

The geological framework of the Pecos Valley and the evolution of the Roswell groundwater basin in Chaves and northern Eddy Counties, New Mexico

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Abstract

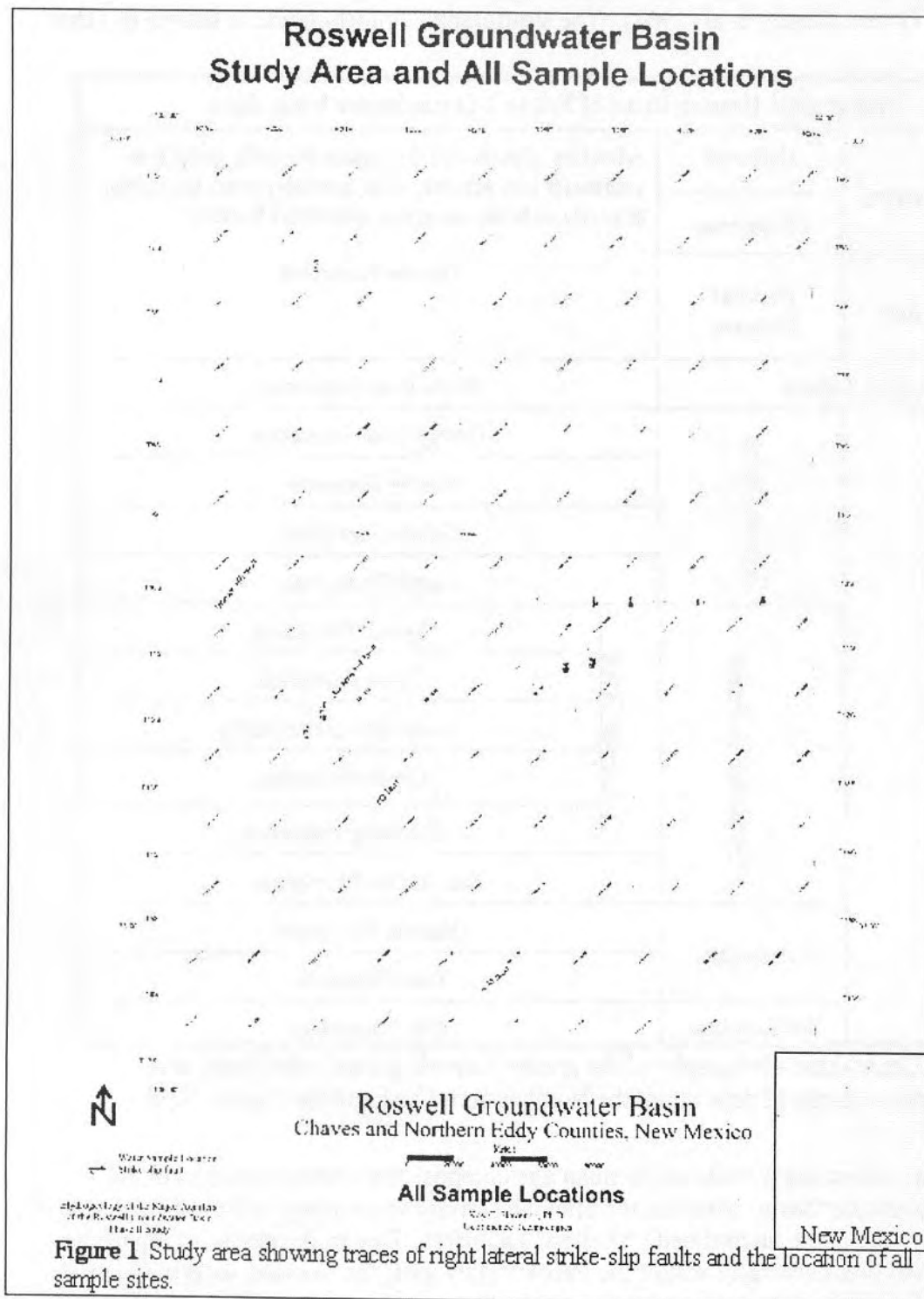
The stratigraphy and geological structure of the Roswell groundwater basin combine to provide a complex *en echelon* series of sub-basins. The Permian age formations have been uptilted, beveled, and displaced by Tertiary-Quaternary neotectonic dextral strike-slip faults. The uplifted, beveled, offset blocks have been subjected to erosion and/or dissolution since early Tertiary. Variations in aridity and temperature, including considerable moisture during the late Pleistocene late glacial maximum, have given rise to important cycles of downcutting and deposition to form the present distributions of Tertiary-Quaternary alluvial deposits, terraces, and youngest alluvial materials of the streams tributary to the Pecos River. The subsurface structural and stratigraphic geology of the study area has been mapped using formation data from 2,486 geophysical logs to construct a geologic framework for study of the groundwater basin.

An examination of the geomorphology, stream sinuosity, and paleoclimatology of the region strongly demonstrates the intertwined influences of stratigraphy, structure, and climate upon the development of the Roswell groundwater basin. Climate drove the erosion of structurally disturbed rock formations and the subsequent deposition of alluvial materials. The Eocene to early Miocene erosional period was indicative of increasing aridity. The late Miocene, Pliocene, and early Pleistocene depositional period pronounced a trend of gently increasing humidity and precipitation. By the end of Pliocene time, about 1.8 Ma, the Pecos fluvial system and its tributaries had buried their valleys and covered the divides that formerly separated them. The cold, moist climate of the late Pleistocene, 70 to 33.5 Ky, enabled the Pecos Slope, Pecos Valley, and Llano Estacado into West Texas to support an extensive sagebrush and grassland distribution. Late Pleistocene glacial maximum produced a pluvial climate in southern New Mexico. The mountainous areas developed some alpine glaciation.

Evidences from latest Pleistocene to the present demonstrate over 10 Ky of increasing aridity resulting in well-dated vegetal changes and extensive sand dune development throughout the region. The conclusions from paleoclimatologic and geomorphologic data in the region are indisputable geologically long-term evidences of decreasing precipitation and increasing evaporation. Short-term periods of slightly increased precipitation or cooler temperatures have occurred during the past 10 Ky, but those cycles are few and geologically short compared to the overall geological-time trend of increasing aridity and higher mean annual temperatures.

Study Area

The area of study covers about 5,400 mi² in Chaves County and the northern edge of Eddy County, New Mexico and is shown in Figure 1.



Stratigraphy

The stratigraphic section relevant to the Roswell groundwater basin includes the Permian, Triassic, Tertiary, and Quaternary periods. Extensive discussions of the stratigraphy of the area are made in Feidler and Nye (1933), Hawley (1993a, b, c), Havenor (1968, 1996, 1998), Kelley (1971), and Kinney et al (1968). The stratigraphic nomenclature is shown in Table 1.

