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Reconnaissance isotopic and hydrochemical study of Cuatro Ciénegas groundwater, Coahuila, México

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Abstract

The springs of the Cuatro Ciénegas bolson (Four Marshes basin), Coahuila, México, support more than 70 endemic species of biota. The specifics of the groundwater flow regime, however, remain a mystery. Water samples were collected from a series of springs and pools and one canal in the Cuatro Ciénegas bolson and analyzed for field parameters (temperature, pH, conductivity, alkalinity) and stable oxygen and hydrogen isotopes in an attempt to begin a systematic study of the hydrogeology of the region. Groundwaters discharging directly along a fault-controlled spring line in Cretaceous carbonate rocks of the Cupido-Aurora aquifer are the most dilute (lowest conductivities) and warmest of those sampled. Cuatro Ciénegas waters are characterized by circumneutral pH (6.9–7.7) and reasonably low alkalinity (160–215 mg/kg as HCO_3). The $\delta^{18}O$ values of Cuatro Ciénegas waters range from -8.2 to -5.7‰, with a mean of -6.5 ± 0.82‰, whereas δD ranges from -52 to -43‰, with a mean of -46.6 ± 3.2‰. The majority of the water samples plot subparallel and beneath the local meteoric water line; those samples collected farthest from the spring line exhibit the most enriched $\delta^{18}O$ and δD values. The stable isotope data indicate that isotopic enrichment of groundwaters by evaporation following discharge and subsequent surface flow is an important process within the Cuatro Ciénegas bolson. The isotope data also suggest that a fraction of Cuatro Ciénegas groundwater originates with local recharge in mountains surrounding the bolson. Those springs that issue from the western base of the Sierra de San Marcos mountain range are recharged in part in these mountains, whereas groundwaters discharging from Laguna Anteojo in the northern part of the bolson are more likely recharged in the higher San de la Madera mountain range. An estimate of the water balance suggests that interbasin flow also may contribute to the considerable groundwater discharge.
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Keywords: Groundwater; Interbasin flow; Semiarid regions; Cuatro Ciénegas; México

1. Introduction

Understanding groundwater flow systems in arid and semiarid regions is of great importance to human populations and indigenous biota that rely on the associated water resources. Furthermore, springs in dry regions commonly harbor endemic species that are remnants of previous pluvial climates (Dudley and Larson, 1976; Contreras-Balderas, 1984; Contreras-Balderas and Loza-no-Vilano, 1996). Such endemic biota can be especially sensitive to perturbations in their habitat that result from decreases in groundwater flow and changes in water quality, both of which can be strongly affected by human population

growth. Moreover, the ongoing detrimental effects of human populations on arid region aquifers may be exacerbated by climate changes resulting from global warming. For example, the forecasted effects on the carbonate Edwards aquifer (Texas, USA) predicted to result from doubling current atmospheric CO_2 concentrations include desiccation of large discharge springs, decreases in potable water supplies and water quality, and the disappearance of endemic species (Loáiciga et al., 2000). These climate change scenarios are particularly compelling for arid-region aquifers that supply water to large urban areas, that contain springs with unique or especially endemic biota, and whose hydrogeology is poorly understood. The Cupido-Aurora carbonate aquifer of northeastern México, which provides water to more than 4 million people, sustains as many as 70 different endemic species of biota

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and is stratigraphically correlative with the Edwards-Trinity aquifer of Texas (Lesser Jones, 1967; Minckley, 1969, 1984; Winsborough, 1990; Barker and Ardis, 1996).

Previous conceptual groundwater flow models for the Cupido-Aurora aquifer in the vicinity of Monterrey, Nuevo León, México, have invoked recharge through exposed carbonate rocks as far as 80–150 km west of the city, within the Sierra Madre Oriental (elevation to 3500 m), and/or within a more enigmatic region to the west-northwest of Monterrey, as typified by the Bolson de Mapimi, the Sierra de Parras (the Cross ranges), and the western ranges of the Sierra Madre Oriental (Fig. 1; Lesser Jones, 1967; Fish, 1977; Lesser and Lesser, 1988). Recharged groundwater has been hypothesized to flow down the hydrologic gradient from the Sierra Madre Oriental to the east-southeast

and the lower Gulf coastal plain region. Because of the resulting hydrostatic pressure, the limestones of the Cupido-Aurora aquifer have produced flowing, artesian wells in the region around Monterrey and the coastal plain to the east of the city (Lesser Jones, 1967). Specifics about the recharge region or regions, however, have not been addressed, nor have the early conceptual flow models been adequately tested. For example, it is not known whether groundwaters of the Cupido-Aurora aquifer are only recharged within the Sierra Madre Oriental, if they originate in the Bolson de Mapimi or Sierra de Parras, or if they represent complex mixtures of these and other potential source regions (Brouste et al., 1997).

