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Determination of the ground water divide in the karst aquifer of Yucatán, Mexico, combining geochemical and hydrogeological data

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RESUMEN

El acuífero de la península de Yucatán es un acuífero cárstico, el cual se caracteriza por su alta permeabilidad. Huellas del proceso de la carstificación, como los túneles y las cavernas (cenotes), se pueden apreciar en toda la península. Sin embargo, hay una acumulación de los mismos a lo largo de una línea circular, el Anillo de Cenotes. El anillo está relacionado con el cráter de Chicxulub, una estructura de impacto enterrada que data del límite del Cretácico/Terciario. El Anillo de Cenotes representa en varios de sus segmentos una zona de alta permeabilidad y se ha propuesto que actúa como un río subterráneo, el cual concentra el agua subterránea y la conduce hacia sus puntos de intersección con la línea costera cerca de Celestún y Dzilam de Bravo. Basado en datos hidrogeológicos, se describe una zona que separa hidráulicamente dos segmentos del anillo. Se usó la relación SO_4/Cl como trazador natural para determinar direcciones de flujo en el área en estudio. La combinación de los resultados permite la identificación del parteaguas del sistema del río subterráneo y su ubicación en la parte sur del área en estudio cruzando el Anillo de Cenotes cerca de la población de Abalá.

PALABRAS CLAVE: Acuífero cárstico de Yucatán, Anillo de Cenotes, parteaguas.

ABSTRACT

The aquifer of the peninsula of Yucatán is a karstic aquifer characterized by its high permeability. Karst features such as underground channels and caverns (cenotes) are widely present throughout the peninsula. However, there is an accumulation of cenotes along a circular line, the Ring of Cenotes. The ring is related to the crater of Chicxulub, a buried impact structure that dates from the K/T boundary. The Ring of Cenotes represents on several segments a high permeability zone and is assumed to act as an underground river that collects ground water and brings it to its two intersection points with the coast line near Celestun and Dzilam de Bravo. Based on hydrogeological data, a dividing zone is described that hydraulically separates two segments of the Ring. Using the SO_4/Cl ratio as a natural tracer, ground water flow directions in the study area are described. Combining the results, the location of the ground water divide of the underground river system is found at the southern part of the study area, crossing the Ring of Cenotes near the village of Abala.

KEY WORDS: Karstic aquifer of Yucatán, Ring of Cenotes, ground water divide.

1. INTRODUCTION

The aquifer of the peninsula of Yucatán is a coastal karstic aquifer. It is unconfined, except for a narrow band parallel to the coast (Perry *et al.*, 1989). The Yucatán platform consists of a mature karst system, with high permeabilities and low hydraulic gradients (Back and Hanshaw, 1970; Marín, 1990; Marín *et al.*, 1987). The regional ground water flow is from southeast to northwest (Steinich and Marín, in press(b)). However, there are several phenomena which cause changes in the flow regime of the aquifer, by altering locally the regional northwest flow direction.

1) The Ring of Cenotes (sinkholes) is a circular zone of high cenote density. The permeability along several segments of this ring is enhanced, thus intercepting the regional ground water flow and causing a concentrated discharge at intersection points with the coast near Celestun on the west coast and near Dzilam de Bravo on the north coast of the peninsula (Marín, 1990; Perry *et al.*, 1995; Pope and Duller, 1989; Pope *et al.*, 1993). The Ring of Cenotes is related to Chicxulub crater (Hildebrand *et al.*, 1995; Perry *et al.*, 1995; Pope *et al.*, 1993), a buried impact structure that dates from the K/T boundary (Hildebrand *et al.*, 1991; Sharpton *et al.*, 1992; Swisher *et al.*, 1992).

(2) The aquifer permeability is dominated by secondary porosity, present as fractures, underground channels and caverns. Steinich and Marín (in press(a)) and Steinich and Marín (in press(b)) describe a zone of decreased permeability in the southern part of the ring of cenotes near Abala (Figure 1) near a zone with good interconnection of voids and typically low tortuosity of the flow path. The chemistry of the ground water is controlled by water-rock interactions, including mixing of the fresh/salt water, dissolution of the carbonate rocks, evaporation/ precipitation (i.e., loss or gain of pure water) and redox reactions (Velázquez Olimán, 1995; Perry *et al.*, in review), as well as dissolution of an evaporitic body in the southern section of the study area (Urrutia-Fucugauchi *et al.*, 1996).

