Gravity Geophysical Analysis of Spring Locations in a Karstic Desert Basin, Cuatro Cienegas Basin, Coahuila, Mexico

Brad D. Wolaver[1], John M. Sharp, Jr.[1], and Juan M. Rodriguez[2]

[1]Department of Geological Sciences, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX 78712-0254

[2]Departamento de Geohidrología y Geofísica, Universidad Autónoma de Nuevo León, San Nicolás de los Garza, N.L., México

Main Menu

Search

Author Index

Papers

Help

ABSTRACT

This research uses land gravity geophysical surveys to infer subsurface geologic controls on springs in the Cuatro Cienegas Basin of Coahuila, Mexico. Cuatro Cienegas Basin is a National Biosphere Reserve that contains groundwater dependent ecosystems with high species endemism (over 70 local species) in an arid climate. Groundwater discharge from dozens of springs supplies irrigated agriculture and municipal water requirements and links the basin to the Rio Grande. Most Rio Grande flow originates from tributaries in Mexico during droughts in the Rocky Mountains. Effective water resources management depends on sustainable Mexican and Texan transboundary water resource development.

Previous studies in the Cuatro Cienegas Basin investigated biologic resources and reconnaissance level hydrogeology, but did not explain hydrogeologic controls on spring locations. Springs occur in lines on either side of the Sierra San Marcos carbonate anticline with both hot and cold springs discharging in close proximity. Hydrogeologic cross sections enable the use of classical hydrogeologic models to understand controls on groundwater discharge in regional flow systems like the Cuatro Cienegas Basin.

This study uses geophysics to infer subsurface geology beneath Cuatro Cienegas Basin springs to test the hypothesis that spring locations are controlled by subsurface geology. Our initial gravity survey results conducted in January 2006 suggest that groundwater flows along normal faults in some locations and that permeability differences between valley-fill alluvium, alluvial fans, and underlying carbonates is another controlling factor.

INTRODUCTION

The objective of this research is the characterization of subsurface influences on spring locations in the Cuatro Cienegas Basin, Coahuila, Mexico (Fig. 1), using land gravity surveys and by generating hydrogeologic cross sections that enables the use of classical hydrogeologic models to understand spring location controls in karstic desert basins globally. The research hypothesizes that subsurface geology (buried anticlines, or faults) controls spring locations (Figs. 2A and 2B, respectively). An alternative hypothesis (Fig. 2C) is that permeability differences between valley-fill alluvium and underlying carbonates is the controlling factor. The hypotheses are

Wolaver, B. D., J. M. Sharp, Jr., and J. M. Rodriguez, 2006, Gravity geophysical analysis of spring locations in a karstic desert basin, Cuatro Cienegas Basin, Coahuila, Mexico: Gulf Coast Association of Geological Societies Transactions, v. 56, p. 885-897.

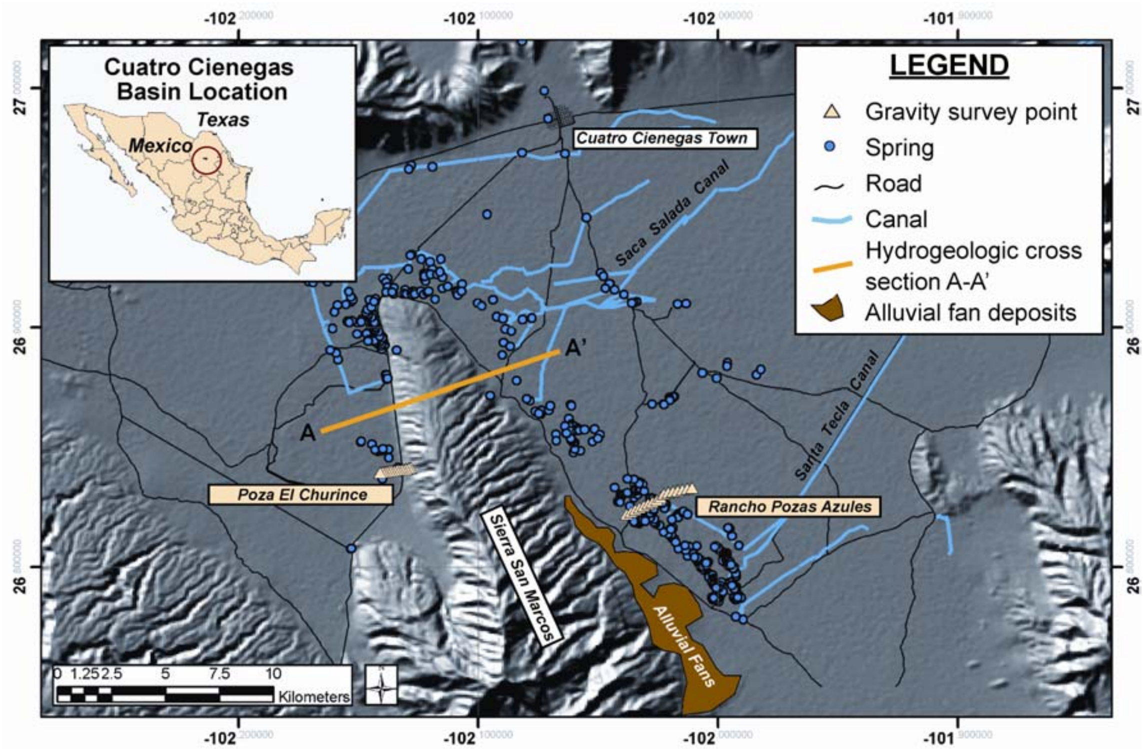

Figure 1. Cuatro Cienegas Basin location. Springs (small circles) occur in lines on either side of the Sierra San Marcos (elevation 2,500 to 7,500 ft; 750 to 2,300 m). Gravity survey points are shown as small triangles for Poza El Churince and Rancho Pozas Azules. Hydrogeologic cross section A-A' refers to Figure 2.

tested by conducting land gravity geophysical surveys in the vicinity of two locations of high spring density: A) Poza El Churince, and B) Rancho Pozas Azules (Fig. 1). If a gravity geophysical analysis shows that subsurface structures exist, then classic models (*e.g.*, Tóth, 1963; Freeze and Witherspoon, 1967) can be used to understand controls on groundwater discharge in regional flow systems.