Furthermore, the early conceptual hydrogeologic models do not readily explain the large discharge springs associated
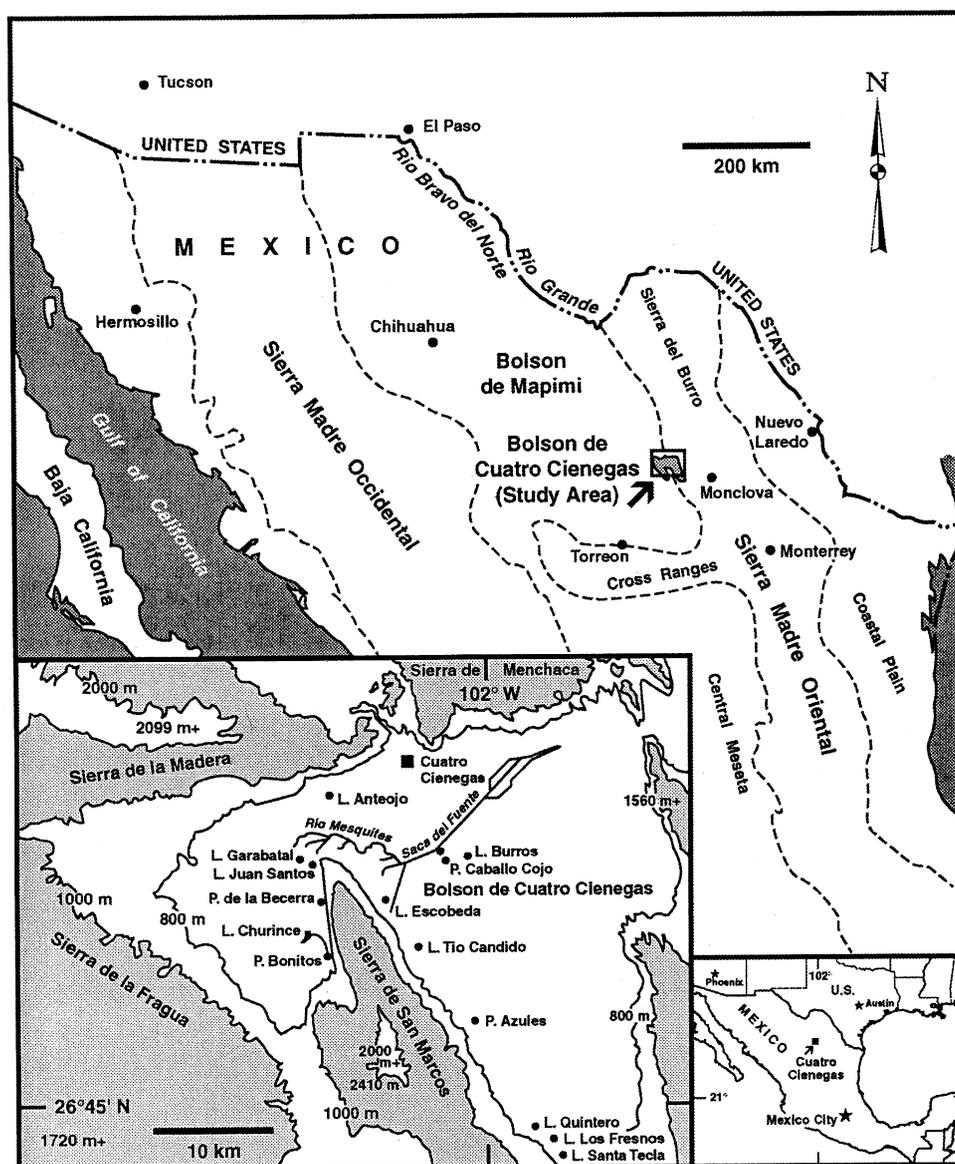

Fig. 1. Location of the Cuatro Ciénegas bolson in Coahuila, México. Large map shows regional geographic features, including the Sierra Madre Occidental, Sierra Madre Oriental, and the Bolson de Mapimi. Insert map shows details of the Cuatro Ciénegas bolson, including location of springs, pools, and canals sampled in this study, as well as springs examined in previous investigations.

with the Cupido-Aurora aquifer in the vicinity of the cities of Monclova, Múzquiz, and Cuatro Ciénegas, Coahuila (Fig. 1). Although in each case fractures that penetrate the Cupido-Aurora aquifer are thought to give rise to springs in these discharge zones (Lesser and Lesser, 1988), the groundwater flow regime in their vicinity is largely unknown. All three discharge regions, for example, are located north and west of the high ranges of the Sierra Madre Oriental and are chiefly surrounded by lower elevation, basin and range-style mountains. Consequently, their geographic locations are not consistent with recharge that occurs dominantly in the high Sierra Madre Oriental or flow of this recharged water toward the Gulf coastal plain to the south and east (e.g. Lesser Jones, 1967; Fish, 1977; Lesser and Lesser, 1988). The lack of adherence to the early conceptual flow models is especially apparent for the springs of the Cuatro Ciénegas bolson, which straddle the physiographic boundary between the Sierra Madre Oriental and the Bolson de Mapimi and therefore are located in the opposite direction of the suggested dominant groundwater flow direction (i.e. east-directed flow from the crest of the Sierra Madre Oriental to the Gulf of Mexico; Lesser Jones, 1967; Lesser and Lesser, 1988). The existence of the Cuatro Ciénegas springs indicates instead that the groundwater flow regime in the region is complex.

Unfortunately, insufficient data currently exist in the literature to (1) ascertain the groundwater flow directions in the Cuatro Ciénegas region or (2) confidently delineate the extent of the hydrogeologic basin that supplies water to this important desert oasis. The carbonate rocks from which the Cuatro Ciénegas spring issues are exposed throughout much of state of Coahuila and portions of Chihuahua, Durango, Nuevo León, and Tamaulipas, as well as in Texas (Baker, 1970; Smith, 1970; Fish, 1977; SARH, 1980; Padilla y Sánchez, 1982; Barker and Ardis, 1996; Small and Lambert, 1998). However, because these carbonate rocks are folded and deformed by basin- and range-style faulting (Padilla y Sanchez, 1982; McKee et al., 1990), the hydrologic flow regime is likely exceptionally complex, as is the case for similarly deformed rocks of southern Nevada's carbonate-rock aquifers (Winograd and Thordarson, 1975; Thomas et al., 1996).

