mexico Water Quality Control Commission. (1988). New Mexico Water Quality Control Commission regulations, as amended through November 25, 1988. New Mexico Water Quality Control Commission, 75 p.

New Mexico Water Quality Control Commission. (1988b) Water quality standards for interstate and intrastate streams in New Mexico. New Mexico Water Quality Control Commission 88–1, 48 p.

New Mexico Water Quality Control Commission (1988c). Water quality and water pollution control in New Mexico. New Mexico Water Quality Control Commission, 212 p.

New Mexico Water Quality Control Commission (1990). Water quality and water pollution control in New Mexico. New Mexico Water Quality Control Commission EID/WPC-90/1, 289 p.

New Mexico Water Quality Control Commission (1991). Water quality standards for interstate and intrastate streams in New Mexico. New Mexico Water Quality Control Commission 91-1, 49 p.

North Central New Mexico Economic Development District Planning District II (1991). Taos County Regional Water Plan. 47 p., Appendix.

Northrop, S. A., and Read, C. B., eds. (1966). Guidebook of Taos-Raton-Spanish Peaks Country, New Mexico and Colorado. New Mexico Geological Society, 17th Field Conference, 128 p.

O'Neill, J. M., and Mehnert, H. H. (1988). Petrology and physiographic evolution of the Ocate volcanic field, north-central New Mexico . U.S. Geological Survey, Professional Paper 1478, 15 p.

Oo-Cluh-Quache (1988). Well drilling and aquifer testing on tract A, Taos Pueblo.

Oo-Cluh-Quache (1988). Well drilling and aquifer testing on tract B, Taos Pueblo.

Pacheco, E. C. (1991). Report on the hydrologic effects on existing water rights and water sources due to El Prado's proposed transfer from surface to ground water. New Mexico State Engineer Office Memorandum, 11/8/91.

Pacheco, E. C. (1991a). Historical water supply on the Rio Lucero, Taos County, New Mexico. State Engineer Office Technical Division Hydrology Report 91-4.

Pacheco, E. C. (1991b). Evaluation Couzens' April 2, 1974 memorandum concerning the historical water supply on the Arroyo Seco, Taos County, New Mexico. State Engineer Office Memorandum, 11/7/91.

Park, C. F., Jr., and McKinlay, P. F. (1948). Geology and ore deposits of Red River and Twining districts, Taos County, New Mexico—A preliminary report. New Mexico Bureau of Mines and Mineral Resources, Circular 18, 35 p.

Pazzaglia, F. J., and Wells, S. G. (1990). Quaternary stratigraphy, soils and geomorphology of the northern Rio Grande rift. **In** Bauer et al., eds. Tectonic development of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society, 41st Field Conference, p. 423–430.

Pearson, J. B. (1986). The Red River-Twining area—A New Mexico mining story. University of New Mexico, Albuquerque, New Mexico, 221 p.

Personius, S. F., and Machette, M. N. (1984). Quaternary and Pliocene faulting the Taos Plateau region, northern New Mexico. **In** Baldridge et al., eds., Guidebook to Rio Grande rift, northern New Mexico, northern New Mexico: New Mexico Geological Society, 35th Field Conference, p. 83–90.

Peterson, J. W. (1969). Geology of the Tienditas Creek–La Junta Canyon area, Taos and Colfax Counties, New Mexico. University of New Mexico, Albuquerque, New Mexico; unpublished M.S. thesis, 82 p.

Potter, D. U. (1986). Intensive survey of the Rio Pueblo de Taos and its tributaries near Taos and Los Cordovas, Taos County, New Mexico, August 13–15, 1986. New Mexico Environmental Improvement Division, Surface Water Quality Bureau–86/10, 60 p.

Purtymun, W. D. (1969). General ground-water conditions in the Taos Pueblo, Tenorio Tract, and Taos Pueblo Tracts A and B, Taos County, New Mexico. U.S. Geological Survey confidential report to the Bureau of Indian Affairs, 12 p.

Ray, L. L. (1940). Glacial chronology of the southern Rocky Mountains. Geological Society of America Bulletin, v. 51, no. 12.

Reed, J. C., Lipman, P. W., and Robertson, J. P. (1983). Geologic map of the Latir Peak and Wheeler Peak Wilderness and Columbine-Hondo Wilderness study area, Taos County, New Mexico. U.S. Geological Survey Miscellaneous Field Investigations Map MP-1570-B, scale 1:50,000.

Reiland, L. J. (1980). Flow Characteristics of New Mexico Streams: Part 1, flow duration. New Mexico State Engineer and U.S. Geological Survey, Special Report, Santa Fe, New Mexico, 115 p.

Saavedra, P. (1987). Surface water irrigation organizations in New Mexico. New Mexico State Engineer Office Report TDDC-87-2, 152 p.

Schilling, J. H. (1956). Geology of the Questa molybdenum (Moly) mine area, Taos County, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Bulletin 51, 87 p.

Schilling, J. H. (1960). Mineral resources of Taos County, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Bulletin 71, 124 p.

Schilling, J. H. (1968). Taos-Red River-Eagle Nest circle drive. New Mexico Bureau of Mines and Mineral Resources, Scenic Trips to Geologic Past 2, 26 p.

Sergent, Hauskins & Beckwith (1990). Hydrogeologic Evaluation Sandia Canyon Subdivision, Taos County. Consulting geotechnical engineers, SHB Job No. E90-1043.

Smith, H. T. U. (1938). Tertiary geology of the "Questa" molybdenite deposit, Taos County, New Mexico. Colorado Science Society, Proceedings, v. 13, no. 11.

Smolka, L. R. (1986). Water quality survey of the Rio Hondo, Taos County, New Mexico during the ski season, November 23, 1985, thru March 27, 1986. New Mexico Environmental Improvement Division, Surface Water Quality Bureau–86/15, 44 p.

Smolka, L. R. (1987a). Intensive water-quality survey of Costilla Creek and its tributaries, Taos County, New Mexico, February 23–26, 1987. New Mexico Environmental Improvement Division, Surface Water Quality Bureau–87/3, 43 p.