BACKGROUND

This section discusses the structure and tectonics, economic geology, groundwater resources and hydrogeology, stratigraphy, and the springs of the Cuatro Cienegas Basin.

Structure and Tectonics

Goldhammer (1999) described the Upper Triassic to upper Middle Jurassic stratigraphy of northeastern Mexico, where the Cuatro Cienegas Basin is located at the northern edge of the highly folded and faulted Sierra Madre Oriental. Lehmann *et al*. (1999) correlated Cretaceous carbonate mountain anticlines surrounding the 450 mi^2 (1,200 km^2) Cuatro Cienegas Basin with rocks in Texas. Murillo (1997) commented that the Lower Cretaceous Cupido Formation, which crops out in the Cuatro Cienegas Basin, is the equivalent of the Sligo Formation of Texas.

According to Goldhammer (1999), northeast Mexico experienced rifting associated with the opening of the Gulf of Mexico, creating basement highs (*e.g.*, Coahuila Platform) and lows, like the Sabinas Basin, which is located approximately 80 mi (125 km) northeast of the Cuatro Cienegas Basin. He stated that from the Late Ju-

Main Menu
Search
Author Index
Papers
Help

Main Menu
Search
Author Index
Papers
Help

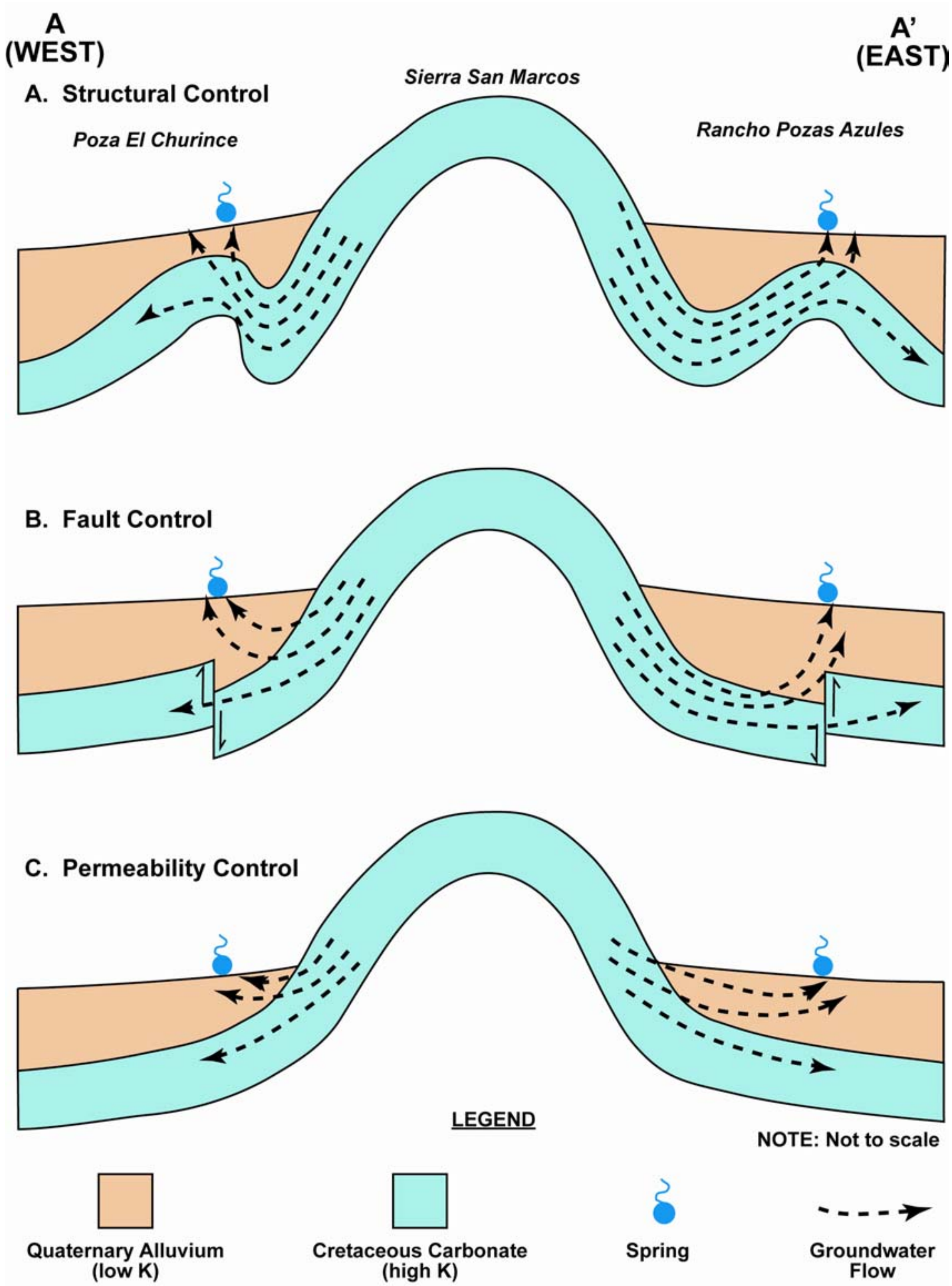

Figure 2. Hydrogeologic conceptual cross sections (A-A'); hypotheses include structural, fault, and permeability controls on spring locations where low hydraulic conductivity valley-fill alluvium overlies a high-permeability Cretaceous carbonate aquifer.

rassic to the Early Late Cretaceous, passive margin accumulation occurred in northeast Mexico. Eguiluz de Antunano (2001) commented that during this time marine sediment accumulation totaled over 16,000 ft (5,000 m) in three supersequences: 1) syn-rift sediments of primarily conglomerates and evaporates; 2) high-frequency cycles of carbonates, evaporates, and coastal siliciclastics deposited on extensive platforms on a passive margin (144 to 96 Ma); and 3) regressive terrigenous clastic facies deposited in a foreland setting (96 to 39.5 Ma).