Stratigraphic Nomenclature of Roswell Groundwater Basin Area				
Late Cenozoic	Quaternary	Holocene	Alluvium, stream and floodplain deposits, gravels in pediments and terraces, soils, aeolian sands, trayer-tine deposits, caliche, collapsed solutional features	
		Pleistocene		
	Tertiary	Pliocene Miocene		
			Gatuña Formation	
Upper Triassic			Santa Rosa Sandstone	
Permian	Ochoan Series	Dewey Lake Formation		
		Rustler Formation		
		Salado Formation		
		Castile Formation		
	Guadalupian Series	Artesia Group	Tansill Formation	
			Yates Formation	
			Seven Rivers Formation	
			Queen Formation	
			Grayburg Formation	
		San Andres Formation		
	Leonardian	Glorieta Formation		
		Yeso Formation		
	Wolfcampian	Abo Formation		

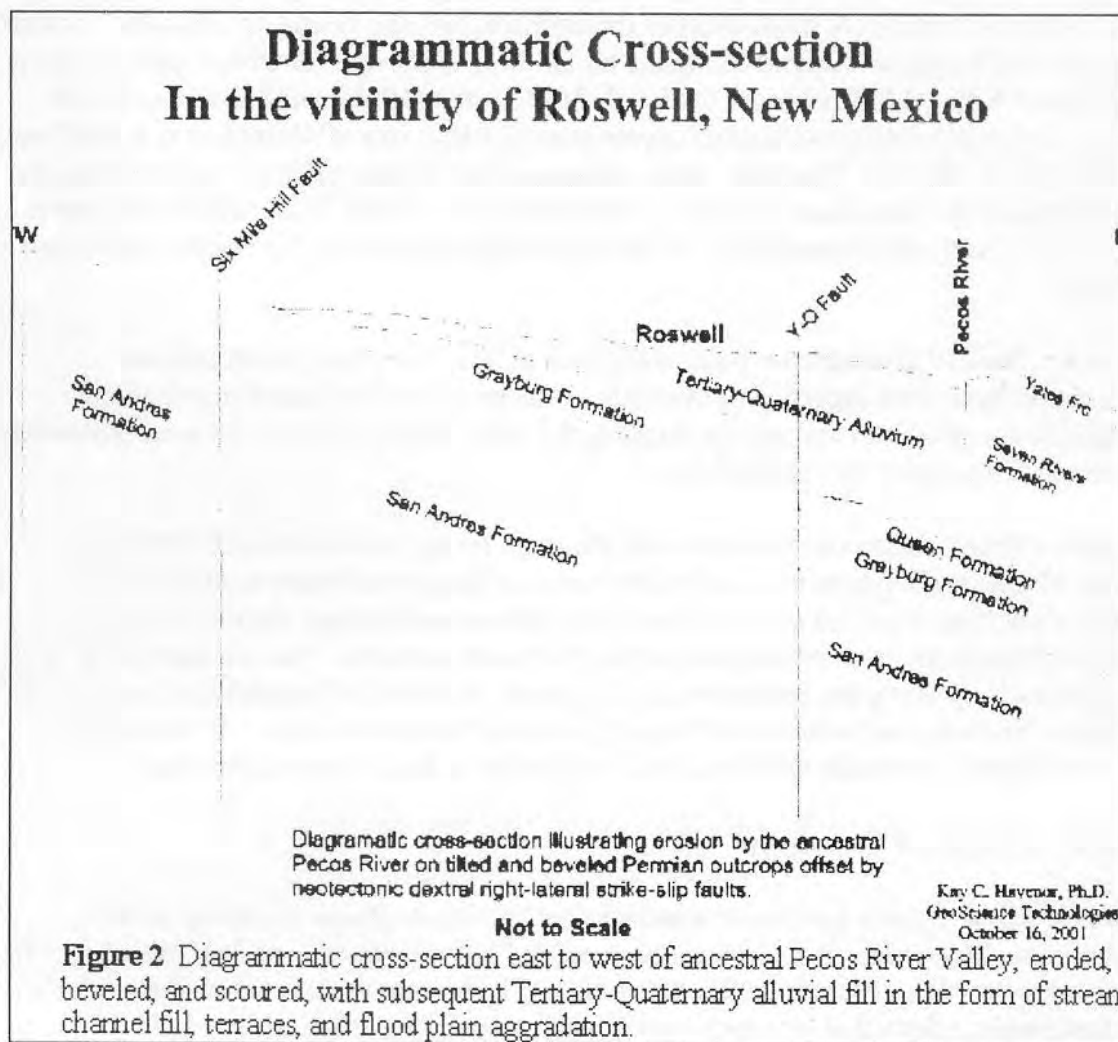
Table 1 Generalized stratigraphy of the greater Roswell groundwater basin area adjoining environments of deposition: the Northwestern Shelf and the Capitan Reef

In general, the sedimentary rocks of Permian age compose the artesian aquifers of the Roswell groundwater basin; whereas, the alluvial Tertiary-Quaternary sediments and Artesia Group rocks makeup the unconfined ("shallow") aquifers. Due to the eastward dip of the Permian formations, especially within the Pecos Valley area, the beveled Artesia Group is progressively overlain in angular unconformity by Tertiary-Quaternary deposits. Beneath

and west of the Pecos River the distribution of the Artesia Group presents generally north-south striking outcrops with subcrops buried beneath the Late Cenozoic alluvial cover.

The Roswell groundwater basin has both unconfined and confined aquifers. The artesian system is developed in the San Andres Formation carbonates and in the solution disturbed boundary zone along the San Andres Formation and Artesia Group contact. The unconfined aquifers are developed in the Tertiary-Quaternary deposits and in contact intervals between porous, permeable Artesia Group formations and the Late Cenozoic alluvial beds or the Gatuña Formation. One of the Tertiary-Quaternary and lower Artesia Group aquifers is unconfined and becomes confined in the northern-half of the study area (Havenor, 1998, 2002).

The complex stratigraphic relationships of the aquifers to structural tilting, faulting, beveling, and repeated stream incision and deposition is diagrammatically shown in Figure 2. The demarcation of Tertiary-Quaternary, especially Gatuña Formation, from Artesia Group is difficult in samples and often misidentified (Kinney et al., 1968; Havenor, 1998, 2002).



Important features in the Permian and Tertiary-Quaternary alluvial deposits have been described and/or mapped by Feidler and Nye (1933), Hawley (1993a, b, c), Havenor (1968, 1996), and Kelley (1973, 1980), including their surface distribution, terraces, pediment deposits, calcrete formation, and solutional collapse.

Structure

Havenor (1996) discussed the different tectonic episodes from the Precambrian to the present that have influenced the groundwater basin during the Cenozoic. These include an undetermined number of Precambrian orogenies and at least three episodes of Phanerozoic deformation: post-Meramec Mississippian to Late Permian, Late Cretaceous to early Tertiary Larimide, and middle Tertiary through Quaternary. Each episode left a distinctive structural signature on the region.

Structure of Precambrian Basement

Outcrops of Precambrian rocks are restricted to two locations in the greater Roswell groundwater basin area. A small inlier of melasyenite, syenite, quartz syenite, alkali granite, and pegmatite located at Pajarito Mountain on the Mescalero Apache Reservation has been described by Kelley (1971), Moore et al. (1988), Bowsher (1991), and Foord and Moore (1991). A second exposure is located approximately 8 km west of Mescalero in a small area near Bent, New Mexico. The Bent Dome, an area of only a few hundred square meters, has been described by Lindgren et al. (1910), Bachman (1954, 1960), Foster (1959), Moore et al. (1988), and Foord and Moore (1991), as diorite and granite overlain by Cambro-Ordovician sandstone.

Within the Roswell groundwater basin study area at least 100 penetrations into the Precambrian have been logged geophysically. It is the subsurface data that provide the greater amount of control and permit mapping the area. Figure 3 shows the present structural configuration on top of the Precambrian.

The present Precambrian configuration sets the stage for an understanding of structural controls on the development of the relatively near-surface groundwater aquifers. The tectonic disturbances visited upon the post-Precambrian sedimentary formations form the structural framework upon which geomorphic processes operated. The northeast structural grain, particularly along the southernmost K-M fault, is probably Precambrian in origin, with Larimide-Cenozoic reactivation—and possibly even strike-slip reversal. All of the faults shown in Figure 3 are believed to be dextral strike-slip in their Cenozoic activity.

Structure of Paleozoic Formations

The top of Mississippian Limestone structure (not shown) is similar to the top of the Precambrian. Mississippian rocks have been eroded off the western one-half of the map area during early Permian Pedernal uplift and erosion. The present dextral offset along the K-M fault is strongly reflected in structural and isopach maps of the Mississippian and Pennsylvanian subsurface.