Smolka, L. R. (1987b). Reconnaissance survey of Rio Santa Barbara, Rio Pueblo, and Embudo Creek, Rio Arriba and Taos Counties, New Mexico, September 2–3, 1986. New Mexico Environmental Improvement Division, Surface Water Quality Bureau–86/26, 16 p.

Smolka, L. R., and Jacobi, G. Z. (1983). Water quality survey of Cordova and Costilla Creeks near the Rio Costilla ski area, October 14–16, 1872. New Mexico Environmental Improvement Division, Water Pollution Control Bureau–83/4, 35 p.

Smolka, L. R., and Jacobi, G. Z. (1986). Water quality survey of the Red River, Taos County, New Mexico, April 15–17, 1986. New Mexico Environmental Improvement Division, Surface Water Quality Bureau–86/11, 61 p.

Smolka, L. R., and Tague, D. F. (1987). Intensive survey of the Red River, Taos County, New Mexico, August 18–21, 1986. New Mexico Environmental Improvement Division, Surface Water Quality Bureau–88/8, 89 p.

Sorensen, E. F. (1977). Water use by categories in New Mexico counties and river basins, and irrigated and dry acreage in 1975. New Mexico State Engineer Office Technical Report 41, 34 p.

Sorensen, E. F. (1982). Water use by categories in New Mexico counties and river basins, and irrigated acreage in 1980. New Mexico State Engineer Office Technical Report 44, 51 p.

Sorensen, E. F., Stotelmeyer, R. B., and Baker, D. H., Jr. (1973). Mineral resources and water requirements for New Mexico minerals industries. New Mexico Bureau of Mines and Mineral Resources, Circular 138, 26 p.

Spiegel, Zane (1954). Llano San Juan (Taos County) community water supply. New Mexico State Land Office Open-File Report, 1 p.

Spiegel, Zane (1955). Water supply for Costilla Mutual Domestic Water Consumers Association. New Mexico State Engineer Open-File Report, 2 p.

Spiegel, Zane (1956). Water supplies for Mutual Domestic Water Consumers Association at South San Ysidro and Ilfeld (San Miguel County) and Canon (Taos County) New Mexico. New Mexico State Engineer Open-File Report, 2 p.

Spiegel, Zane (1962). Hydraulics of certain stream-connected aquifer systems. New Mexico State Engineer Special Report, 102 p.

Spiegel, Zane (1962). Geology and ground-water conditions at Arroyo Hondo, Taos County, New Mexico. New Mexico State Engineer Open-File Report, 4 p.

Spiegel, Zane (1969). Geology and ground-water conditions at Arroyo Hondo, Taos County, New Mexico. New Mexico State Engineer Open-File Report, 22 p.

Spiegel, Zane, and Couse, I. W. (1969). Availability of ground water for supplemental irrigation and municipal-industrial uses in the Taos Unit of the U.S. Bureau of Reclamation San Juan–Chama Project, Taos County, New Mexico. New Mexico State Engineer, Open-File Report, 22 p.

Stamets, R. L. (1957). Ground-water report, Des Montes (Taos County). Consultant report to W. F. Turney and Associates, 3 p.

Stamets, R. L. (1960). Ground-water report, Vadito (Taos County). Consultant report to W. F. Turney and Associates, 3 p.

Stamets, R. L. (1960). Ground-water report, Rio Lucio (Taos County). Consultant report to W. F. Turney and Associates, 3 p.

Stamets, R. L. (1960). Ground-water report, Valdez (Taos County). Consultant report to W. F. Turney and Associates, 3 p.

Stewart, Peter (1981). Watershed characteristics part B decreases in flow in the Rio Hondo. U.S. Forest Service, Carson National Forest.

Stone, D. N. (1983). Application for Permit to Appropriate and for a Supplemental Well to Appropriate the Underground Waters of the State of New Mexico, File RG-40450 and RG-40450-S. State Engineer Office Memorandum, 12/7/83.

Summers, W. K. (1965a). A preliminary report on New Mexico's geothermal energy resources. New Mexico Bureau of Mines and Mineral Resources, Circular 80, 41 p.

Summers, W. K. (1965b). Chemical characteristics of New Mexico's thermal waters—A critique. New Mexico Bureau of Mines and Mineral Resources, 27 p.

Summers, W. K. (1976). Catalog of thermal waters in New Mexico. New Mexico Bureau of Mines and Mineral Resources, Hydrologic Report 4, 80 p.

Summers, W. K., and Hargis, L. L. (1985). Commentary on hydrogeologic cross section through Sunshine Valley, Taos County, New Mexico. New Mexico Geology, v. 7, no. 3, p. 54–55.

Turney, Sayre and Turney (1982). A study on the feasibility of development and construction of a San Juan-Chama diversion water system for the town of Taos, New Mexico. Turney, Sayre and Turney Engineers, Santa Fe, New Mexico.

Upson, J. E. (1939). Physiographic subdivisions of the San Luis Valley, southern Colorado. Journal of Geology, v. 47, no. 7, p. 721–736.

U.S. Army Corps of Engineers (1977). Flood plain information, Taos County, New Mexico, parts I and II. Albuquerque District, New Mexico, 27 p.

U.S. Congress (1968). Wild and Scenic Rivers Act.

U.S. Congress (1973). Endangered Species Act of 1973 (Amended). The Bureau of National Affairs, Washington, D.C.

U.S. Department of Agriculture (1981). Land Resource Regions and Major Land Resource Areas. Soil Conservation Service, Agriculture Handbook 296, 156 p.

U.S. Department of Agriculture (1986). New Mexico agricultural statistics, 1985. U.S. Department of Agriculture and New Mexico Department of Agriculture.

U.S. Department of Agriculture (1989). New Mexico annual data summary of federal-state-private cooperative snow surveys, water year 1988. Soil Conservation Service, 10 p.