Economic Geology: Sabinas Basin Hydrocarbon Resources

In terms of economic geology, the region surrounding the Cuatro Cienegas Basin is important. Goldhammer (1999) said that creation of structural hydrocarbon traps in the Sabinas Basin started in the late Late Cretaceous associated with Laramide basin reactivation. Eguiluz de Antunano (2001), in addition to Gonzalez-Partida and Carrillo-Chavez (2001), asserted that the natural fractures permit migration of petroleum from the Upper Jurassic La Casita formation. In addition, Eguiluz de Antunano (2001) estimated gas reserves at 1,000 billion cubic feet (BCF) and coalbed methane reserves at approximately 150 BCF. Eguiluz de Antunano and Torres (2003) described bituminous coal at the top of the Cretaceous section to a depth of approximately 290 ft (900 m) below ground surface (bgs) in regressive, high-frequency deltaic sequences. Subsurface geology (*e.g*., structures, faults, and permeability differences) of the Sabinas Basin may also be the mechanisms that influence the formation springs in the Cuatro Cienegas Basin.

Groundwater Resources and Hydrogeology

Irrigation pumping of groundwater that started in the mid-1900s has caused groundwater level declines of dozens of feet in neighboring valleys and dried up surface water that previously flowed into the Cuatro Cienegas Basin (D. A. Hendrickson, 2005, personal communication; J. M. Rodriguez, 2005, personal communication; Rodriguez *et al*., 2005a). Concerns exist that continued regional groundwater resource development may decrease Cuatro Cienegas Basin spring discharge. Furthermore, the Cupido Aquifer of the Cuatro Cienegas Basin supplies water to approximately five million people in the cities of Saltillo and Monterrey and experiences significant overdrafts (H. De León Gomez, 2006, personal communication).

Lesser y Asociados (2001) presented a regional hydrogeologic conceptual model of parallel mountain anticlines and synclines filled with alluvium and lacustrine sediments. Both the mountains surrounding the Cuatro Cienegas Basin and the valley-fill alluvium are highly karstified (Badino *et al*., 2004). Miele *et al*. (2000) used magnetotelluric soundings to image buried carbonate anticlines for groundwater development in an adjacent basin, and Rodriguez *et al*. (2005b) used time-domain electromagnetics (TDEM) to estimate an average Cuatro Cienegas Basin alluvium depth of 600 ft (200 m).

Stratigraphy

Evans (2005) described the stratigraphy in the Cuatro Cienegas Basin as primarily comprised of Jurassic and Cretaceous age carbonates, evaporites, and sandstone overlying a Permian igneous basement. Table 1 presents a generalized hydrostratigraphic column of the Cuatro Cienegas Basin.

Springs: Cuatro Cienegas Basin and Analogous Locations

Adkins (1920) conducted the first hydrogeologic assessment of the Cuatro Cienegas Basin and inferred that faults influence the linear trend of dozens of springs on either side of the Sierra San Marcos anticline (Fig. 1). Minckley and Cole (1968) described the Cuatro Cienegas Basin spring water chemistry from an aquatic biology perspective, and Evans (2005) defined groundwater flow paths within the basin based on hydrochemical facies. Evans (2005) found that spring discharge temperatures range from 23.7-34.7°C and source spring water electrical conductivities range from approximately 1,400 to 2,500 microSiemens per centimeter (μS/cm), or approximately

Main Menu
Search
Author Index
Papers
Help

Table 1. Generalized hydrostratigraphic column of the Cuatro Cienegas Basin (modified after Evans, 2005; Rodriguez and Sanchez, 2000; McKee *et al.*, 1990; Lesser y Asociados, 2001).

Age	Formation	Description	Permeability
Quaternary	Alluvium	Sand, gravel, lake deposits, evaporate deposits, travertine	Variable
Cretaceous	Eagle Ford	Clay, lutite, calcite	Low
Cretaceous	Buda	Calcite, stratified, interbedded sand and gravel	Low
Cretaceous	Del Rio	Sandy limestone, stratified	Low
Cretaceous	Georgetown	Gray limestone, stratified	Moderate
Cretaceous	Washita Group	Limestone	Moderate
Cretaceous	Kiamichi	Lutite, limestone	Low
Cretaceous	Auroroa	Limestone, gypsum	Aquifer
Cretaceous	La Peña	Dark laminated shale, hematitic	Low
Cretaceous	Cupido	Ooolitic grainstone, gypsum	Aquifer
J/K	La Virgen	Gypsum, dolomite, limestone, shale and clay	Low
J/K	La Mula	Hematitic shale, sandstone, limestone, conglomerate with feldspar and quartz-rich detritus	Low
J/K	La Padillla	Massive dolomite, interbedded shale, sandstone and evaporites	Low
J/K	San Marcos	Sandstone, hematitic cement, interbedded conglomerate	Low
Permian	Basement	Igneous: primarily granite and diorite	Low

900 to 1,600 milligrams per liter total dissolved solids, mg/L TDS), to over 11,000 µS/cm (approximately 7,000 mg/L TDS) at terminal playa lakes. Within the valley, spring water flows on the surface and through subsurface channels in karstified alluvium. Johannesson *et al*. (2004) used stable isotopes to suggest that the groundwater recharge occurs as mountain (higher altitude) precipitation, but did not specify from which mountain range. Meyer (1973) used radiocarbon dating and pollen analyses to infer that basin springs have been active for over 30,000 years. Wolaver *et al*. (2005) conducted a chloride mass balance (Dettinger, 1989) and inferred that inter-basin groundwater flow provides the majority of Cuatro Cienegas Basin groundwater discharge. Bushman *et al*. (2005) used seismic reflection to show fault influences on spring locations in Ash Meadows, Nevada, an analogous arid region with an alluvial-fill valley aquifer overlying a carbonate aquifer. In Death Valley, Jansen *et al*. (2004) mapped a carbonate aquifer top to determine well locations using land gravity, a method this research also uses.