Structure onTop of Precambrian "Basement"

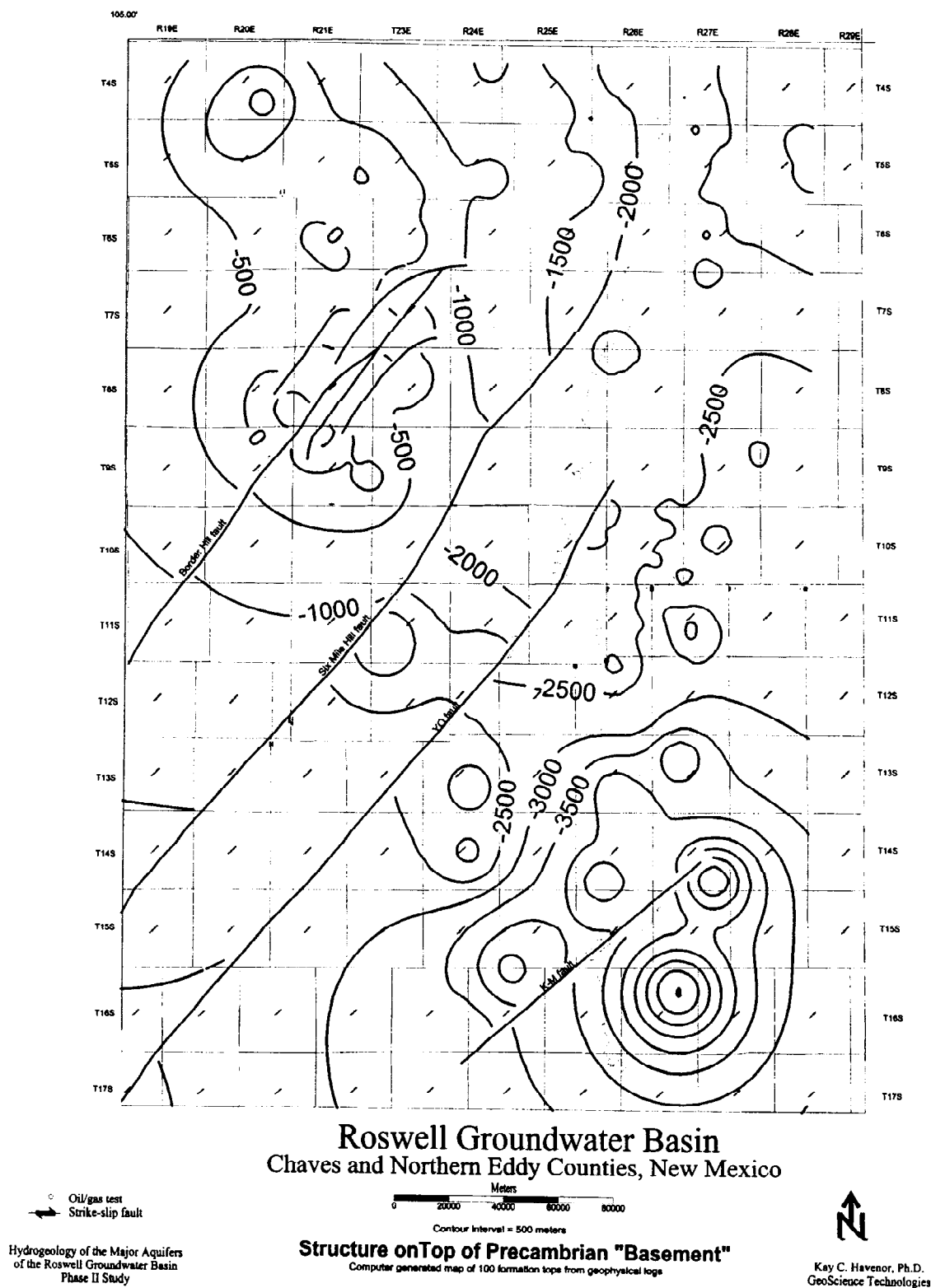


Figure 3. Structure on top of the Precambrian.

Structure on top of the Early Wolfcampian Permian Abo Formation is provided by 1,509 subsurface geophysical logs and is shown in Figure 4.

Structure onTop of Abo Formation

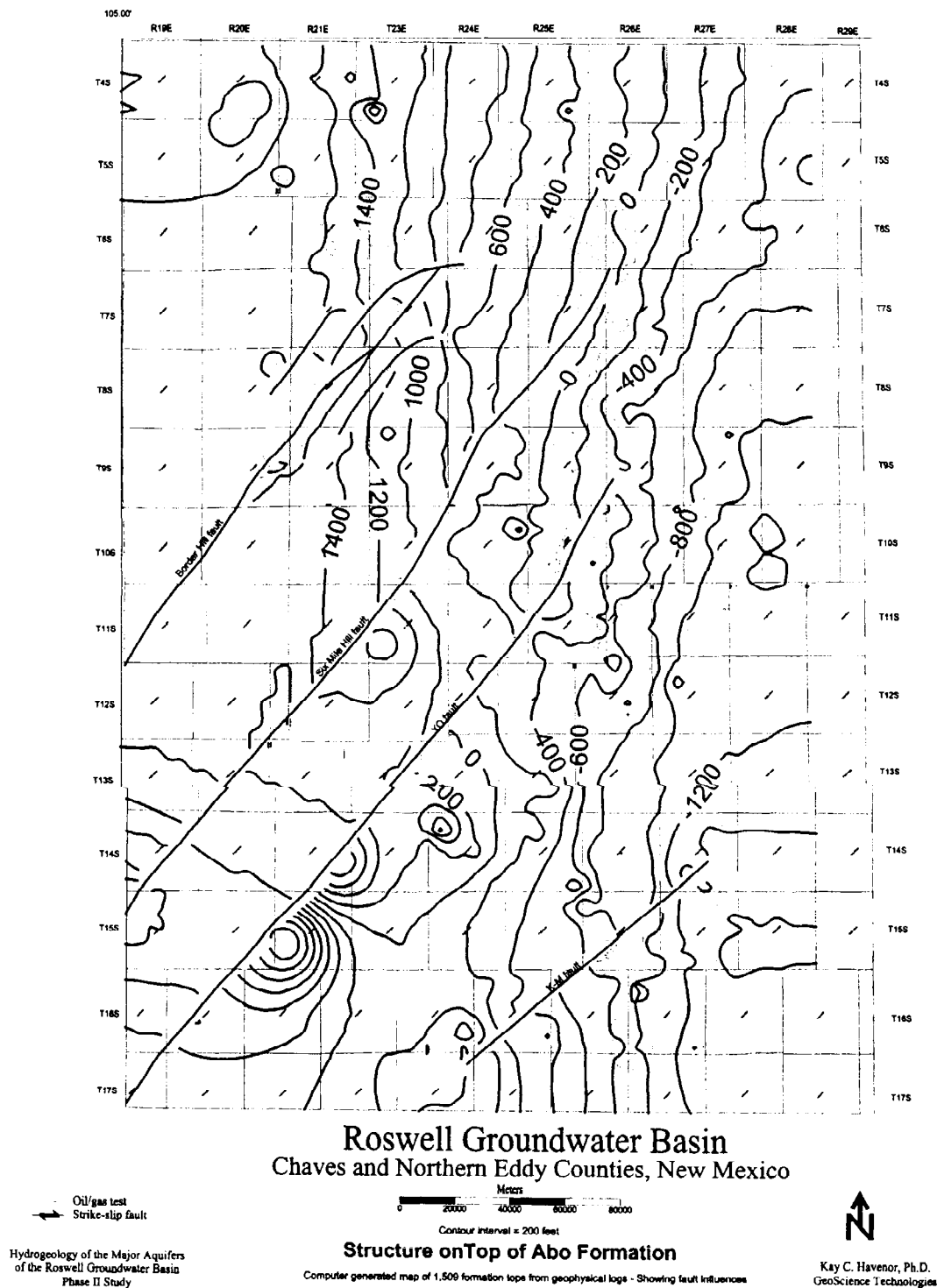


Figure 4. Structure on top of Abo Formation.