It is important to note that groundwaters from the Cupido-Aurora aquifer in the Torreón area, less than 200 km southwest of Cuatro Ciénegas, range from modern precipitation to waters as old as 30,000 years (Brouste et al., 1997). The paleowaters contrast with previous observations of the rapid response of the Cupido-Aurora aquifer in the Monterrey region to storm events that suggest rapid through-flow of recharge waters (Lesser Jones, 1967; Lesser and Lesser, 1988; Worthington and Ford, 1995). Although the differences in groundwater ages may reflect different flow systems, the paleowaters of the Cupido-Aurora aquifer in the Torreón region raise questions about the age of the Cuatro Ciénegas groundwaters. In this study, we employ existing hydrochemical data for the Cupido-Aurora aquifer

and new field parameter and stable oxygen and hydrogen isotope data for spring waters and related surface waters from the Cuatro Ciénegas bolson to suggest a preliminary hydrogeologic model for the groundwaters discharging from the Cupido-Aurora aquifer. This contribution is the first in a series of planned studies that will include hydrogeologic investigations, as well as new major and minor solute chemical data, additional stable isotope data, groundwater age dating, and trace element analysis of the waters discharging in the Cuatro Ciénegas bolson and surrounding regions.

2. Regional setting

The Cuatro Ciénegas bolson (Four Marshes basin), a 1200 km^2 Chihuahuan desert basin located in the northeast Méxican state of Coahuila, is one of the most important discharge zones of the Cupido-Aurora aquifer in terms of the number of springs in the basin and the multitude of endemic species that they support (Minckley, 1969, 1984; Fig. 1). Cuatro Ciénegas is situated on the eastern edge of the larger Bolson de Mapimi, an approximately 26,000 km^2 area of internal drainage. Geologically, the Cuatro Ciénegas bolson is located within the Coahuila marginal folded belt (Laramide) on the eastern flank of the Sierra Madre Oriental (Murray, 1961; Baker, 1970; Lehmann et al., 1999). The region is characterized by steeply folded Cretaceous marine sedimentary rocks (principally limestones; Lesser Jones, 1967). Both normal and thrust faults are associated with some of these folds (INEGI, 1975). Fold axes trend northwest, and associated axial planes dip to the southwest, similar to other Laramide structures in North America (Murray, 1961; Lehmann et al., 1999). Laramide reactivation along the San Marcos fault during the Tertiary uplifted the north block, juxtaposing Jurassic with Cretaceous (chiefly carbonate) strata. The San Marcos fault defines, in part, the southern edge of the Sierra de San Marcos, which transects the Cuatro Ciénegas bolson from the southeast (Fig. 1; McKee et al., 1990; Lehmann et al., 1999). This transcurrent fault likely plays an important hydrogeologic role, because many springs occur along its trace southeast of the bolson (INEGI, 1991). In addition, a west-dipping normal fault is mapped along the entire western base of the Sierra de San Marcos. A segment of another east-dipping, normal fault is mapped along a portion of the east side of the Sierra de San Marcos range, from just south of Pozos Azules to approximately Laguna Santa Tecla (Fig. 1; INEGI, 1975). This normal fault disappears beneath alluvium near Pozos Azules and Laguna Santa Tecla. The Coahuila fold belt is displaced by basin and range normal faults of Miocene or younger age, some of which have reactivated older Laramide reverse faults. Rocks cropping out in the mountains adjacent to Cuatro Ciénegas are primarily Mesozoic and early Tertiary carbonates and shales with minor coarse clastic, coal, and evaporite units.

The principal aquifers in the study region include shallow, alluvial basin-fill systems and the regional Cupido-Aurora carbonate aquifer (Lesser Jones, 1967). The Cupido-Aurora aquifer consists of the Early Aptian (Lower Cretaceous) Cupido limestone and the younger Albian-Cenomanian Aurora limestone, both of which are characterized by karst features, including solution channels (Smith, 1970). Although the percentage of carbonate rocks that are karst has not been quantified in Cuatro Ciénegas, some recharge likely occurs directly through such features with minimal loss of volume due to evaporation. The Aurora limestone may be equivalent to the Tamaulipas Superior limestone of the Monterrey region or correlative with the Glen Rose (limestone) Formation of Texas (Smith, 1970; Padilla y Sánchez, 1982). Many investigators place the Glen Rose Formation stratigraphically below the Lower Cretaceous Edwards Group, to which the Edwards aquifer of Texas belongs (Small and Lambert, 1998). However, Smith (1970) indicates that the Edwards limestone, the overlying McKnight and Georgetown (limestones) Formations, and the underlying Glen Rose Formation are correlative with the Aurora limestone. The Glen Rose Formation commonly is placed in the Trinity strata of the overall Edwards-Trinity aquifer system (e.g. Barker and Ardis, 1996).