Main Menu
Search
Author Index
Papers
Help

METHODS: GRAVITY SURVEYS

Two land gravity surveys were conducted in the Cuatro Cienegas Basin during January 2006 at 1) Poza El Churince; and 2) Rancho Pozas Azules to test the hypothesis that subsurface geology controls spring locations (Fig. 1) by calculating the residual Bouguer gravity anomaly and fitting a simple two-layer inverse geologic model comprised of alluvium overlying carbonate. The land geophysical gravity survey is selected instead of alternative geophysical methods because it is 1) inexpensive, 2) easy to implement, 3) non-intrusive, and 4) relatively simple to process and interpret the data. Jansen *et al*. (2004) used land geophysical gravity surveys to determine subsurface influences on spring locations in similar carbonate terrains; Langenheim *et al*. (2002) used gravity to determine alluvium-filled valley thickness.

While seismic reflection or refraction may provide detailed information on subsurface geology influencing spring locations (Bushman *et al*., 2005) and exploratory borehole drilling would effectively determine alluvium thickness, these methods were not considered due to high cost and complex execution. Ground penetrating radar (GPR) was tested in the vicinity of springs in the Cuatro Cienegas Basin, but shallow groundwater, saline surface waters and soil hindered collection of useful subsurface data.

Data Acquisition

A Lacoste & Romberg gravimeter was used to measure (relative) gravity at survey stations along two land gravity geophysical survey lines (Fig. 1, small triangles). A handheld global positioning system (GPS) determined base station coordinates. A Total Station (optical transit and electronic distance measuring device) measured station coordinates to a high accuracy with a station spacing of approximately 300 ft (100 m) for Poza El Churince and 600 ft (200 m) for Rancho Pozas Azules (equal to or less than the anticipated alluvium depth; V. E. Langenheim, 2005, personal communication). The station locationss were determined using a tape measure and compass bearing perpendicular to the linear spring trend. Three or more gravity measurements were conducted at each station. Reynolds (1997) outlined procedures for gravity data survey implementation and data acquisition.

Data Processing

Gravity measurement at any point are a function of many variables, such as the gravitational pull of sun and moon on the shape of the Earth, gravity meter drift, latitude, topography using a 1,000 ft^2 (90 m^2) digital elevation model (DEM) for local topography and a 3-sec DEM for regional topography, and differences in density of subsurface geology (including the crust and upper mantle; Langenheim *et al*., 2002). Gravity data processing applies corrections so that only effects of density differences remain, creating a Bouguer residual gravity anomaly. Telford *et al*. (1990) and Nettleton (1971) provided descriptions of gravity data processing. GravMaster^{TM} software (Geotools, Inc., 2000a) is used to compute corrections to measured gravity data.

Data Interpretation

The hypotheses presented in Figure 2 are considered evaluated when it is determined by visual inspection which of the three hypotheses most closely matches the inverse geologic model created from field data. GravModeler™ software (Geotools, Inc., 2000b) was used to create an inverse geologic model that best fitted the measured data using the Talwani algorithm (Talwni *et al*., 1959) to calculate rapidly the gravity response using a line integration method.

GravModeler™ calculates the gravity response of a single body (*i.e*., a polygon determined by the user based on reasonable estimates of subsurface geology) at each observation point due to: 1) density differences between background and body (*e.g*., alluvium and carbonate rock); 2) geometry of body defined by vertices; and 3) location at which gravitational response is calculated (Telford *et al*., 1990; Nettleton, 1971). The Talwani algorithm calculates a curve of the residual Bouguer gravity anomaly which represents the gravitational response due to bodies in the model with effects of elevation and topography removed. Alluvial and carbonate thickness and density were changed to create a geologically-plausible model with a resulting gravity anomaly that most closely matched the observed data.

RESULTS

Summary results of land gravity geophysical surveys are shown in Table 2. The residual Bouguer gravity anomaly and best-fit inverse geologic models for Poza El Churince and Rancho Pozas Azules are presented on Figure 3. For Poza El Churince, the best-fit inverse model for observed Bouguer anomaly results from carbonate with thickness of 8,000 ft (2,400 m) and density of 170 lb/ft^3 (2.70 g/cm^3) overlain by alluvium with thickness of 11,000 ft (3,400 m) and density of 120 lb/ft^3 (1.91 g/cm^3) that decreases in thickness towards the Sierra San Marcos to the east. The residual Bouguer gravity anomaly for Poza El Churince ranges from -89.823 to -5.617 mGal, while the best-fit model varies from approximately -95 to -88 mGal. The best-fit inverse model for the observed Bouguer anomaly for the Rancho Pozas Azules line is calculated from carbonate with thickness of 10,500 to 13,000 ft (3,200 to 4,000 m) and density of 170 lb/ft^3 (2.70 g/cm^3) overlain by alluvium with thickness of 6,000 to 8,500 ft (1,800 to 2,600 m) and density of 120 lbs/ft^3 (1.90 g/cm^3); alluvial depth increases to the east away from the Sierra San Marcos to the east. The residual Bouguer gravity anomaly for Poza El Churince ranges from -79.698 to -73.946 mGal; the best-fit model varies from approximately -81 to -74 mGal.

DISCUSSION

The hydrogeologic conceptual model for the subsurface geologic controls on springs in the Cuatro Cienegas Basin is presented on Figure 4. Two distinct geologic mechanisms influence spring locations: a normal fault on the west flank, and permeability differences on the east flank of the Sierra San Marcos.