The effects of dextral strike-slip faulting on the present top of Guadalupian San Andres carbonates are compounded by Late Laramide and Tertiary uplift, eastward tilting, and extensive erosional beveling of the Yeso, San Andres, and Artesia Group. Beveling exposed the Artesia Group in the present Pecos Valley. The San Andres Formation is exposed immediately to the west of the valley, and the Yeso and Abo formations are exposed in the Sacramento Mountains to the west. The structure on top of the San Andres Formation, shown in Figure 5, was developed using 1,484 geophysical log tops.

The top of San Andres (looking southwest), a 3-D representation, is shown in Figure 6. The 3-D view shows the present low structural surface (on the east side) without the overlying, westward thinning, beveled edge of east-dipping Artesia Group. These units formed the geomorphic surface of the pre-valley-fill deposits of the Pecos River system and the northeastward shifting beveled-wedge blocks created by strike-slip faulting. This 3-D view symbolizes the compound effects of synchronous tilting, extensive erosion, and dextral strike-slip offset.

The appearance of vertical offset along the faults actually is the result of northeast displacement of the tilted, beveled wedges of resistant San Andres Formation carbonates. In the area beneath the present location of the Pecos River, the fault displacements also place some of the San Andres carbonates in juxtaposition with wedges of Artesia Group on the southern side of the faults. These configurations are significant in their control of the movement and quality of meteoric water occupying the aquifers.

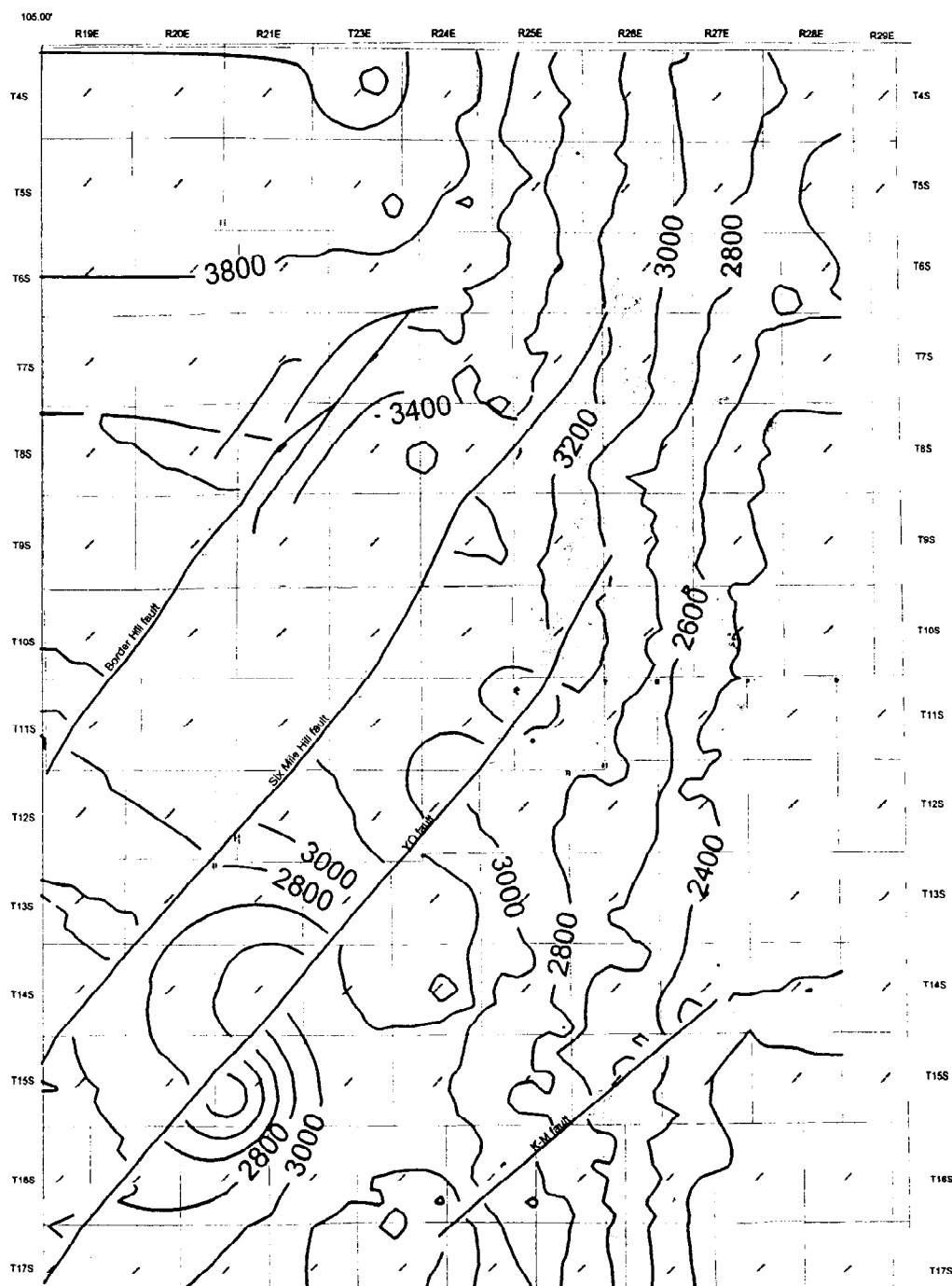
Dating of Faulting

Insufficient information is available to closely date the strike-slip faulting in the study area. Kelley (1971, p. 1) stated, "These buckles are right-wrench fold-faults which are undoubtedly Precambrian rooted and show evidence of activity at least as old as Permian." Robert Casavant (pers. comm. 2000, 2001) also argues that the faults follow well-established Precambrian trends and may in some cases exhibit displacement reversals. It is possible that the K-M fault displacement may be reactivation along a pre-existing Precambrian fault. However, the Border Hills, Six-Mile Hill, and Y-O faults appear more related to the stress fields originated in the Laramide to early Tertiary regional tectonics of the Colorado Plateau movement during development of the Rio Grande rift, intrusion of the Sierra Blanca volcanic pile, and uplift of the Capitan Mountains stock.

The Border Hills, Six-Mile Hill, Y-O, and K-M faults exhibit many incidents of right-lateral stream offsets that support middle to late Tertiary and Quaternary tectonic activity. Current (1999-2000) mild earthquake activity has been recorded along the southwest end of the K-M fault suggesting the probability of continued (neotectonic) activity. No reports of historical seismic activity have been noted involving the other faults in the study area.

Stream sinuosity plots of both the Pecos River and its tributaries clearly demark the locations where the streams cross or parallel these fault systems. One of the most impressive stream deflections occurs along the K-M fault immediately below Lake Arthur, New Mexico.