Mean annual precipitation on the floor of the bolson is less than 200 mm, whereas potential evapotranspiration exceeds 2000 mm/yr (Garcia et al., 1975; Caran and Winsborough, 1986). Similar mean annual evapotranspiration has been reported for nearby San Luis Potosi (1930 mm/yr; Carrillo-Rivera et al., 1992). Precipitation in the region is seasonal, dominated by the Gulf of Mexico during the summer (June–September) and the Pacific Ocean during the winter (October–May; Brouste et al., 1997). The floor of the bolson averages 740 m above mean sea level (amsl), and the surrounding mountains reach elevations as high as 3000 m (Minckley, 1969; Baker, 1970). The majority of the springs in the Cuatro Ciénegas bolson consist of pools (*pozas*), some of which contain more than 1000 m^3 of water. However, larger, spring-fed pools or shallow lakes (*lagunas*) are also common (Minckley and Cole, 1968; Rodriguez-Almaraz et al., 1997; Contreras-Arquieta, 1998). Springs occur along both the eastern and western base of the Sierra de San Marcos (Fig. 1), as well as at the base of the Sierra de la Madera (e.g. Laguna Anteojo). Groundwater that discharges from many of the springs typically flows through marshy areas into large, shallow pools or *lagunas* (e.g. Laguna Grande, Laguna de los Burros). Due to time constraints and other logistical issues (e.g. locked gates), we concentrated on sampling the most accessible springs. Future investigations will include the numerous springs that issue from the eastern base of the Sierra de San Marcos (Fig. 1).

The largest spring in the Cuatro Ciénegas bolson discharges groundwater at roughly 4 m^3/s or 1.26×10^8 m^3/yr (SARH, 1980). Using the discharge from this spring, the estimated annual precipitation ($\sim$ 200 mm/yr), and potential evapotranspiration (2000 mm/yr), a rudimentary hydrologic budget can be calculated for the 1200 km^2 Cuatro Ciénegas bolson, assuming that precipitation and evapotranspiration are uniformly distributed. The calculation suggests a total precipitation value of 2.4×10^8 m^3/yr, whereas the basin-wide evapotranspiration, in conjunction with the groundwater issuing from the largest spring, gives an estimated discharge of 2.5×10^9 m^3/yr, or a factor of more than 10 greater than the precipitation. Again, this estimate only includes one spring; hence, the actual basin discharge is even greater, especially because the density of springs and seeps along the alluvial fans of the Sierra de San Marcos is as high as 12–15 springs per square kilometer (Winsborough, 1990). Although admittedly crude, our preliminary hydrologic budget estimate suggests that a component of water discharging from the Cuatro Ciénegas springs may originate outside the bolson. Whether the possible interbasin flow originates from the east in the Sierra Madre Oriental, north from the Sierra del Burro, west from the Bolson de Mapimi, or south from the Sierra de Parras (Fig. 1) is unknown. However, the early conceptual flow models that suggest groundwater is recharged in the Sierra Madre Oriental and subsequently only flows east toward the Gulf coastal plain appear to be in need of revision. The relatively poor understanding of the hydrogeology of the Cupido-Aurora aquifer in the vicinity of the Cuatro Ciénegas bolson warrants additional study, especially in light of the growing local populations, increasing agricultural irrigation in the region, and the endemic biota supported by the bolson's spring waters.

3. Methods

Groundwater samples were collected from a series of springs in the Cuatro Ciénegas bolson in January 1999 for stable oxygen and hydrogen isotope analysis. For the isotope samples, we used 1 l borosilicate glass bottles with Teflon® lined caps. To eliminate any potential contaminants that remained in the bottles from their manufacture, prior to sample collection, we triple-rinsed them with MilliQ water (18 mΩ-cm) and then filled them with a 50%, v/v solution of reagent-grade HCl and MilliQ water. The bottles were allowed to sit with the HCl solution for approximately 6 h before the acid was removed, and then they were triple-rinsed with MilliQ water. At this point, the bottles were placed in a laminar flow hood and allowed to dry overnight before being placed in plastic, zip-style bags.

Stable isotope samples were collected from 6 springs (Laguna del Garabatal, Laguna del Juan Santos, Poza de la Becerra, Pozos Bonitos, Poza Caballo Cojo, and Laguna Anteojo), one of the shallow lakes (Laguna de los Burros), and the Saca del Fuente canal (Fig. 1). The waters flowing in Saca del Fuente, as well as those sampled from Laguna de los Burros and Poza Caballo Cojo, are thought to be part of the Rio Mesquites drainage system, which includes the springs that discharge from the western base of

Table 1

Stable isotope, pH, temperature (°C), conductivity (μmhos), and alkalinity for some Cuatro Ciénegas spring and surface waters (e.g. Saca del Fuente is a canal that originates as water from the Río Mesquites; Minckley, 1969)

Sample	δ^{18}O (‰)	δD (‰)	pH	T (°C)	Conductivity (μmhos)	Alkalinity as HCO_3 (mg/kg)	Recharge elevation (m)
Laguna del Garabatal	−6.4	−46	7.5	18.6	4810	180.4	1500
Laguna del Juan Santos	−6.4	−46	7.21	26.7	5820	185.3	1500
Poza de la Becerra	−6.7	−48	6.92	32.4	2420	200	1600
Pozos Bonitos	−7.1	−50	7.03	26.2	2250	170.7	1800
Pozo Caballo Cojo	−5.7	−43	7.22	16.8	3830	214.6	1170
Laguna de los Burros	−6	−44	7.69	13.2	3110	160.9	1300
Saca del Fuente	−5.8	−44	7.58	17.1	3120	190.2	1200
Laguna Anteojo	−8.2	−52	6.94	26.2	1620	190.2	2350

Alkalinity is reported as mg HCO_3/kg of solution and was determined by titration in the field. δ^{18}O and δD are reported (as ‰) relative to the standard VSMOW. Recharge elevation was estimated using the relationship, developed for the Basin of México, δ^{18}O = −2.37(Z) − 3.2, where Z is elevation in kilometers (Cortés and Durazo, 2001).

the Sierra de San Marcos (Laguna del Garabatal, Laguna del Juan Santos, Poza de la Becerra, Pozos Bonitos; Fig. 1). Laguna Anteojo discharges to the north and at the base of the Sierra de la Madera (Fig. 1). Unfortunately, again owing to time constraints and logistical difficulties encountered during the sample collection trip, we did not collect samples from the springs that discharge along the eastern front of the Sierra de San Marcos (Laguna Escobeda, Laguna Tio Candido, Pozos Azules, Laguna Quintero, Laguna Los Fresnos, Laguna Santa Tecla; Fig. 1). Future investigations will include these and possibly other springs along the eastern base of the Sierra de San Marcos range.