2. OBJECTIVES

The objectives of this study are: to investigate local flow directions with (1) hydrogeological and (2) geochemical data, and (3) to integrate the results in order to deter–

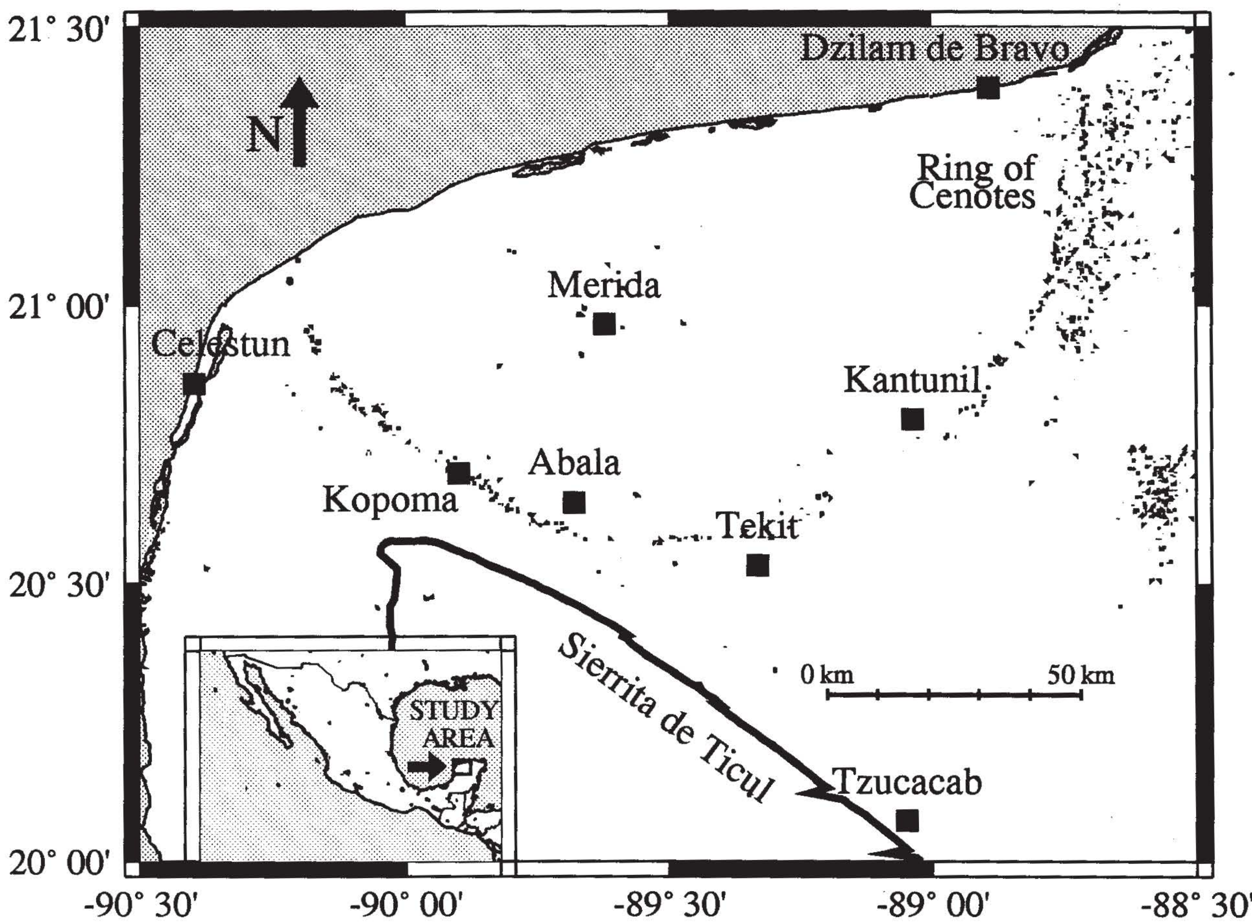

Fig. 1 Study area in the northwestern peninsula of Yucatán, Mexico. Black dots are cenotes that were digitized by the senior author from topographic maps (Anonymous, 1984).

mine the location of the ground water divide in the aquifer of northwestern Yucatán.