Structure onTop of San Andres Formation



Roswell Groundwater Basin Chaves and Northern Eddy Counties, New Mexico

Oil/gas test
Strike-slip fault

Hydrogeology of the Major Aquifers
of the Roswell Groundwater Basin
Phase II Study

Structure onTop of San Andres Formation

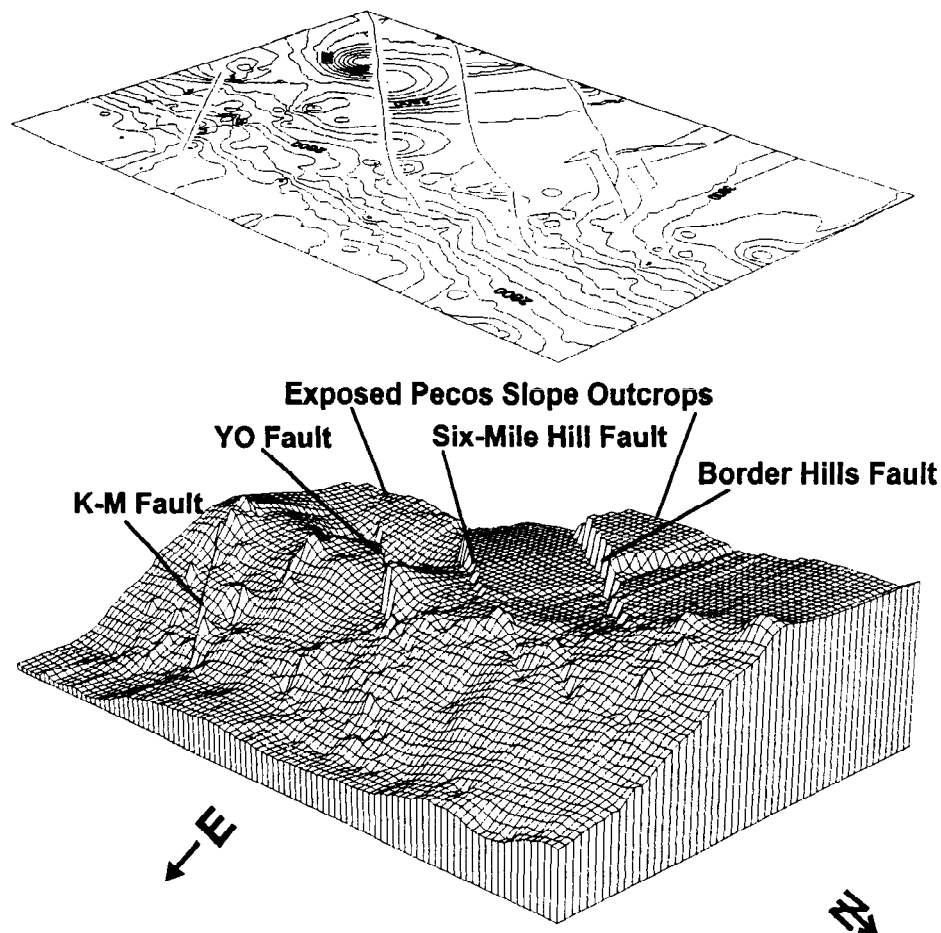
Computer generated map of 1,464 formation tops from geophysical logs



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Figure 5. Top of San Andres Formation.

3D View Top San Andres Formation - Looking Southwest



Roswell Groundwater Basin Chaves and Northern Eddy Counties, New Mexico

Hydrogeology of the Major Aquifers
of the Roswell Groundwater Basin
Phase II Study

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Figure 6. 3-D Top of San Andres Formation looking southwest.

The Pecos River has strong right-lateral offset, and the eastward continuation of the fault coincides with the northeast trending Long Arroyo.

Figure 7, below, is a LandSat 7 satellite image of the Lake Arthur, New Mexico, area showing the southwest (right-lateral) offset to the course of the Pecos River and the trace of the northeastward trending Long Arroyo. The presence of this fault was first identified in 1965 by the author in the subsurface about 10 miles to the northeast of this image. This LandSat 7 image was captured July 7, 1999.

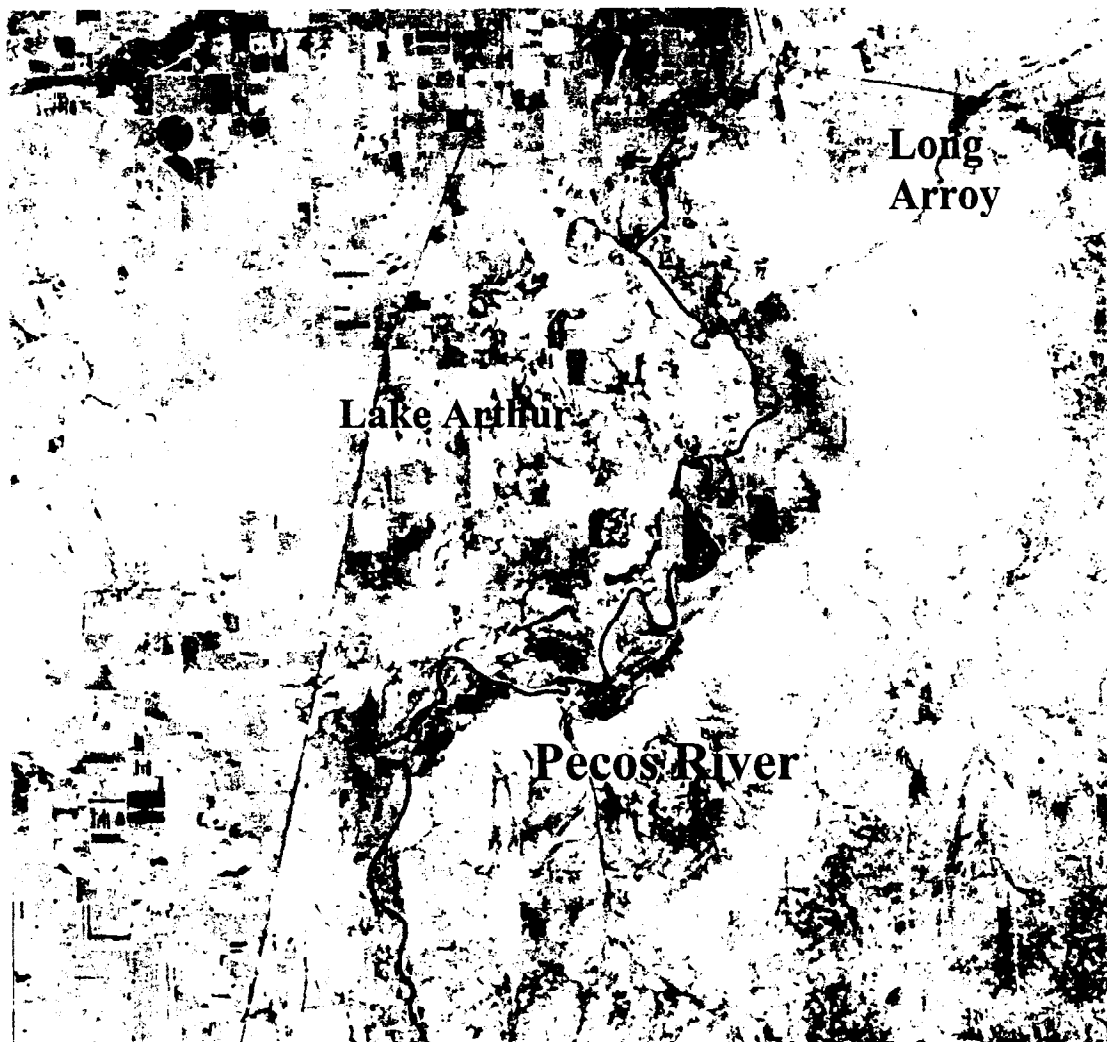


Figure 7. LandSat 7 satellite image of right-lateral Pecos River stream deflection along the K-M fault. Image date July 7, 1999. Image processing by Dr. Kevin Horstman, Tucson, Ariz., and the author.

A sinuosity plot from north of Roswell to below Artesia, New Mexico, shows a marked anomaly crossing the location of the K-M fault. Tributary streams, such as the Cottonwood and Walnut Creek, also show an anomaly in the sinuosity plots where they cross the projected trace of the K-M fault southwest of the Pecos River.

Figure 8 is a sinuosity plot along Walnut Creek beginning approximately 45 km west of the Pecos River. Walnut Creek crosses the K-M fault at the 30 km point. This is a geomorphic tool that is useful in detecting structural anomalies such as the strike-slip faults present in southeastern New Mexico (Dr. Robert Cassavant, pers. comm. 2000, 2001).