U.S. Department of Agriculture (1991). New Mexico agricultural statistics, 1990. U.S. Department of Agriculture and New Mexico Department of Agriculture, 72 p.

U.S. Department of Agriculture (1993). The Principal Laws Relating to Forest Service Activities. Forest Service Legislative Affairs Office, Washington, D.C., p. 369–426.

U.S. Department of Commerce (1991). 1990 summary population and housing characteristics, New Mexico. Bureau of the Census, 1990 CPH-1-33, 33, 63 p.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service (1954–89). Annual summary, New Mexico: Climatological data. No. 13, v. 58–93, National Climatic Center, Asheville, North Carolina.

U.S. Department of Commerce (1982). Evaporation atlas for the contiguous 48 United States. National Oceanic and Atmospheric Administration Technical Report NWS 33, Washington, D.C., 26 p. and 4 atlases.

U.S. Department of Health, Education and Welfare (1966). Ground-water characteristics. **In** Water-quality survey, Red River of the Rio Grande, New Mexico. U.S. Department of Health, Education, and Welfare report, p. V-23 to V-25.

U.S. Department of Interior (1988). Taos Resource Management Plan. Bureau of Land Management, Albuquerque District, Taos Resource Area, variously paged.

U.S. Environmental Protection Agency (1982). Site specific water quality assessment—Red River, New Mexico. U.S. Environmental Protection Agency 600/x-82-025, 118 p.

U.S. Environmental Protection Agency (1988a). National revised primary drinking water regulations: Maximum contaminant levels (subpart G of part 141, National interim primary drinking-water regulations). U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised July 1, 1988, p. 586–587.

U.S. Environmental Protection Agency (1988b). Secondary maximum contaminant levels (Section 143, 3 of part 143), National secondary drinking water regulations. U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised July 1, 1988, p. 608.

U.S. Geological Survey (1907–1991). Water Resource data of the surface water supply of New Mexico. Surface water flow data is provided in annual reports and is maintained in a computer database. Ground-water levels in selected wells are measured every five years and this data is also maintained by the Survey in a database.

U.S. Geological Survey (1976). Hydrologic Unit Map–1974: State of New Mexico. U.S. Geological Survey, Reston, Virginia, 1973 edition, scale 1:500,000.

Vail, R. E. (1973). Summary of domestic water supply situation, Tres Piedras Mutual Domestic Water Consumers Association, Tres Piedras (Taos County), New Mexico. Consultant report to Tres Piedras, 4 p.

Vail, R. E. (1981). Engineering report and feasibility study, Tres Piedras Mutual Domestic Water Consumers Association, Taos County, New Mexico . Consultant report to Tres Piedras.

Vail, S. G. (1982). Summary of geology around Guadalupe Mountain, Taos County, New Mexico. Unpublished report prepared for Molycorp, Inc., 5 p.

Von Eschen, G. F. (no date). Climate of Taos, New Mexico. **In** Climatological summaries for 35 weather stations in the State. U.S. Commerce Department–Weather Bureau and the University of New

Mexico, Bureau of Business Research, Business Information Series No. 37, State Climatologist Office, Albuquerque.

Waltemeyer, S. D. (1988). Statistical summaries of steamflow data in New Mexico through 1985. U.S. Geological Survey, Water-Resources Investigations Report 88-4228, 204 p.

Walton, G. E. (1883). Agua Caliente (Grant County), Las Vegas Hot Springs (San Miguel County), and Ojo Caliente (Taos County). **In** The mineral springs of the United States and Canada. D. Appleton and Co., New York, ch. XVI, p. 309, and appendix, p. 426–427 and 436.

Weller, L. L. (1987). Exploratory Geohydrogeologic Investigations on the Taos Pueblo, Taos County, New Mexico. Louis L. Weller Architects, P.C.

West, F. G. (1961). Geological report, Red River, Taos County, New Mexico. Consultant report to W. F. Turney and Associates, 2 p.

West, F. G. (1961). Geological report, Upper Arroyo Hondo, Taos County, New Mexico. Consultant report to W. F. Turney and Associates, 1 p.

Wilkins, D. W., Scott, W. B., and Kaehler, C. A. (1980). Planning report for the Southwest Alluvial Basins (east) regional aquifer system analysis, parts of Colorado, New Mexico and Texas. U.S. Geological Survey, Open-File Report 80-564, 39 p.

Williams, J. L. (1986). New Mexico in Maps. University of New Mexico Press, Albuquerque, New Mexico, 409 p.

Williams, R. S., Jr. and Hammond, S. E. (1989). Selected water quality characteristics and flow of ground water in the San Luis Basin, including the Conejos River subbasin, Colorado and New Mexico. U.S. Geological Survey, Water Resources Investigations Report 89-4040, 43 p.

Wilson, B. C. (1986). Water use in New Mexico in 1985. New Mexico State Engineer Office, Technical Report 46, 84 p.

Wilson, B. C. (1992). Water use by categories in New Mexico counties and river basins, and irrigated acreage in 1990. New Mexico State Engineer Office, Technical Report 47, 141 p.

Wilson, L., Anderson, S. T., Classan, A. et al. (1980). Future water issues, Taos County, New Mexico. Lee Wilson and Associates, Inc., Consultant report prepared for the Taos County Board of Commissioners, variously paginated.

Wilson, L., Anderson, S. T., Jenkins, D., and Lovato, P. (1978). Water availability and water quality Taos County, New Mexico. Lee Wilson and Associates, Inc., Consultant report prepared for the Taos County Board of Commissioners, variously paginated.

Wilson, Lee & Associates (1978). Water availability and water quality, Taos County, New Mexico: Phase A Report.

Wilson, Lee & Associates (1980). Ground-water supplies and quantity. **In** Future Water Issues, Taos County, New Mexico: consultant report to the Taos County Board of Commissioners, p. V-1 to V-20.

Wilson, Lee & Associates (1983). Surface water inventory, Taos, San Juan and Santa Clara Pueblos. Volume I, Main Report, Taos Pueblo.