3. DESCRIPTION OF THE STUDY AREA

The study area includes the region between 88° 30' and 90° 30' west and 20°00' and 21°30' north (Figure 1). The Ring of Cenotes traverses the area from west near Celestun to northeast near Dzilam de Bravo (Figure 1). The study area is characterized by a flat topography which is cut by the Sierrita de Ticul (Figure 1), a small land step elevating levels from typically 15 meters above mean sea level (MSL) to the north, to levels in the range of 50 to 100 meters to the south (Anonymous, 1984).

4. METHODOLOGY

Water level measurements were conducted in October, 1994, in nine observation wells within the central part of the study area. Most were hand-driven water supply wells and some were cenotes (water-filled sinkholes). A first-order topographic survey conducted by INEGI exists for the area. Distances from the wells to the nearest benchmark are less than 300 m; well elevations were determined with a maximum error of 0.2 cm. Water levels were measured with respect to the reference point with a maximum error of 1 cm. Measurements in the observation wells were repeated up to four times over a two-week period in order to compare the oscillations of the water levels.

Twenty-one water samples were collected from water supply wells. Parameters measured in the field were temperature, pH, conductivity, dissolved oxygen, and redox potential using a Datasonde 3. Three samples were taken at each site for the determination of alkalinity, anions, and cations. Alkalinity was determined within 24 hours by Gran titration (Stumm and Morgan, 1981), using a Hach kit and 1.6 N H_2SO_4. Samples for anions and cations were collected in 125 ml plastic bottles previously washed in dilute 10% HNO_3 acid. Water samples were filtered using a 0.2 μm pore diameter. Samples were stored in a cooler and in a dark refrigerator at 4°C previous to analysis. Anions were analyzed using an ion chromatograph with a Dionex ion suppressor and a conductivity cell. The cations were analyzed using a Beckman V DC plasma. The laboratory analyses were conducted at the Geology Department at Northern Illinois University. All samples had a mass balance error of less than 5 % (Velázquez Olimán, 1995). The pH-meter was calibrated using 4.0 and 7.0 buffers. The electrodes for redox were calibrated using quinhydrone. A flow-through device was used for the field parameters. Readings were taken after the samples had stabilized.

5. RESULTS AND DISCUSSION

(a) Hydrogeological data

Marín (1990) and Marín *et al.* (1989) proposed that the Ring of Cenotes is a high-permeability zone that acts as an underground river intersecting ground water flow as it flows from south to north. Ground water is intercepted by the Ring discharges at two intersections with the Gulf of Mexico. Since ground water is discharging at both ends, there should be a ground water divide somewhere within the Ring. This hypothesis is supported by three lines of evidence: (1) on two north-south transects, the water level first increases with distance away from the sea and then decreases, showing a local minima at the intersection with the Ring. (2) A higher density of submarine springs is observed using Thematic Mapper images at Dzilam de Bravo, where the eastern portion of the Ring reaches the sea (Marín *et al.*, 1989). (3) Sand bars at the intersections of Celestun and Dzilam de Bravo (Figure 1) remain open (sand transport occurs from East to West along the coast) (Marín, 1990).

Marín (1990) mentions that ground water probably flows across the Ring in its southern part. Steinich and Marín (in press(a)) describe lateral permeability variations along the Ring. Using electrical soundings they identified a zone of relatively low permeability near Abala (Figure 1). West of Abala there is a narrow band with high cenote density, but the segment near Tekit (Figure 1) shows a broad band and lower cenote density. Marín (1990) suggested that ground water flows across the Ring near Kantunil. Steinich and Marín (in press(b)) proposed that this zone is highly variable with respect to water levels and flow regime.

The nine wells monitored are located within the transition area between the low permeability and the highly variable zone. Figure 2 shows the water level variations within a period of 14 days in October 1994. Water level changed drastically in some wells and remained stable in another group of wells. The distance between these two groups of wells is only a few kilometers and the karst aquifer is assumed to be highly permeable; yet water loss in the lower wells (c to i in Figure 2) was not compensated by flow from the higher wells (a and b in Figure 2) during the first three days. It is assumed that the two subsystems are disconnected hydraulically within the aquifer by a dividing zone of no flow or very slow flow. Figure 3 shows the location of this zone as a shaded area.