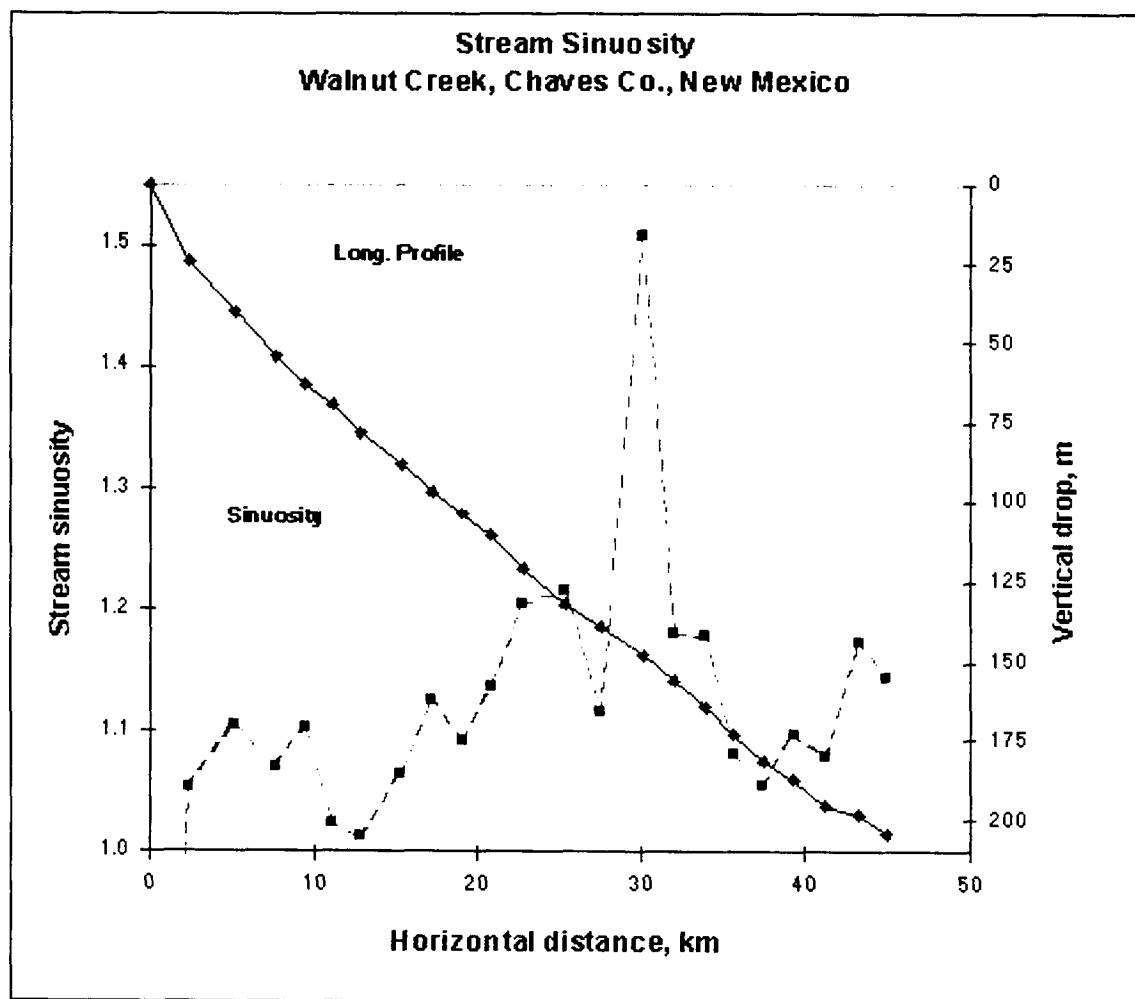


Figure 8. Sinuosity plot along Walnut Creek, southern Chaves County, New Mexico.

Evidence of Fault Control of Groundwater Movement

Mazor (1991, p. 83) said, "... one can never deduce flow directions from water levels alone." This statement is abundantly clear in the Roswell groundwater basin. The Roswell groundwater basin is composed of seven aquifers (Havenor, 1998, 2002): three unconfined ("shallow"), three confined (deep or "artesian"), and one both unconfined and confined ("undifferentiated"). Water level data accumulated over the years have been traditionally allocated to the "shallow" aquifer or the "artesian" aquifer. With water levels combined from four unconfined ("shallow") or four confined ("artesian") aquifers and mapped as if they were two units, Mazor's statement is especially meaningful.

Understanding that the chloride in groundwater is a conservatory ion—no water-rock reactions *remove* chloride from the water—allows the generalization that the longer/further the groundwater moves through the rock, the concentrations only will increase. It follows that mapping chloride concentrations in individual aquifers will yield directions of groundwater movement within that aquifer. Stated in an alternative manner: water

Chloride Concentrations Artesia Group-San Andres Melange (M) Aquifer

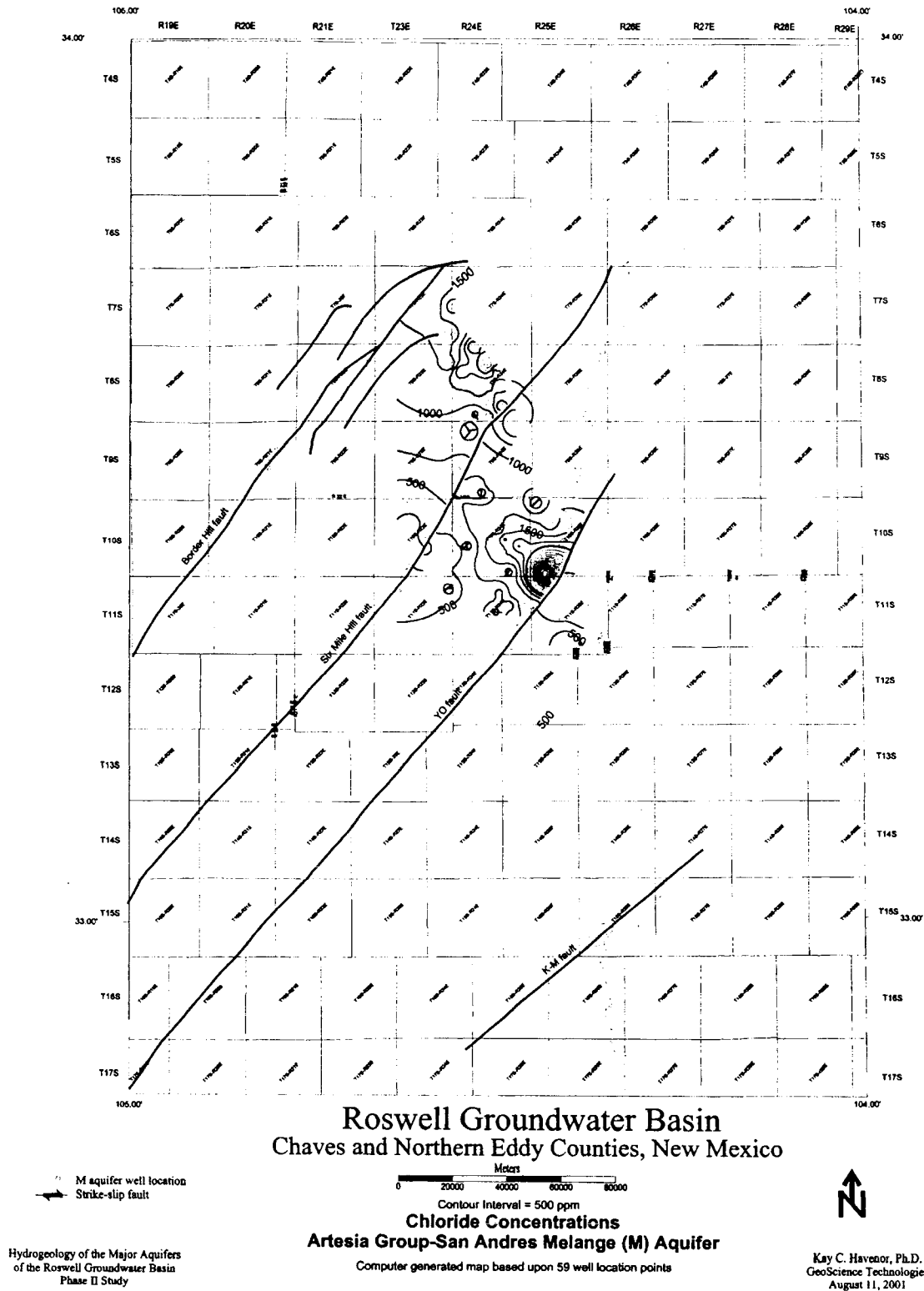


Figure 9. Isochlor of San Andres—Artesia Group Melange Aquifer, Chaves County, New Mexico.

flowing down-gradient does not improve its water quality relative to chloride concentrations. This is especially useful in a geologically complex aquifer system.