Wilson, Lee & Associates (1983). Surface water inventory, Taos, San Juan and Santa Clara Pueblos. Volume II, appendices.

Wilson, L. G., DeCook, K. J., and Neuman, S. P. (1980). Final report, regional recharge research for southwest alluvial basins. Water Resources Research Center, University of Arizona.

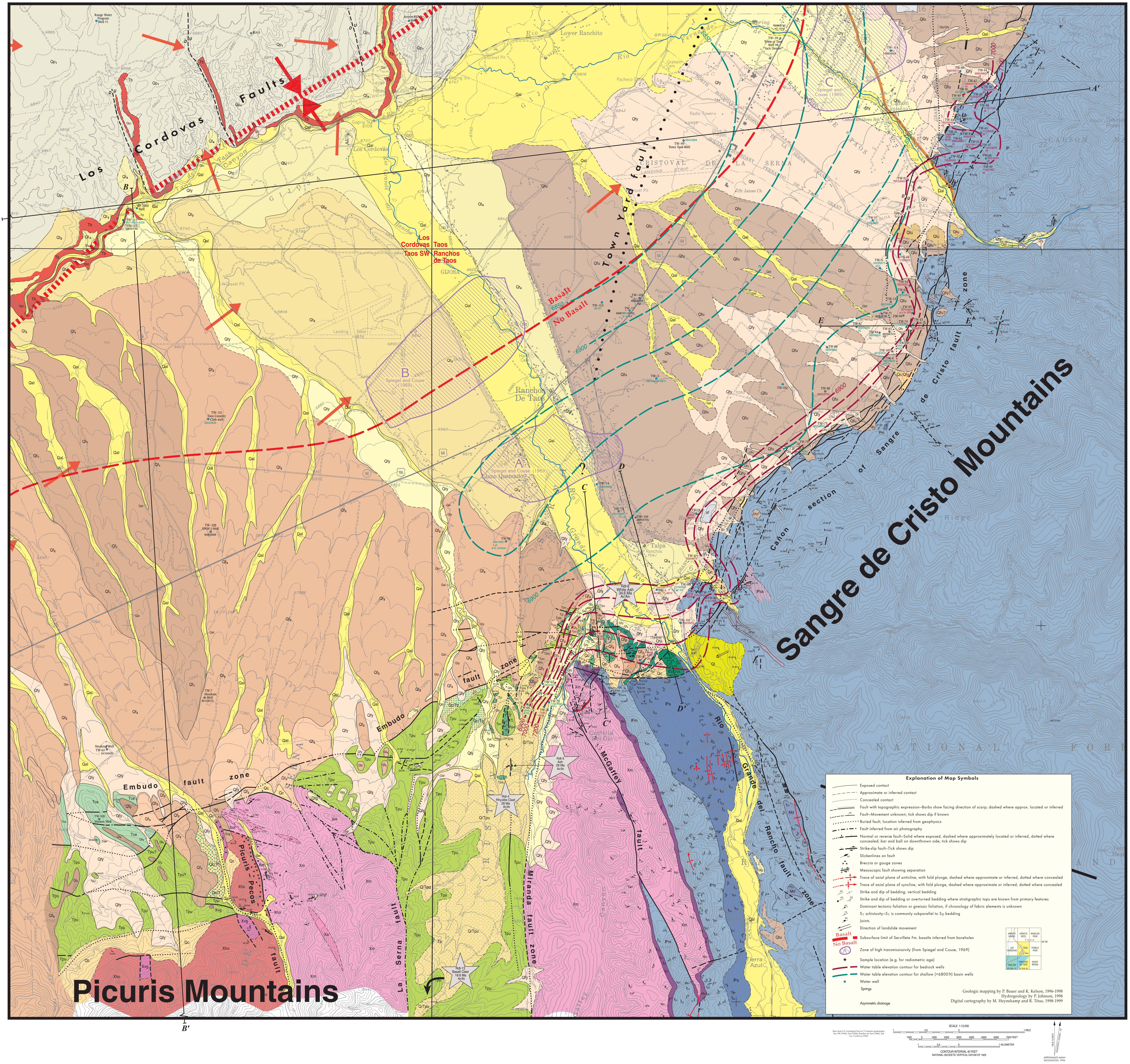
Winkler, H. A. (1951). Seismic exploration, Sunshine Valley, New Mexico. New Institute of Mining and Technology, 5 p.

Winkler, H. A. (1953). A geophysical section of the Sunshine Valley ground-water basin in New Mexico. New Mexico Institute of Mining and Technology, 12 p.

Winograd, I. J. (1955). Groundwater for stock and domestic purposes in the vicinity of Taos Junction, Tres Piedras, and No Aqua, Taos and Rio Arriba Counties, New Mexico. U.S. Geological Survey, Open-File Report, 20 p.

Winograd, I. J. (1959). Ground-water conditions and geology of Sunshine Valley and western Taos County, New Mexico. New Mexico State Engineer Office, Technical Report 12, 70 p.

Plate 1. Geologic map and potentiometric surface map of the southern Taos Valley.



Geologic mapping by P. Bauer and K. Kelson, 1996-1998
Hydrogeology by P. Johnson, 1998
Digital cartography by M. Heynekamp and R. Titus, 1998-1999

Base from U.S. Geological Survey 7.5-minute quadrangles Taos SW (1964), Taos (1964), Ranchos de Taos (1964), and Los Cordovas (1964)

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Plates 2 & 4.