Water samples for the stable isotope analyses were collected by immersing the 1 l sample bottles in the spring waters (hands were covered with polyethylene gloves) and filling the bottle below the water surface. Before each sample was collected, the sample bottle was rinsed three times with the sample water for conditioning. With the fourth filling, the bottle was capped tightly, placed back the plastic bag, and then placed in a cooler to keep the samples cool and in the dark until they could be stored in a laboratory refrigerator until the analysis. For each sample collection site, pH, conductivity, and alkalinity were measured on site using standard field procedures. The alkalinity was determined at each site by titration, using phenolphthalein and bromcresol green-methyl red. The isotope samples were measured at Geochron Laboratories in Cambridge, Massachusetts.

4. Results

Stable oxygen and hydrogen isotope data for waters from the Cuatro Ciénegas bolson are presented in Table 1. The stable isotope data are plotted in Fig. 2a, along with Craig's (1961) global meteoric water line (GMWL) and a local meteoric water line (LMWL) determined by a linear
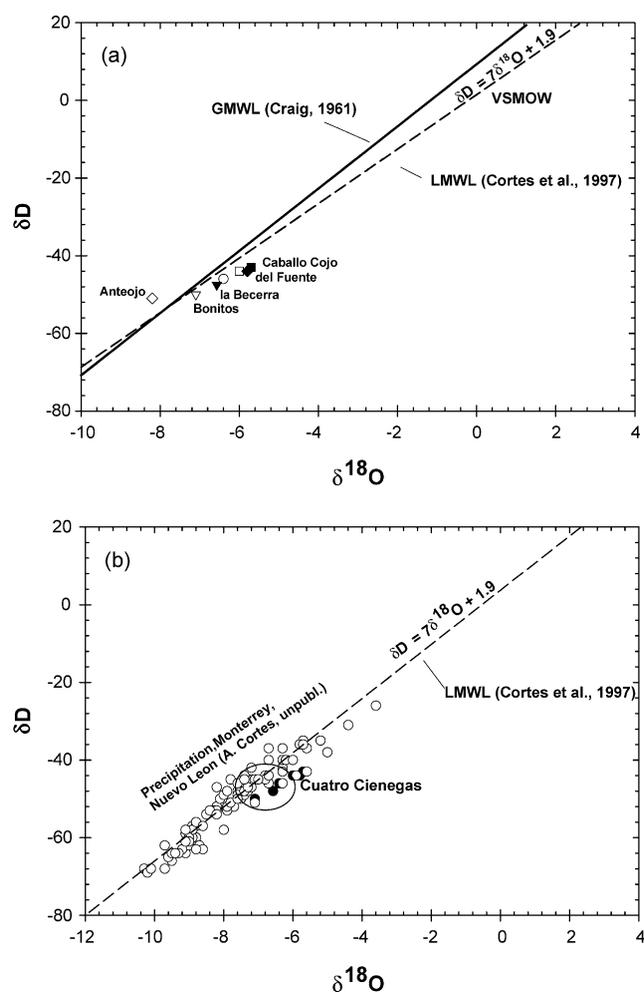

Fig. 2. Stable oxygen and hydrogen isotope data for (a) waters sampled from the Cuatro Ciénegas bolson in this study and (b) precipitation from the region surrounding Monterrey, Nuevo León (Cortés, unpublished data). The LMWL is from nearby Chihuahua (Cortés et al., 1997). The LMWL for the Monterrey precipitation is the same as that shown for Chihuahua and therefore is appropriate for use in this study in the absence of precipitation data for the Cuatro Ciénegas bolson.

regression of more than 20 years of data from the nearby International Atomic Energy Agent (IAEA) station at Chihuahua, México (IAEA, 1981; Cortés et al., 1997). In addition, multiyear stable oxygen and hydrogen isotope data for precipitation from Monterrey, Nuevo León (Cortés, unpublished data) are plotted in Fig. 2b. Although δD and $\delta^{18}O$ have not been measured for precipitation within the Cuatro Ciénegas bolson, precipitation from Chihuahua and Monterrey (Fig. 2b), which geographically bound it (Fig. 1), define essentially the same meteoric water line (Chihuahua, $\delta D = 7\delta^{18}O + 1.9$, $n = 121$; Monterrey, $\delta D = 6.8\delta^{18}O + 1.85$, $n = 102$), which suggests that the LMWL is appropriate for modern precipitation. Furthermore, the identical LMWLs for Chihuahua and Monterrey strongly suggest that both cities receive seasonally influenced precipitation from the same sources: the Gulf of Mexico in the summer and the Pacific during the winter.