Figure 9 is an isochlor map of the upper-most “carbonate” artesian aquifer, the Melange aquifer (Havenor, 1996), in the top of the San Andres Formation and basal Artesia Group. The Artesia Group forms the aquiclude/aquitard above the aquifer. On the eastern margin of the Roswell groundwater basin, the Melange aquifer is cut and right-laterally offset by the Y-O fault. The northern beveled block, the Roswell block, places the Melange aquifer in juxtaposition with the portion of the Artesia Group that 1) forms the aquiclude/aquitard and 2) contains abundant evaporitic deposits—including halite.

The contours on the northside of the Y-O fault show a high chloride value of 6931 mg/l compared to 310 and 428 mg/l on the south-side (Havenor, 2002). The Y-O fault is a significant boundary preventing contamination of the potable water portion of the Melange aquifer on the south. It also can be noted in Figure 9 that isochlor gradients depict different flow directions on the Roswell block and the Six-Mile Hill block to the north. Undifferentiated artesian aquifer water levels (potentiometric surface levels) show a groundwater flow toward the east-southeast. Similar effects are demonstrated in other aquifers within the (Havenor, 2002).

Tertiary-Quaternary Geomorphology and Climatology

The Pecos Slope was tectonically disturbed by early to middle Tertiary (Eocene to Oligocene) by igneous felsic intrusions, volcanics, and dikes of the Sierra Blanca complex 37.3 Ma to 25.8 Ma (Cather, 1991) and late Oligocene Capitan Mountain stock emplacement 26.2 ± 1.2 Ma (Allen, 1988). Some Southern Rocky Mountain uplift, with considerable Rio Grande rift activity, continued throughout the Tertiary. The Rio Grande rift related fault block uplift, the cause of the major structures and topography of the Sacramento dip slope, was completed in early Pliocene, approximately 4 Ma (Hawley, 1993a, 1993c). Permian San Andres Formation beds dip eastward from elevations of >2,135 m in the Sacramento Mountains to >-1,525 m msl near the New Mexico and Texas state boundary.

By middle Miocene (approximately 15 Ma), southeast-flowing streams had completed most of their downcutting and created valleys developed in Paleozoic rocks. In the upper Sacramento Mountains, erosional beveling cut into east-dipping Yeso and Abo formations. In the Duncan – Hondo areas, beveling had cut into the middle San Andres Formation. The entrenched present Pecos Valley progressively exposed Artesia Group formations stratigraphically as high as the Yates Formation and portions of the overlying Rustler Formation. During this time most of the cavernous porosity in the Melange and other San Andres Formation carbonate aquifers probably developed by circulating meteoric water. The scoured-out Permian exposures in the Pecos Valley developed extensive karstic, solutional, and cavernous porosity.

Late Miocene through Pliocene (approximately 12 Ma to 2 Ma) saw fluvial and eolian aggradation from north, west, and east that locally buried the scoured-out and solutional subsidence features in the Pecos Valley. The thickness of Cenozoic deposits in the southern

portion of the study area is presently up to 100 m (Welder, 1983). Deposits of Ogallala and Gatuña Formation, both fluvial and eolian, formed the basal beds in the valley and also created the Llano Estacado region of eastern New Mexico and West Texas.

Miocene to Pliocene time was one of increasing aridity. Hawley (1993a) characterized the Pliocene to mid-Pleistocene as an arid and continental climate. Decreasing aridity in the late Pliocene to early Pleistocene, with wetter, cooler glacial-interglacial cycles, fostered some re-entrenchment in the Pecos Valley—probably because of base level lowering resulting from on-going solutional subsidence in the Toyah basin to the south, in Texas (Dr. John Hawley, 2002, pers. comm.).

The convergence of stream and terrace profiles associated with increasing aridity have been demonstrated by Peizhen et al. (2000), Skotnicki and Spencer (2000), and Pèwè (1978). Similar observations are noted in the terraces of the Pecos Valley described by Nye (Fiedler and Nye, 1933).

Soon after early Pleistocene, the ancestral Pecos River captured east-flowing montane drainage north of the study area (Dolliver, 1984). Hawley (1993a) and Hawley et al. (1976) indicate that the increased moisture of early to middle Pleistocene allowed the headward and eastward eroding Pecos River to capture the ancestral Brazos River above Ft. Sumner, New Mexico.

From both enlargement of its drainage basin in glaciated headwater areas and lowering of its base level downstream in the Toyah basin to the south, the Pecos River and tributary streams began downcutting into the alluvial cover. The Cenozoic alluvial deposits developed upon the valley floor, scoured-out of upper Paleozoic rocks, are now recognized as Nye's (1933) Diamond A—Mescalero, Blackdom, Orchard Park, and Lakewood terraces (also see Hawley, 1993a, 1993c; Hawley et al., 1976). The re-entrenched Pecos Valley alluvial deposits were re-buried in the Quaternary cycle of stream and floodplain deposition.

The shallow alluvial (unconfined) aquifers were developed within this complex of Cenozoic alluvium and Permian Artesia Group beveled beds below the alluvium. Where shallow alluvial aquifers are in angular unconformity with porous sandstones, dolomites, and solution affected evaporates of the Artesia Group, portions of the Artesia Group become part of the shallow unconfined (and confined) aquifer system. It often is difficult to distinguish in samples the Tertiary-Quaternary and Artesia Group boundary (Kinney et al., 1968), especially where the Tertiary-Quaternary beds contain redbeds and evaporates, as in the Gatuña Formation (Hawley, 1993b; Kelley, 1980). The first redbeds drilled does not necessarily define Permian rocks.

Throughout the earlier Tertiary, while erosion was exposing the Artesia Group within the Pecos Valley and older Permian beds to the west, the northeast trending strike-slip faults were active. Currently observed offsets seen in the Pecos River and the eastward flowing tributary streams probably reflect displacements that have occurred since mid-Pliocene (approximately 5 to 4 Ma). As discussed above, these faults possibly are neotectonic, although the major Laramide and Rio Grande rift stress fields have all but disappeared

(Dr. John Hawley, pers. comm., 2002 suggests that the river offsets also may be caused by differential erosion and the stream accessed the easiest path).

Paleoclimatology

Plate tectonics and regional tectonics are the primary factors that have influenced climatic conditions since the Laramide. Gregory and Chase (1992), in their study of a major late Eocene erosional surface in southern Colorado, concluded that without violent flood events, such as the 1976 Big Thompson flood, the deep canyons seen today would not exist.