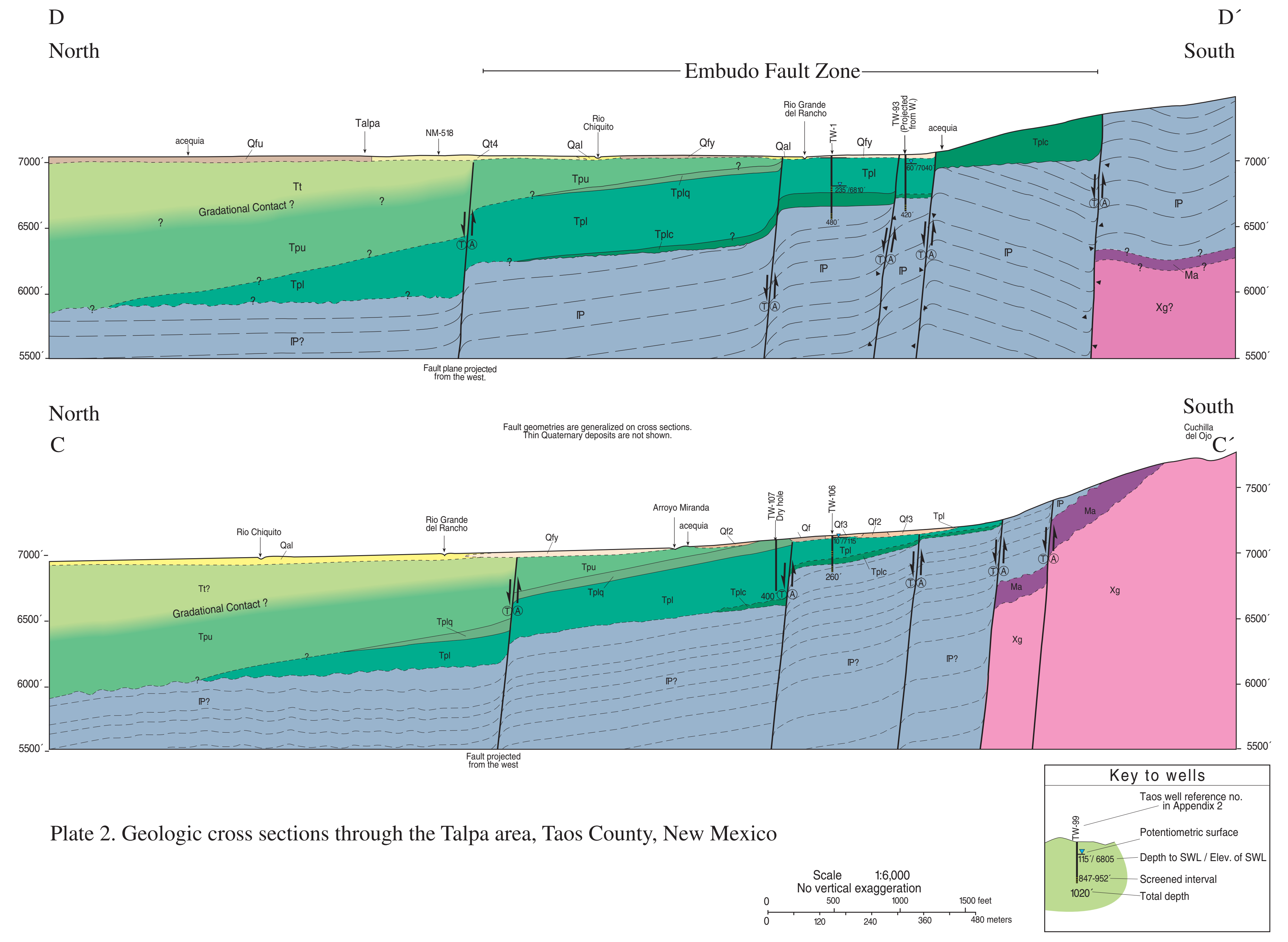


Plate 2. Geologic cross sections through the Talpa area, Taos County, New Mexico