In addition to the stable oxygen and hydrogen isotope data, pH, temperature ($°C$), conductivity (μmhos), and alkalinity (as mg/kg HCO_3^-) data for the water samples are presented in Table 1. All samples are of circumneutral pH. The groundwaters discharging directly from the subsurface along the base of local mountain ranges (Poza de la Becerra, Pozos Bonitos, Laguna Anteojo; Fig. 1) have the lowest pH values and exhibit the lowest conductivities (2420, 2250, and 1620 μmhos, respectively). Moreover, except for Laguna del Juan Santos, waters issuing from these three springs are warmer than other waters sampled from the Cuatro Ciénegas bolson (Table 1). Consequently, of the water samples collected, these three springs discharge waters that most closely reflect the composition of groundwater in the Cupido-Aurora aquifer. In other words, the other collected water samples likely were modified by evapotranspiration, interaction with surficial deposits, and/or cooling subsequent to issuing from the Cupido-Aurora aquifer.

5. Discussion

5.1. Stable isotopes

All of the Cuatro Ciénegas water samples but one (Laguna Anteojo) plot below and subparallel to the LMWL (Fig. 2a). These waters are shifted toward heavier $\delta^{18}O$ values, which suggests they are enriched by evapotranspiration. The waters farthest from the spring line, along the western base of the Sierra de San Marcos (Poza Caballo Cojo, Laguna de los Burros, Saca del Fuente; Figs. 1 and 2), exhibit the greatest stable isotope enrichments, consistent with a greater degree of evaporation following discharge along the western base of the Sierra de San Marcos and subsequent flow, as surface waters, toward the central region of the Cuatro Ciénegas bolson. Linear regression of the data (without Laguna Anteojo) gives a slope of 4.9 for the hypothesized evaporation line (Fig. 3). Extrapolation of the evaporation curve back to the LMWL reveals that these
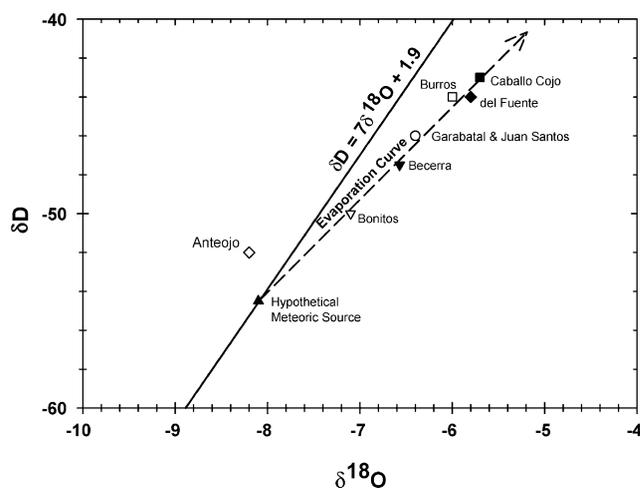

Fig. 3. Details of the Cuatro Ciénegas stable isotope data presented in Fig. 2 showing the projection of the linear regression line through the data and back to the LMWL. The intersection of these lines occurs at the point $\delta^{18}O = -8.1‰$, $\delta D = -54.5‰$. We interpret the regression line through our data as an evaporation line of local precipitation with stable oxygen and hydrogen isotope values equal to the values defined by the intersection of the evaporation line and the LMWL.

spring waters could be evaporated meteoric water that had original $\delta^{18}O$ and δD values of -8.1 and $-54.5‰$, respectively (Fig. 3).

Laguna Anteojo water is the most depleted sample in terms of $\delta^{18}O$ and δD and does not plot on the hypothesized evaporation line (Figs. 2 and 3). However, Laguna Anteojo water falls within the range reported for modern precipitation from the Monterrey region (Fig. 2b). Compared with the other Cuatro Ciénegas waters, Laguna Anteojo groundwater plots above both the LMWL and the GMWL (Fig. 2a). Thus, it is possible that Laguna Anteojo water reflects either the natural variation of local precipitation or reevaporated, reprecipitated meteoric water. Evaporation of local meteoric waters could produce water vapor depleted in $\delta^{18}O$ and δD compared with the LMWL (e.g. Ingraham and Matthews, 1988; Lauriol and Clark, 1993). If this water vapor were to condense before reequilibrating with the atmosphere (Clark and Fritz, 1997), the corresponding precipitation would be depleted and plot above the LMWL. However, if this is the case, Laguna Anteojo water should plot along the extension of the evaporation line (though to the left of the LMWL) defined by the other Cuatro Ciénegas waters. It is clear that from Fig. 3 that Laguna Anteojo water does not. Another possibility is that Laguna Anteojo water is different from those that discharge along the western spring line. For example, Laguna Anteojo could represent local precipitation that recharged the Cupido-Aurora aquifer at a different elevation, time of the year, or climate conditions (i.e. paleowaters) than that of those that issue along the western base of the Sierra de San Marcos.

If the relationship between recharge elevation and $\delta^{18}O$ developed for the basin of México (Cortés and Durazo, 2001; $\delta^{18}O = -2.37Z - 3.2$, where $Z =$ elevation in

kilometers) can be applied to the Cuatro Ciénegas bolson to estimate the recharge elevations for the local groundwaters, values of 1200–2400 m amsl, with a mean of 1552.5 ± 385 m, are obtained (Table 1). However, the estimated elevation of recharge for Laguna Anteojo spring water is substantially higher than that of the other Cuatro Ciénegas water samples (2350 m; Table 1). If Laguna Anteojo water is not considered, the mean elevation of recharge for the Cuatro Ciénegas waters is 1436 ± 228 m (Table 1). In addition, the estimated recharge elevation of the hypothesized, preevaporated meteoric water source of the bulk of the Cuatro Ciénegas samples would be 2070 m ($\delta^{18}O = -8.1‰$), or 280 m lower than the estimated recharge elevation for Laguna Anteojo water. On the basis of the stable isotope data alone, the recharge elevation estimates suggest that the bulk of the Cuatro Ciénegas groundwaters could represent recharge in the surrounding mountains (i.e. Sierra de San Marcos, Sierra de la Madera, Sierra de Menchaca; Fig. 1). The mean estimated recharge elevation value (not including Laguna Anteojo) of 1436 m, along with the proximity of these springs to the base of the Sierra de San Marcos range, points to recharge in these mountains. The Laguna Anteojo spring waters discharge at the base of the Sierra de la Madera, which ranges up to 3020 m in elevation (INEGI, 1975). The higher estimated recharge elevation for Laguna Anteojo water thus is consistent with recharge in the higher Sierra de la Madera range.