On the west flank, the Sierra San Marcos anticline dips steeply to the west at from approximately 50 to 80 degrees. The mountain crops out in nearly straight line for approximately 6 mi (10 km), and the linear orifice of Poza La Becerra suggests the presence of a fault. Similarly, in Ash Meadows, Nevada, springs discharge from a 10 mi (16 km) long fault (Winograd and Pearson, 1976). In order to constrain results of the gravity geophysical analyses, additional hydrogeologic data were considered. Wolaver *et al*. (in press) measured spring discharge in the Cuatro Cienegas Basin. Springs on the west side of the basin contribute to approximately 88 percent of basin discharge of approximately 37,000 acre-ft/year (45.000 Mm^3/yr), suggesting high-volume spring discharge occurs along a linear fault zone from a deeper carbonate aquifer. Evans (2005) presented geochemical data for spring waters, with an electrical conductivity that ranges from 2,360 to 2,550 mS/cm in the west side of the basin. Similarly, Uliana and Sharp (2001) noted that springs on a regional flow path in western Texas exhibit electrical conductivity values between 3,100 and 4,400 mS/cm, suggesting that springs on the western flank of the Sierra San Marcos also discharge from a regional flow system.

In the eastern portion of the basin, springs contribute only 12 percent of basin flow (Wolaver *et al*., in press), suggesting that high-discharge fault-related fracturing and associated dissolution does not control spring loca-

Table 2. Summary results of land gravity geophysical surveys.

Survey Line	Number of Stations	Approximate Station Spacing (m)	Approximate Line Length (km)
Poza El Churince	14	100	1.4
Rancho Pozas Azules	16	200	3.2

tions, which is consistent with gravity survey results. Instead, the potentiometric surface of a shallower carbonate aquifer is intersected by down-cut stream channels (which also occurs in Central Texas karst springs; Veni, 2005) associated with alluvial fans, permitting relatively low-discharge springs from a shallow carbonate aquifer. Groundwater flows in permeable layers of the alluvial fans beneath observed low-conductivity caliche layers, as also occurs on alluvial fans in West Texas (Darling, 1997). At the base of the alluvial fans, groundwater forms springs because it cannot infiltrate into low-permeability lacustrine alluvial valley-fill. The electrical conductivity of springs in the eastern half of the basin is approximately 1,390 mS/cm. Thus, lower electrical conductivity in eastern springs may indicate that locally-derived low-conductivity mountain recharge mixes with higher-conductivity regional groundwater flow.

The gravity geophysical surveys allow interpretation of broad subsurface geologic trends, but the thicknesses of the two-layers of the best-fit inverse model may be too thick, because regional structural trends may be drowning out local structure gravity effects, or the simple two-layer geologic models are not sufficient. Future gravity geophysical surveys in the Cuatro Cienegas Basin should consider: 1) implementing a tighter station spacing (*e.g*., 33 ft; 10 m) instead of 300 and 600 ft (100 m and 200 m); and 2) incorporating additional data, such as a complementary method (*e.g*., magnetics geophysical survey) or exploratory boreholes to reduce the non-uniqueness of the inverse model.

CONCLUSIONS AND FUTURE RESEARCH

The results of land gravity geophysical surveys in the Cuatro Cienegas Basin produce hydrogeologic cross sections that allow a general interpretation of subsurface geologic controls on spring location where additional hydrogeologic data, including groundwater quality, spring discharge rates, field observation of spring location, and strike and dip of exposed bedrock are considered. Higher-resolution geophysical methods and exploratory boreholes are desirable, but were beyond the scope of this study.

This study indicates that: 1) High-angle normal faulting on the west flank of the Sierra San Marcos permits high-discharge flow of groundwater from a deep regional Cretaceous carbonate aquifer. 2) Major faults and subsurface structures are not present on the east flank of the Sierra San Marcos; instead, ancestral stream-incised canyons intersect the potentiometric surface of a shallow Cretaceous carbonate aquifer permitting relatively low groundwater discharge from regionally- and locally-derived sources. Groundwater flows through and discharges at the base of permeable modern alluvial fans because low-permeability valley-fill sediments and shallow water table restrict significant infiltration. 3) Classical hydrogeologic models may be used to understand how a deep highly-permeable Cretaceous carbonate aquifer transmits regional groundwater and discharges in springs at a regional elevation low. However, buried structures do not appear to create springs by emplacing permeable carbonates close to the land surface.

Future research in the Cuatro Cienegas Basin will include: 1) Incorporation of additional land gravity geophysical survey lines and complementary magnetic data to reduce the non-uniqueness of geologic interpretations. 2) Delineation of the regional groundwater flow system of a regional karstic aquifer providing groundwater to the arid Cuatro Cienegas Basin using a water budget approach.