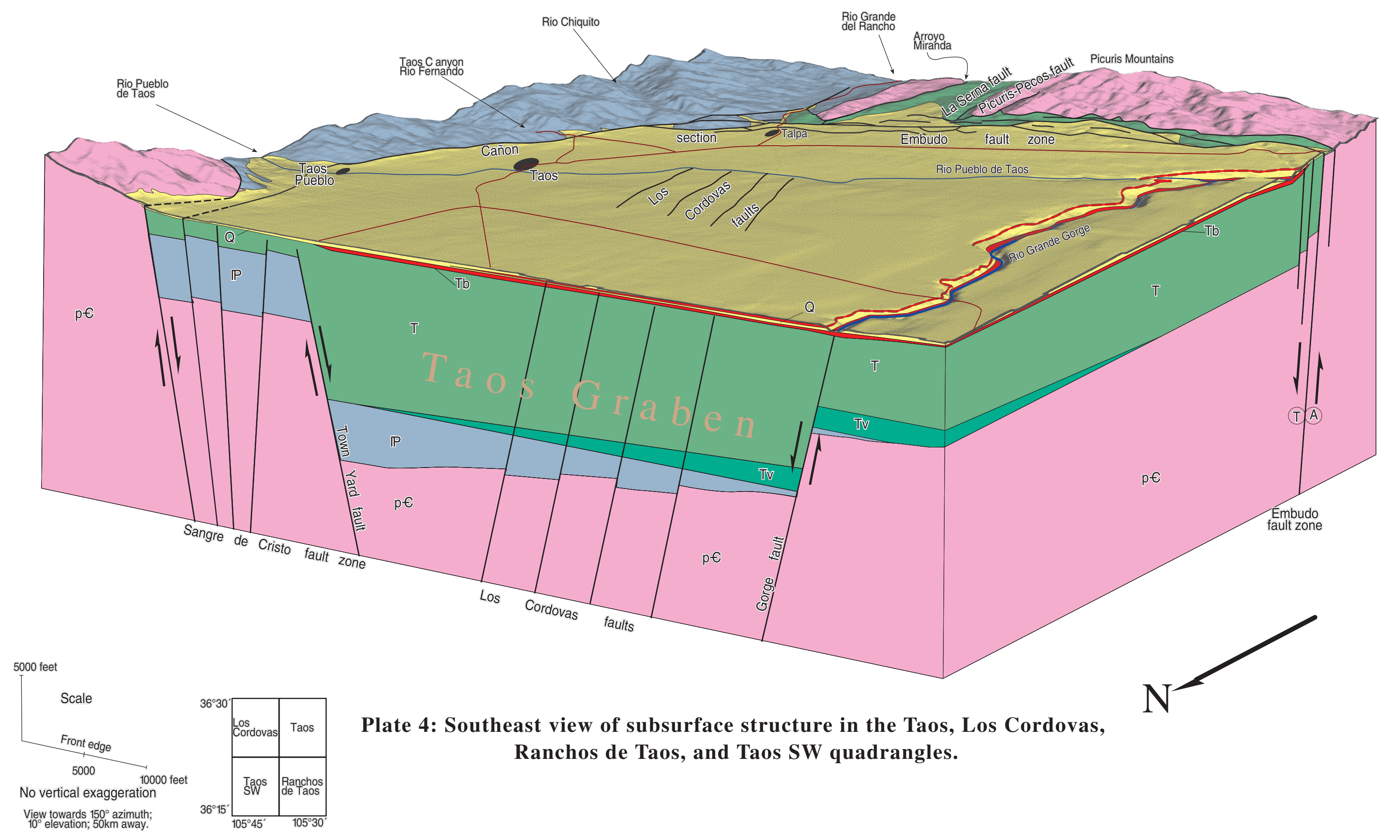
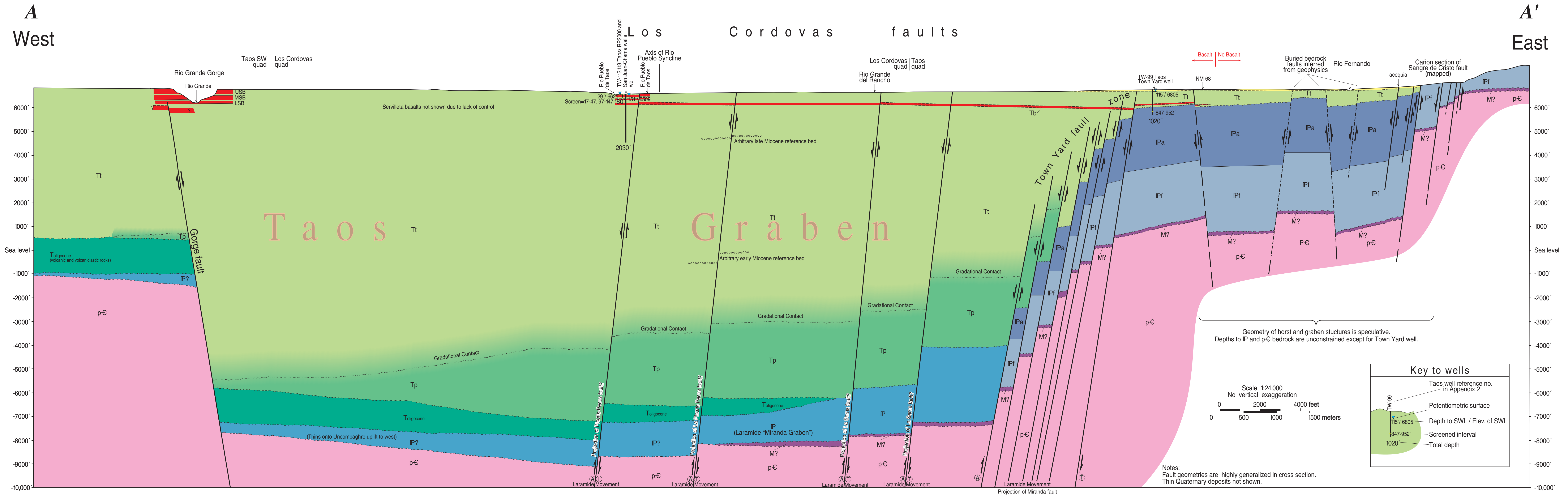
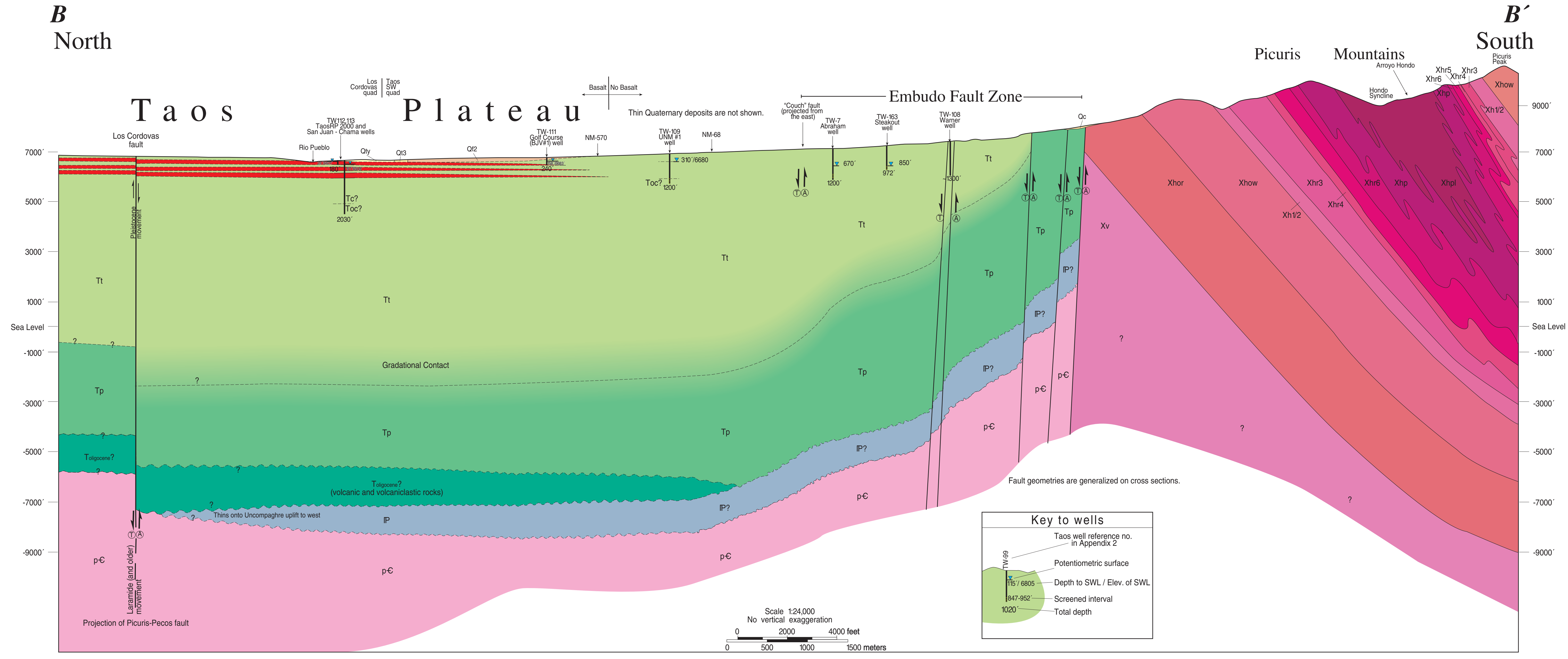