However, it is critical to point out that other mountains ranges, such as the Sierra del Burro, Sierra Madre Oriental, and Sierra de Parras, cannot be ruled out as potential recharge areas of Cuatro Ciénegas groundwaters on the basis of the existing stable isotope data. For example, peaks within the Sierra Madre Oriental attain elevations of 3140–3500 m amsl, whereas the Sierra de Parras ranges up to 3120 amsl (INEGI, 1975). Furthermore, the temperature of Laguna Anteojo, Pozos Bonitos, and Poza del la Becerra water (32.4 EC; Table 1) is consistent with deep, regional groundwater flow (e.g. Winograd and Thordarson, 1975; Thomas et al., 1996). Finally, our crude water budget estimate for the Cuatro Ciénegas bolson (again, based on only one spring) suggests that a component of groundwater discharging within the bolson may originate outside the basin, which would constitute interbasin flow. However, more study, including additional stable isotope, geochemical, and hydrogeologic data, is needed before the groundwater flow regime in Cuatro Ciénegas can be delineated with confidence.

Table 2

Summary of preexisting major solute data (in mg/kg) for groundwaters from the Cupido-Aurora aquifer system from the Cuatro Ciénegas bolson in Coahuila (Winsborough, 1990), the Comarca Lagunara in Durango (Brouste et al., 1997), and the portion of the Sierra Madre Oriental in Tamaulipas, México (Hose, 1996). Alkalinity is presented as mg/kg of HCO_3

	Ca	Mg	Na	K	Cl	Alkalinity	SO$_4$
Cuatro Ciénegas[a]							
Pozos Bonitos[b]	440	54	140	9.3	108	171	1250
Laguna Grande	588	262	373	29.9	307	116	2900
Pozo de la Becerra[b]	360	105	142	14.8	104	200	1262
Rio Mequites	440	151	213	22.5	157	150	1750
El Mojarral (west)	347	101	160	8.9	110	163	1225
Escobeda	353	100	116	11.6	107	167	500
Tio Candido	335	91	145	11.5	119	143	1000
Laguna Anteojo[b]	232	63	29	5.3	17	190	706
Laguna Santa Tecla	128	41	38	3.5	29	227	225
Laguna de los Fresnos	168	44	85	5.5	48	317	281
Laguna Tio Quintero	240	63	85	9.3	68	318	625
Laguna Salada	1232	14,414	6000	1250	10,200	512	66,500
Laguna del Garabatal[b]	393	124	186	11	121	180	1547
Comarca Lagunera[c]							
Recent groundwater	112	20	94	5	43	304	264
Intermed. groundwater	156	28	141	5	56	170	576
Old groundwater	121	21	176	5	77	137	517
Tamaulipas[d]							
Allarines	105	5	4	0.5	50	85	4
Conrado Castillo Well	104	7	1	1.9	50	85	1
Canon El Infiernillo	73	18	1	0.5	50	73	2
Los Hervores	90	17	1	0.5	50	85	1

Some surface waters (e.g. Rio Mesquites) are included from the Cuatro Ciénegas bolson for comparison.

[a] Winsborough (1990).

[b] Alkalinity values from this study (Table 1).
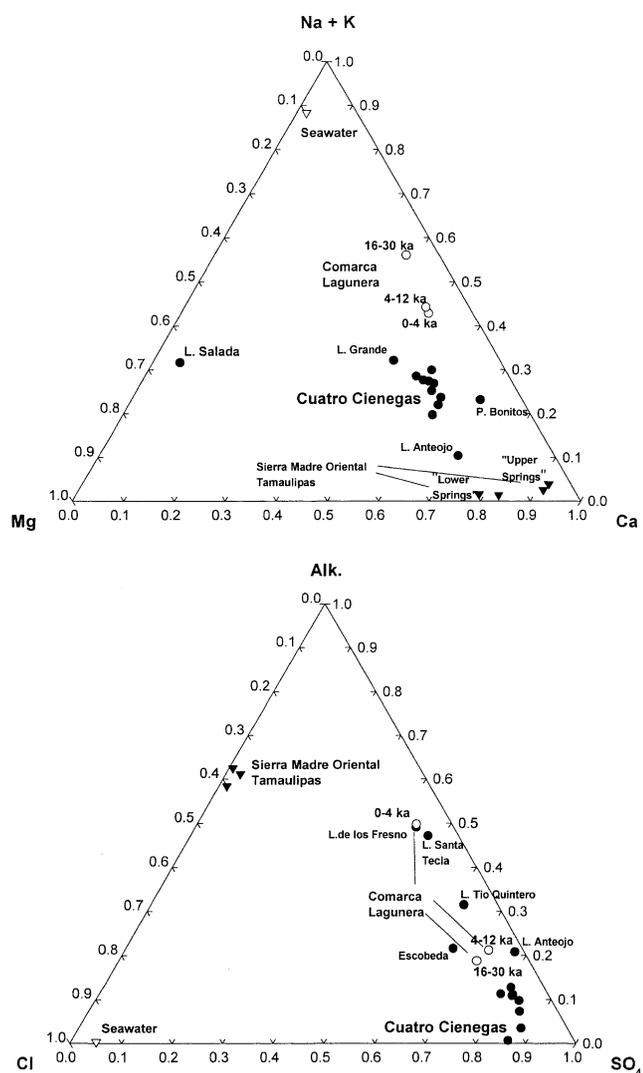
[c] Brouste et al. (1997).