Main Menu
Search
Author Index
Papers
Help

Main Menu
Search
Author Index
Papers
Help

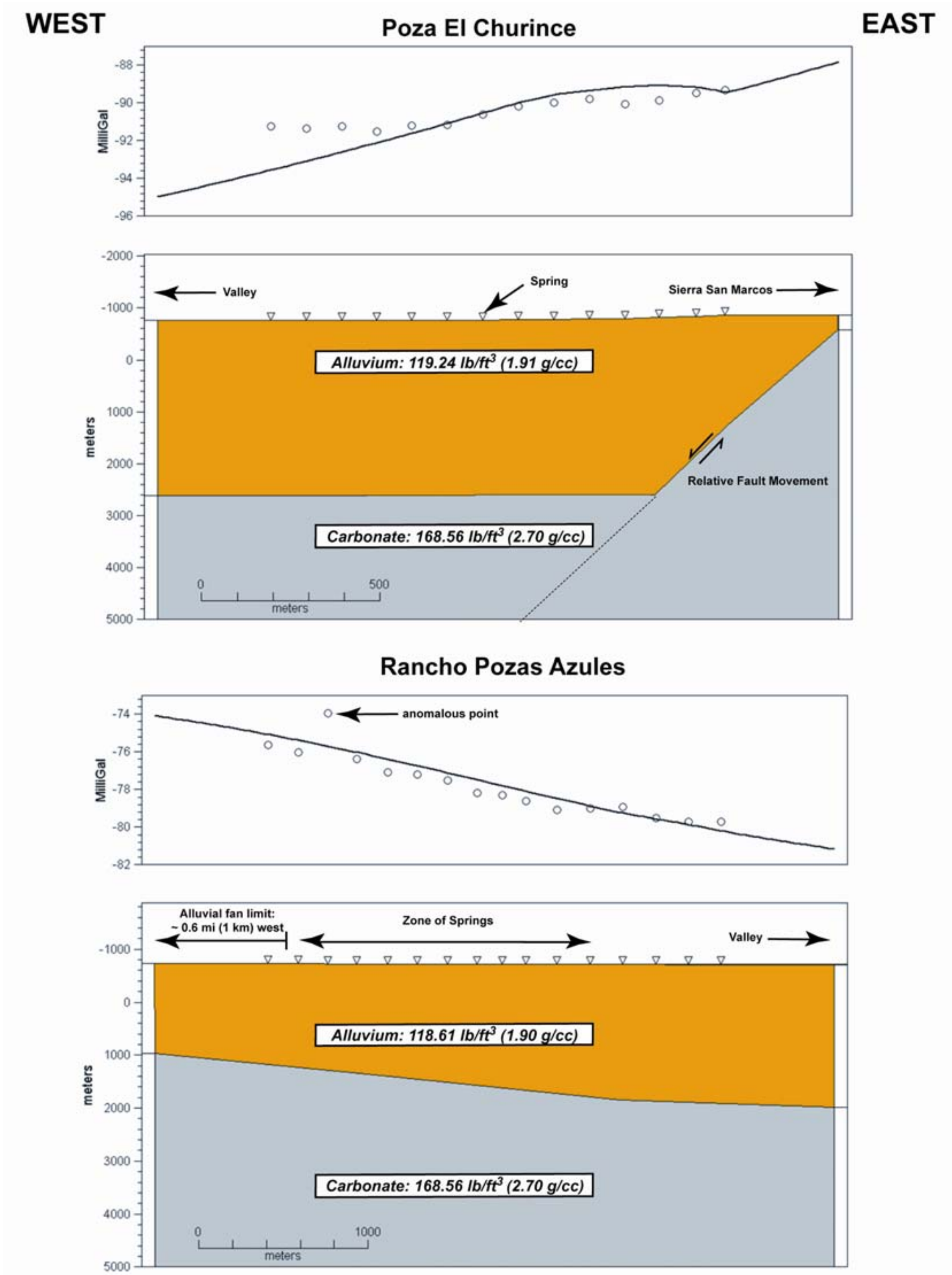

Figure 3. Results of gravity surveys (locations shown in Figure 1) show residual Bouguer gravity anomalies and best-fit inverse geologic models. This permits interpretation of broad subsurface geologic trends, but the thicknesses of the two-layers of the models may be too large. At Poza El Churince, a normal fault is inferred. At Rancho Pozas Azules, no fault is evident; instead, Cretaceous carbonates dip to the east.