Plate 4: Southeast view of subsurface structure in the Taos, Los Cordovas, Ranchos de Taos, and Taos SW quadrangles.

Plate 1. Cross sections to accompany Plate 1 1:12,000 geologic map.



Geologic cross section through the Taos, Los Cordovas, and Taos SW 7.5´ Quadrangles, Taos County, New Mexico



North - south cross section from the Taos Plateau to the Picuris Mtns., Taos SW, and Los Cordovas quadrangles, Taos County, New Mexico

Cross Sections through Weimer neighborhood, Ranchos de Taos quad, Taos County, New Mexico

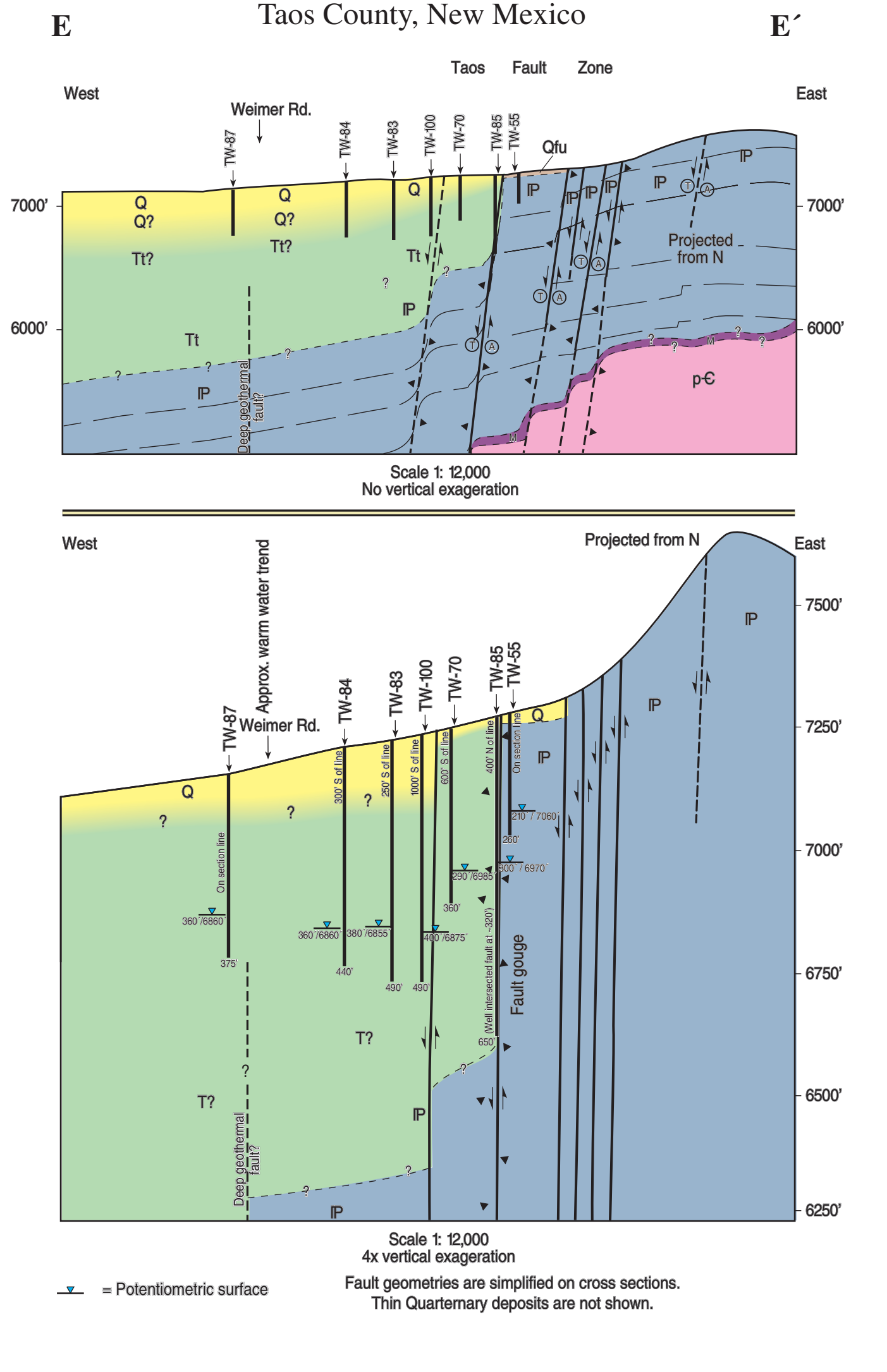
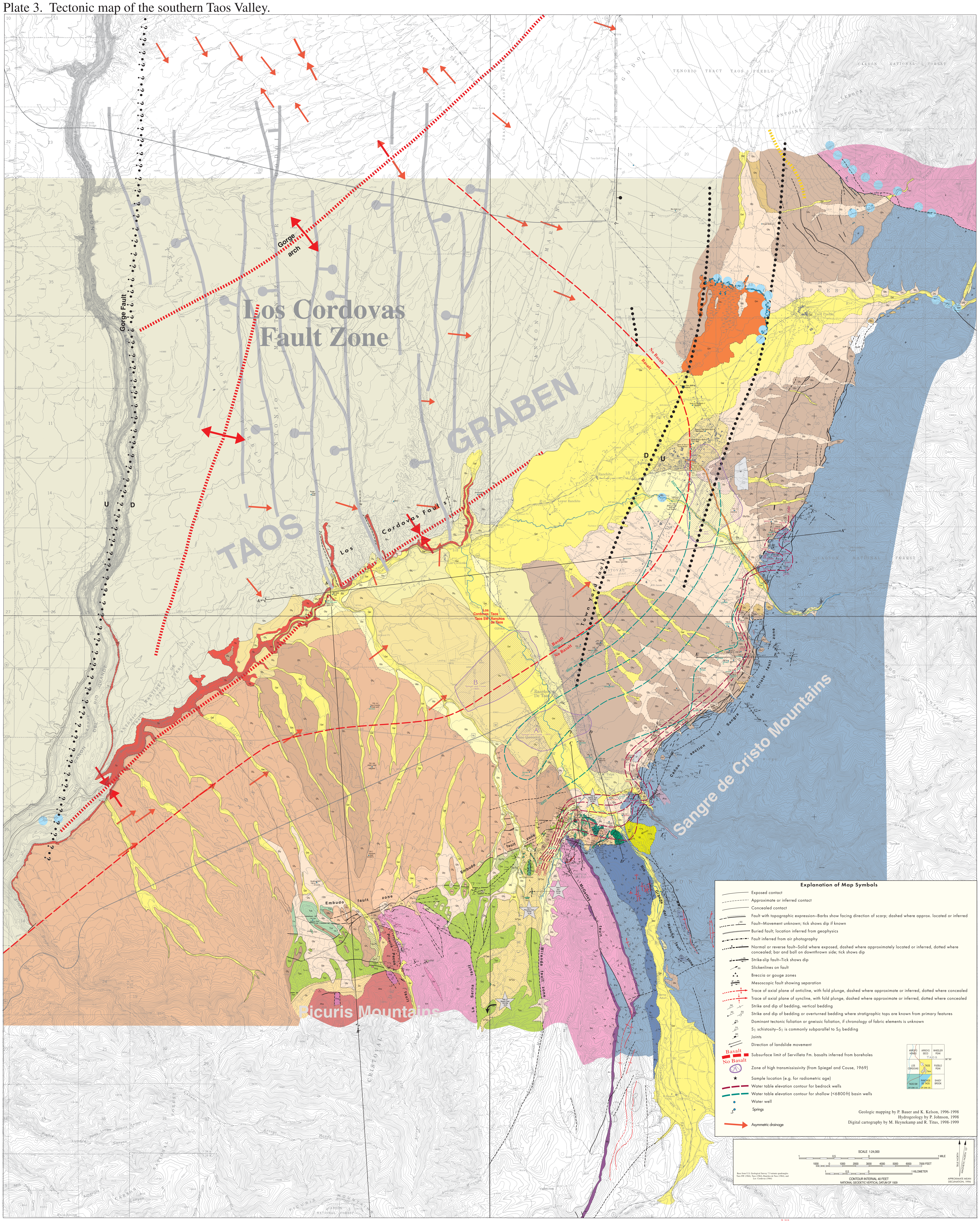