[d] Hose (1996).

Fig. 4. Ternary plots of major solute data for waters from the Cuatro Ciénegas bolson. Data are for groundwaters from the Sierra Madre Oriental in Tamaulipas, México, and the Comarca Lagunera in the Torreón region; seawater data shown for comparison.

5.2. Major solutes

Existing major solute data for various waters from the Cuatro Ciénegas bolson are reported in Table 2 and plotted in Fig. 4. The Cuatro Ciénegas data are summarized from Minckley and Cole (1968) and Winsborough (1990), and data for some spring waters discharging from the Cupido-Aurora aquifer within the Sierra Madre Oriental (Hose, 1996) and the nearby Comarca Lagunera (Brouste et al., 1997) are included for comparison. Although it is preferable to compare samples collected at roughly the same time and analyzed in the same laboratory, research shows that a comparison of hydrochemical data from different decades indicates essentially no change in groundwater chemistry (for example, see the hydrogeologically similar Ash Meadows region of southern Nevada, USA; Winograd and Thordarson, 1975; Stetzenbach et al., 1994, 2001;

Thomas et al., 1996). We therefore assume that the compositions of spring waters within Cuatro Ciénegas have remained relatively constant with time.

The bulk of the Cuatro Ciénegas waters is substantially more sulfate rich than the Sierra Madre Oriental waters, which are chiefly HCO_3–Cl (Fig. 4; Hose, 1996). Gypsum deposits occur within the Sierra de la Fragua on the southwest border of the bolson (Fig. 1), and gypsum dunes are present within the bolson itself (Contreras-Balderas, 1984). If a component of the Cuatro Ciénegas groundwaters is recharged in the Sierra Madre Oriental, the anion data suggest either significant interaction of these waters with evaporites during their residence time in the aquifer or deep, regional flow with a possible thermal component (e.g. Worthington and Ford, 1995). The Cuatro Ciénegas waters that are enriched in sulfate (e.g. Pozos Bonitos, Poza de la Becerra, Laguna Grande, Laguna del Garabatal, Laguna del Juan Santos) discharge along the western side of the Sierra de San Marcos, whereas groundwaters that issue from springs along the eastern side of the Sierra de San Marcos (Laguna de los Fresno, Laguna Santa Tecla, Laguna Tio Quintero, Laguna Escobedo) and Laguna Anteojo are relatively more enriched in HCO_3 (Fig. 4). The geographic distribution and major solute compositions of Cuatro Ciénegas springs suggest that (1) they are fault controlled and (2) groundwaters issuing from the two spring lines have different hydrochemical histories and origins.

As mentioned previously, normal faults bound both the western and eastern flanks of the Sierra de San Marcos (INEGI, 1975). The major anion compositions (Fig. 4) indicate that groundwaters discharging on the eastern flank are compositionally similar to paleowaters within the Cupido-Aurora aquifer in the Comarca Lagunera region near Torreón, southwest of the Cuatro Ciénegas bolson (Fig. 1; Brouste et al., 1997). Although we recognize that the anion data are insufficient evidence to conclude that Cuatro Ciénegas groundwaters are hydrogeologically connected to those of the Comarca Lagunara or represent paleowaters, it is clear that compositional differences exist among the Cuatro Ciénegas groundwaters, and these chemical differences correspond to the waters' discharge location in the bolson. However, it is unclear what these observed compositional differences mean in terms of the hydrogeology of the aquifer, though they certainly warrant a more comprehensive sampling, both spatially and temporally, of the bolson and surrounding regions.

6. Conclusions

The Cuatro Ciénegas bolson is one of two unique desert oases within central America and the American southwest (the other is Ash Meadows in Nevada, USA) that supports numerous endemic species, chiefly as a result of significant groundwater discharge. Despite the importance of these

groundwater discharges, little is currently known about the Cuatro Ciénegas groundwater flow regime. The preliminary environmental isotope data presented here suggest that a significant component of Cuatro Ciénegas groundwaters may be recharged in the local mountain ranges surrounding the bolson.

Furthermore, these data are consistent with that for water that discharges from springs along the western base of the Sierra de San Marcos, which originate by recharge in the Sierra de San Marcos range, whereas the $\delta^{18}O$ and δD data for Laguna Anteojo in the northern part of the bolson is consistent with recharge in the higher San de la Madera range. However, a crude water balance estimate for the Cuatro Ciénegas bolson indicates that groundwater originating outside of the basin probably contributes to the abundant spring discharge within it. Regional groundwater flow is also supported by the relatively warm temperatures of some of the groundwaters issuing from the Cupido-Aurora aquifer within the Cuatro Ciénegas bolson. Existing major solute data indicate that compositional differences exist among groundwater discharging within the Cuatro Ciénegas bolson, though these differences have not yet been interpreted in terms of the hydrogeology. Additional investigation could identify and better constrain the hydrogeology of the Cupido-Aurora aquifer in Cuatro Ciénegas.

Acknowledgements

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