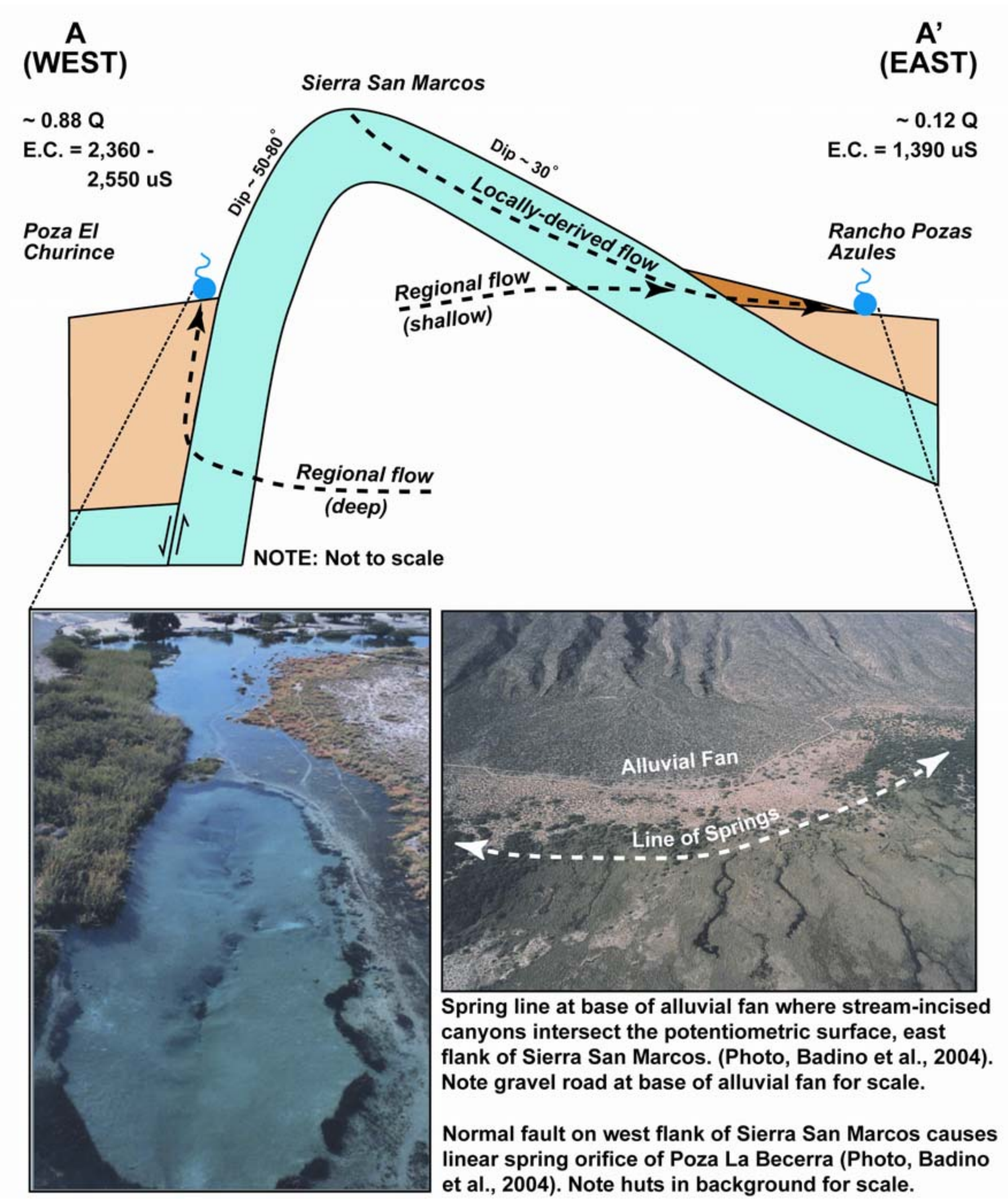

Figure 4. Hydrogeologic conceptual model shows subsurface geologic controls on spring locations and additional hydrogeologic data (see legend of Figure 2). On the west flank of the Sierra San Marcos, high-angle normal faults permit flow from a deep regional carbonate aquifer (~0.88 Q; E.C. = 2,360-2,550 µS/cm). On the east flank, faults are not present; stream channels intersect the potentiometric surface of a shallow carbonate aquifer supplied by local and regional groundwater and discharge at the base of alluvial fans (~0.12 Q; E.C. = 1,390 µS/cm). Note: Q = 50.959 ft^3/sec or 36,892 acre-ft/yr (1,443 L/sec, or 45.566 Mm^3/yr).

Main Menu
Search
Author Index
Papers
Help

This study focused on the Cuatro Cienegas Basin of Coahuila, Mexico, but approaches developed by this research can be used to characterize arid karstic basins globally.

ACKNOWLEDGMENTS

The author would like to thank GCAGS for the award of a Student Research Grant, which facilitated this study. The Tinker Foundation and the Jackson School of Geosciences provided additional financial support. Juan Manuel Rodriguez of the Universidad Autónoma de Nuevo León (UANL) at Monterrey assisted with data collection and provided guidance as the larger Ph.D. project developed. Vsevolod Yutsis of UANL, Linares campus, provided survey suggestions. Students and faculty at the Department of Geological Sciences at The University of Texas at Austin assisted with fieldwork and helped improve this paper. John Jansen and Joy Loughry of Aquifer Science & Technology, Inc. provided assistance with Geotools™ software. In Cuatro Cienegas, Juan Carlos Ibarra Flores of the Secretaría de Medio Ambiente y Recursos Natural (SEMARNAT) provided assistance, Alma Zertuche of DESUVALLE coordinated local lodging, Arturo Lerma of PRONATURA graciously granted access to the Rancho Pozas Azules reserve, and Gilberto Arocha opened Poza El Churince. Dean Hendrickson of The University of Texas, Texas Memorial Museum, helped get this project started.

REFERENCES CITED

Adkins, W. S., 1920, Cuatro Cienegas, Coahuila — Water resources: Walter Scott Adkins Collection, Center for American History, The University of Texas at Austin, COL2/M329, AR89-194, 19 p.

Badino, G., T. Bernabei, and A. De Vivo, 2004, Under the desert: The mysterious waters of Cuatro Cienegas: La Venta Expeditions, Treviso, Italy, 273 p.

Bushman, M., J. H. McBride, S. T. Nelson, and A. L. Mayo, 2005, Preliminary results from a shallow, high-resolution seismic survey and potential field data filtering near Devil's Hole at Ash Meadows, Nevada: Geological Society of America Abstracts with Program, v. 37, no. 7, p. 373.

Darling, B. K., 1997, Delineation of the ground-water flow systems of the Eagle Flat and Red Light basins of Trans-Pecos Texas: Ph.D. dissertation, The University of Texas at Austin, 179 p.

Dettinger, M. D., 1989, Reconnaissance estimates of natural recharge to desert basins in Nevada, U.S.A. by using chloride-balance calculations: Journal of Hydrology, v. 106, p. 55-78.

Eguiluz de Antunano, S., 2001, Geologic evolution and gas resources of the Sabinas Basin in northeastern Mexico, *in* C. Bartolini, R. T. Buffler, and A. Cantu-Chapa, eds., The western Gulf of Mexico Basin; tectonics, sedimentary basins, and petroleum systems: American Association of Petroleum Geologists Memoir 75, p. 241-270.

Eguiluz de Antunano, S., and N. Torres, 2003, Coalbed methane resources of the Sabinas Basin, Coahuila, Mexico, *in* C. Bartolini, R. T. Buffler, and J. F. Blickwede, eds., The circum-Gulf of Mexico and the Caribbean; hydrocarbon habitats, basin formation, and plate tectonics: American Association of Petroleum Geologists Memoir 79, p. 395-402.

Evans, S. B., 2005, Using geochemical data to define flow systems in Cuatro Cienegas, Coahuila, Mexico: M.S. thesis, The University of Texas at Austin, 114 p.

Freeze, R. A., and P. A. Witherspoon, 1967, Theoretical analysis of regional groundwater flow; Part 2, Effect of water-table configuration and subsurface permeability variation: Water Resources Research, v. 3, no. 2, p. 623-634.

Geotools, Inc., 2000a, GravMaster user's manual, revision 1.30, December 31, 2000: Geotools Corporation, Austin, Texas, 88 p.

Geotools, Inc., 2000b, GravModeler user's manual, revision 1.3, December 31, 2000: Geotools Corporation, Austin, Texas, 38 p.

Goldhammer, R. K., 1999, Mesozoic sequence stratigraphy and paleogeographic evolution of northeast Mexico, *in* C. Bartolini, J. L. Wilson, and T. F. Lawton, eds., Mesozoic sedimentary and tectonic history of north-central Mexico: Geological Society of America Special Paper 340, p. 1-58.

Gonzalez-Partida, E., and A. Carrillo-Chavez, 2001, Petroleum-rich fluid inclusions in fluorite, Coahuila, Mexico; implications for sources of oil and fluorine: Geological Society of America Abstracts with Program, v. 33, no. 6, p. 420.

Jansen, J., M. J. King, J. Loughry, T. Powell, and D. Laymon, 2004, An overview of Inyo County's 2003 Death Valley California area geophysical program: Proceedings of the 2004 Symposium on the Application of Geophysics to Environmental and Engineering Problems, p. 981-991.