Plate 3. Tectonic map of the southern Taos Valley.



Explanation of Map Symbols

- Exposed contact
- Approximate or inferred contact
- Concealed contact
- Fault with topographic expression—Barbs show facing direction of scarp; dashed where approx. located or inferred
- Fault—Movement unknown; tick shows dip if known
- Buried fault; location inferred from geophysics
- Fault inferred from air photography
- Normal or reverse fault—Solid where exposed, dashed where approximately located or inferred, dotted where concealed; bar and ball on downthrown side; tick shows dip
- Strike-slip fault—Tick shows dip
- Slickenlines on fault
- Breccia or gouge zones
- Mesoscopic fault showing separation
- Trace of axial plane of anticline, with fold plunge, dashed where approximate or inferred, dotted where concealed
- Trace of axial plane of syncline, with fold plunge, dashed where approximate or inferred, dotted where concealed
- Strike and dip of bedding, vertical bedding
- Strike and dip of bedding or overturned bedding where stratigraphic tops are known from primary features
- Dominant tectonic foliation or gneissic foliation, if chronology of fabric elements is unknown
- S_1 schistosity—S_1 is commonly subparallel to S_0 bedding
- Joints
- Direction of landslide movement
- Basalt / No Basalt: Subsurface limit of Servilleta Fm. basalts inferred from boreholes
- A: Zone of high transmissivity (from Spiegel and Couse, 1969)
- Sample location (e.g. for radiometric age)
- Water table elevation contour for bedrock wells
- Water table elevation contour for shallow (<6800 ft) basin wells
- Water well
- Springs
- Asymmetric drainage

ARROYO HONDO	ARROYO SECO	WHEELER PEAK
LOS CORDOVAS	TAOS	PUEBLO PEAK
TAOS SW OF-DM-12	RANCHOS DE TAOS OF-DM-33	SHADY BROOK

Geologic mapping by P. Bauer and K. Kelson, 1996-1998
Hydrogeology by P. Johnson, 1998
Digital cartography by M. Heynekamp and R. Titus, 1998-1999

Base from U.S. Geological Survey 7.5-minute quadrangles
Taos SW (1964), Taos (1964), Ranchos de Taos (1964), and
Los Cordovas (1964)

SCALE 1:24,000

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

TRUE NORTH
MAGNETIC NORTH 10°
APPROXIMATE MEAN DECLINATION, 1996