The present elevations of the Sierra Blanca and Capitan Mountains (3,900 to 3,000 m, respectively) are probably much less than when originally emplaced or uplifted. The amount of Paleozoic and Mesozoic sediment that had to be removed to bevel the formations to their present stratigraphic levels probably exceeds 3,500 km³. The incised stream deposits of the tributaries to the Rio Hondo, Rio Felix, and others in the area contain boulders and cobbles that attest to the existence of steep gradients and significant flow volumes. Figure 10 is a digital elevation model of the greater study area showing the present-day drainage system. The drainage of the Rio Hondo is a dominating feature, although unquestionably with greatly diminished present-day flow.

Late Miocene to early Pliocene, approximately 12 to 4 Ma, was the time of alluvial deposition in the scoured-out and solutional depression fill of the ancestral Pecos Valley and its tributary's stream valleys. As the previous erosional period (Eocene to early Miocene) was indicative of increasing aridity, the late Miocene, Pliocene, and early Pleistocene deposition resulted from gently increasing humidity and precipitation—although the area remained arid.

The Pleistocene epoch signaled episodic moist, cooler conditions. The colder, wetter late Pleistocene, ca. 70 to 33.5 ky, supported an extensive sagebrush and grassland distribution throughout the Pecos Slope, Pecos Valley, and Llano Estacado into West Texas (Hall, 2001). The Wisconsin Stage of the late Pleistocene produced a pluvial climate in southern New Mexico, although rock glaciers represent strong evidences of alpine ice conditions in the mountains (Blagbrough, 1999, 1991, 1984, 1976). Late Wisconsin wet conditions with massive runoff is suggested by the deep incisions seen in the Pecos, Rio Grande, Canadian, and Gila river systems (Reeves, 1976). Significantly colder and wetter climates than today are documented by sedimentary deposits, plant and animal fossils, perennial lakes, and pedologic features (Hall, 2001; Hawley, 1933a, b; Hawley, et al., 1976).

Climate fluctuations such as the Little Ice Age (ca. 1450-1850 A.D.) have occurred in the first millennium A.D. Similarly, there were cycles of climate variation in the late Pleistocene. These climatic variations have occurred worldwide and also have affected southeastern New Mexico. The evidence clearly demonstrates that since ca. 12 ky B.P. to the present, the region has become more arid (Allen and Anderson, 2000). Since the beginning of the Holocene, 10 ky B.P., drought periods have predominated and have been increasingly prolonged. Sand sheets and dunes began accumulating in the region ca. 11 ky B.P. as reported by Holliday (2001).

Digital Elevation Model of Greater Roswell Groundwater Basin Area

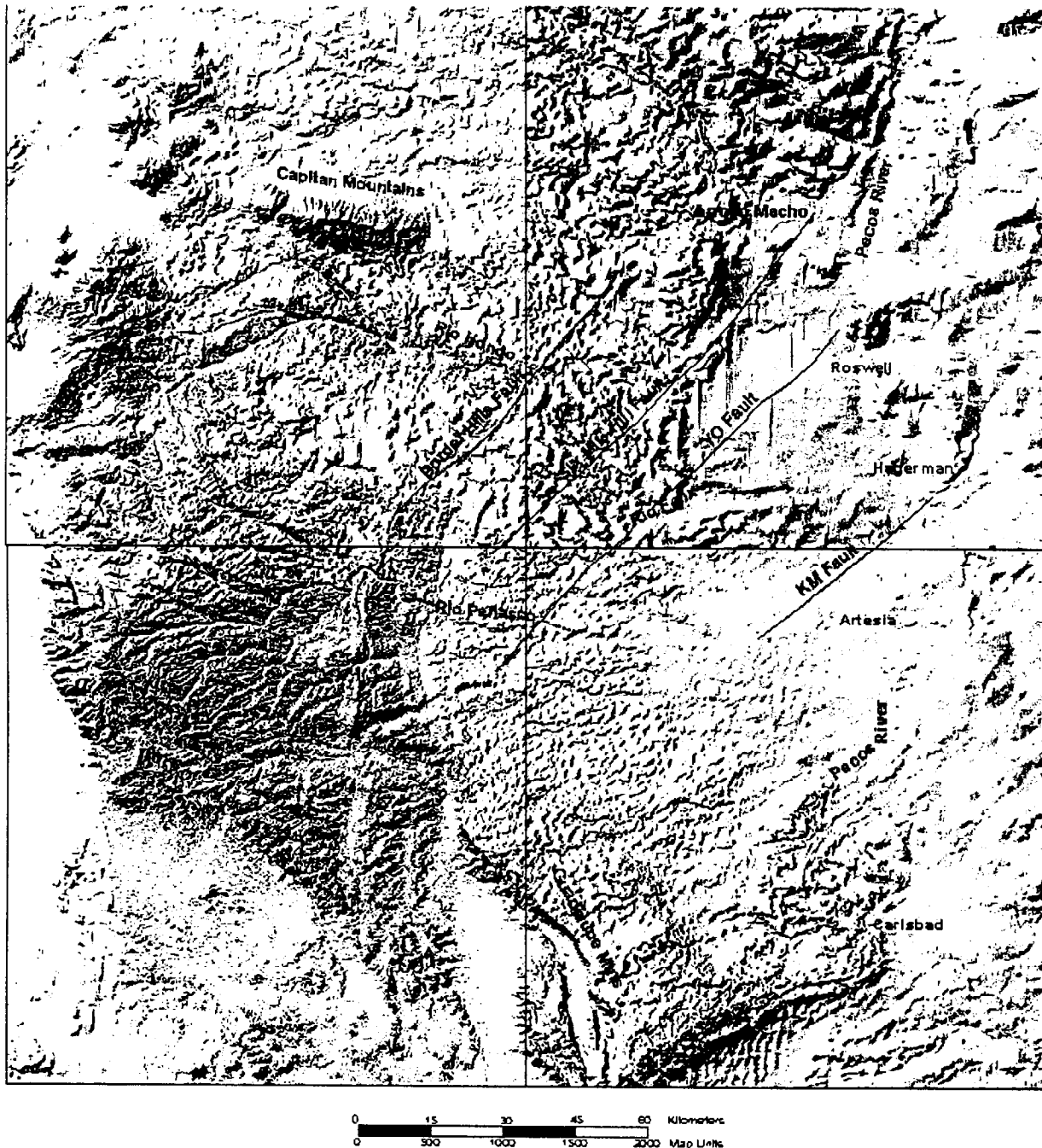


Figure 10. Digital elevation model of the greater Roswell groundwater

The climatic conclusion is simple: indisputable long-term decreasing availability of recharge to the aquifers of the region. Humans are, however, eternally optimistic that more basin precipitation is in the next set of clouds, despite knowing that drought conditions have historically predominated and may last for decades.

Conclusions

The Roswell groundwater basin is the result of a combination of tectonic uplift, igneous intrusions into the Paleozoic and Mesozoic sedimentary formations, and extensive climate driven erosional and depositional cycles during the Cenozoic. Long-term exposure, erosion, and solutational activity by circulating meteoric waters developed the porosity and permeability that embody the artesian carbonate aquifers. The unconfined aquifers are the result of stream and floodplain sand and gravel distributions and, in some cases, connect and coexist with porous and permeable Artesia Group members in angular unconformity.

The present distribution of the aquifers has been progressively modified by on-going dextral strike-slip fault activity throughout most of the Cenozoic. Modern earthquake activity, although of low magnitude, suggests that at least the K-M fault is neotectonic. The faulting of the Roswell groundwater basin has created an echelon offset erosional wedges that form a series of structural and hydrologic sub-basins through which the Pecos River flows.

The combination of sedimentary, stratigraphic, structural, and geomorphic processes that was climatically driven has developed an aquifer system composed of numerous complex, separate, unconfined, and confined aquifers. The development processes began over 60 Ma and are continuing today. Understanding how the Roswell groundwater basin was formed and how the aquifers and the streams relate will enable us to realistically manage them.

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