Johannesson, K. H., A. Cortés, and K. C. Kilroy, 2004, Reconnaissance isotopic and hydrochemical study of Cuatro Ciénegas groundwater, Coahuila, México: Journal of South American Earth Sciences, v. 17, p. 171-180 .

Langenheim, V. E., J. P. Hoffmann, K. W. Blasch, E. Dewitt, and L. Wirt, 2002, Preliminary report on geophysical data in Yavapai County, Arizona: U.S. Geological Survey Open-File Report 02-352, 19 p.

Lehmann, C., D. A. Osleger, I. P. Montanez, W. V. Sliter, A. Arnaud-Vanneau, and J. L. Banner, 1999, Evolution of Cupido and Coahuila carbonate platforms, Early Cretaceous, northeastern Mexico: Geological Society of America Bulletin, v. 111, p. 1,010-1,029.

Lesser y Asociados, 2001, *Sinopsis del estudio de evaluación hidrogeologógica e isotópica en el Valle del Hundido, Coahuila*: Comisión Nacional del Agua, Subdirección General Técnica, Gerencia de Aguas Subterráneas, Pathe, Querétaro, México, 20 p.

McKee, J. W., N. W. Jones, and L. E. Long, 1990, Stratigraphy and provenance of strata along the San Marcos Fault, central Coahuila, Mexico: Geological Society of America Bulletin, v. 54, p. 982-995.

Meyer, E. R., 1973, Late-Quaternary paleoecology of the Cuatro Ciénegas Basin, Coahuila, Mexico: Ecology, v. 54, p. 982-995.

Miele, M.J., J. Jansen, J. E. Davila Arizpe, and M. A. Magallanes Mercado, 2000, A regional groundwater evaluation using magnetotelluric soundings for Monclova, Mexico: Proceedings of the 2000 Symposium on the Application of Geophysics to Environmental and Engineering Problems, p. 699-708.

Minckley, W. L., and G. A. Cole, 1968, Preliminary limnologic information on waters of the Cuatro Cienegas Basin, Coahuila, Mexico: The Southwestern Naturalist, v. 13, p. 421-431.

Murillo, G., 1997, Sequence stratigraphy and diagenesis of the Lower Cretaceous Cupido carbonate platform margin, northeastern Mexico: American Association of Petroleum Geologists Bulletin, v. 81, p. 1,779.

Nettleton, L. L., 1971, Elementary gravity and magnetics for geologists and seismologists: Society of Exploration Geophysicists, Geophysical Monograph Series No. 1, 120 p.

Reynolds, J. M., 1997, An introduction to applied and environmental geophysics: John Wiley and Sons, Chichester, United Kingdom, p. 31-115.

Rodriguez, J. M., and J. A. V. Sanchez, 2000, *Disponibilidad de recursos hídricos en el Canon de las Calaveras como una alternativa de abastecimiento de agua para el municipio de Cuatro Cienegas, Coahuila*: Departamento de Biotecnología, Facultad de Ciencias Químicas, Universidad Autónoma de Coahuila, Saltillo, México, p. 12.

Rodriguez, J. M., S. V. Souza, S.V., and L. E. Arriaga Diaz de Leon, 2005a, The overexploitation of the aquifer of the Hundido Valley and the corresponding ecological impact on the reserves of Cuatro Cienegas Valley of Coahuila, Mexico: Proceedings of the International Conference and Field Seminars, Water Resources and Environmental Problems in Karst: International Association of Hydrogeologists, Belgrade, Serbia and Montenegro, p. 303-310.

Rodriguez, A. A. A., F. J. A. Mijares, C. G. Ojeda, M. M. Morales, L.G. Hita, G. H. Zamarrón, I. M. Arellano, M. A. M. González, G. O. Flores, P. G. Almanza, R. L. Sánchez, J. L. P. López, G. R. Arzate, P. Fritz, and J. R. Espinoza, 2005b, *Estudio hidrogeológico de los acuíferos el Hundido y Cuatrociénegas, Coahuila*: Secretaria de Medio Ambiente y Recursos Naturales, Instituto Mexicano de Tecnología del Agua, Comisión Nacional del Agua, Instituto Nacional de Ecología, Distrito Federal, México, 314 p.

Talwani, M., J. L. Worzel, and M. Landisman, 1959, Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone: Journal of Geophysical Research, v. 64, p. 49-59.

Telford, W. M., L. P. Geldart, and R. E. Sheriff, 1990, Applied geophysics: Cambridge University Press, Cambridge, United Kingdom, p. 6-60.

Tóth, J. A., 1963, A theoretical analysis of ground-water flow in small drainage basins: Journal of Geophysical Research, v. 68, p. 4,795-4,811.

Uliana, M. M., and J. M. Sharp, Jr., 2001, Tracing regional flow paths to major springs in Trans-Pecos Texas using geochemical data and geochemical models: Chemical Geology, v. 179, p. 53-72.

Veni, G., 2005, Declaration of Dr. George Veni: U.S. District Court for the Western District of Texas, San Antonio Division, No. Civ. SA-05-CA-1170-XR, p. 15.

Winograd, I. J., and F. J. Pearson, Jr., 1976, Major carbon 14 anomaly in a regional carbonate aquifer: Possible evidence for megascale channeling, south central Great Basin: Water Resources Research, v. 12, p. 1,125-1,143.

Wolaver, B. D., J. L. Banner, and J. M. Sharp, Jr., 2005, Groundwater recharge in the Cuatro Cienegas Basin, Mexico: Insights from strontium isotope and trace element analyses: Geological Society of America Abstracts with Program, v. 37, no. 7, p. 361.

Wolaver, B. D., J. M. Sharp, Jr., and J. M. Rodriguez, in press, Regional flow system delineation in arid karstic basins with sparse hydrogeologic data: Cuatro Cienegas Basin, Coahuila, Mexico: Proceedings of the 34th Congress of the International Association of Hydrogeologists, Beijing, China.

Main Menu
Search
Author Index
Papers
Help

NOTES

Main Menu
Search
Author Index
Papers
Help