(b) Geochemical data

The geochemical data are presented in more detail elsewhere (Velázquez Olimán, 1995; Perry *et al.*, in review). The geochemistry of the ground water in Yucatán is primarily controlled by mixing of water in a fresh water lens with an underlying salt water intrusion and by the dissolution of evaporite and carbonate rocks. Dissolution of evaporite leads to an enrichment in sulfate, so the ratio of SO_4/

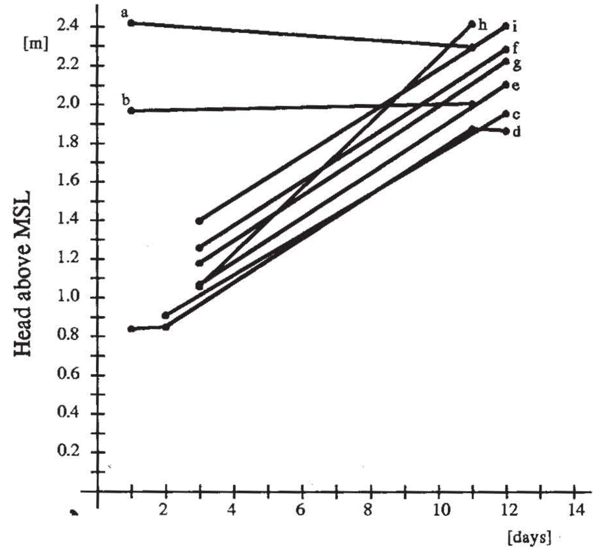

Fig. 2. Water level variations in nine observation wells in the central part of the study area. Measurements are from a two-week period in October of 1994; day one is Oct. 9. Well locations are shown in Figure 3. Wells (a) and (b) are located west and wells (c) to (i) east of the interpreted dividing zone. Water levels are in meters above mean sea level.

Cl can be used as a natural tracer (Velázquez Olimán, 1995; Perry *et al.*, 1995). Values of SO_4, Cl and the ratio SO_4/*Cl* of twenty-one observation wells are reported in Table 1.

Table 1

Values of SO_4, Cl, and ratio of (SO_4/Cl) x 1000 for the twenty-one ground water samples. Numbers after the site names in the first column are as in Figure 4.

Sample site	Sampling date	SO4 [meq/l]	Cl [meq/l]	SO4/Cl x 1000
Abala [01]	08/25/94	3.75	7.62	492.1
Chochola [02]	08/22/94	2.76	10.91	253.0
Homun [03]	06/22/93	0.35	3.11	112.5
Huhi [04]	06/22/93	0.38	3.36	113.1
Kantunil [05]	04/25/94	0.46	4.63	99.4
Kinchil [06]	12/20/93	1.30	9.42	138.0
Kopoma [07]	09/10/93	7.31	17.25	423.8
Mama [08]	06/22/93	3.20	5.23	611.9
Mani [09]	06/24/93	4.82	5.76	836.8
Opichen [10]	08/25/94	7.74	13.11	590.4
Oxkutzcab [11]	09/10/93	2.45	5.30	462.3
Sacalum [12]	08/25/94	5.85	11.80	495.8
S.Antonio T. [13]	12/22/93	3.08	12.44	247.6
S.Jose T. [14]	12/18/93	8.30	14.56	570.1
Sotuta [15]	06/22/93	0.52	3.52	147.7
Tecoh [16]	08/23/94	0.47	4.46	105.4
Tekax [17]	09/10/93	2.45	6.99	350.5
Tekit [18]	09/09/93	0.90	3.57	252.1
Telchaquillo [19]	06/24/93	0.55	3.42	160.8
Ticul [20]	12/17/93	3.91	6.99	559.4
Tzucacab [21]	09/09/93	11.36	10.37	1095.5
Sea water*		56.42	545.84	103.4

* The ratio (SO_4/Cl)x1000 for sea water is taken from Drever (1988).

Waters from the fresh water lens can be grouped as follows: (1) samples with a sulfate-to-chloride ratio similar to that of sea water (Drever, 1988); and (2) samples with a ra–

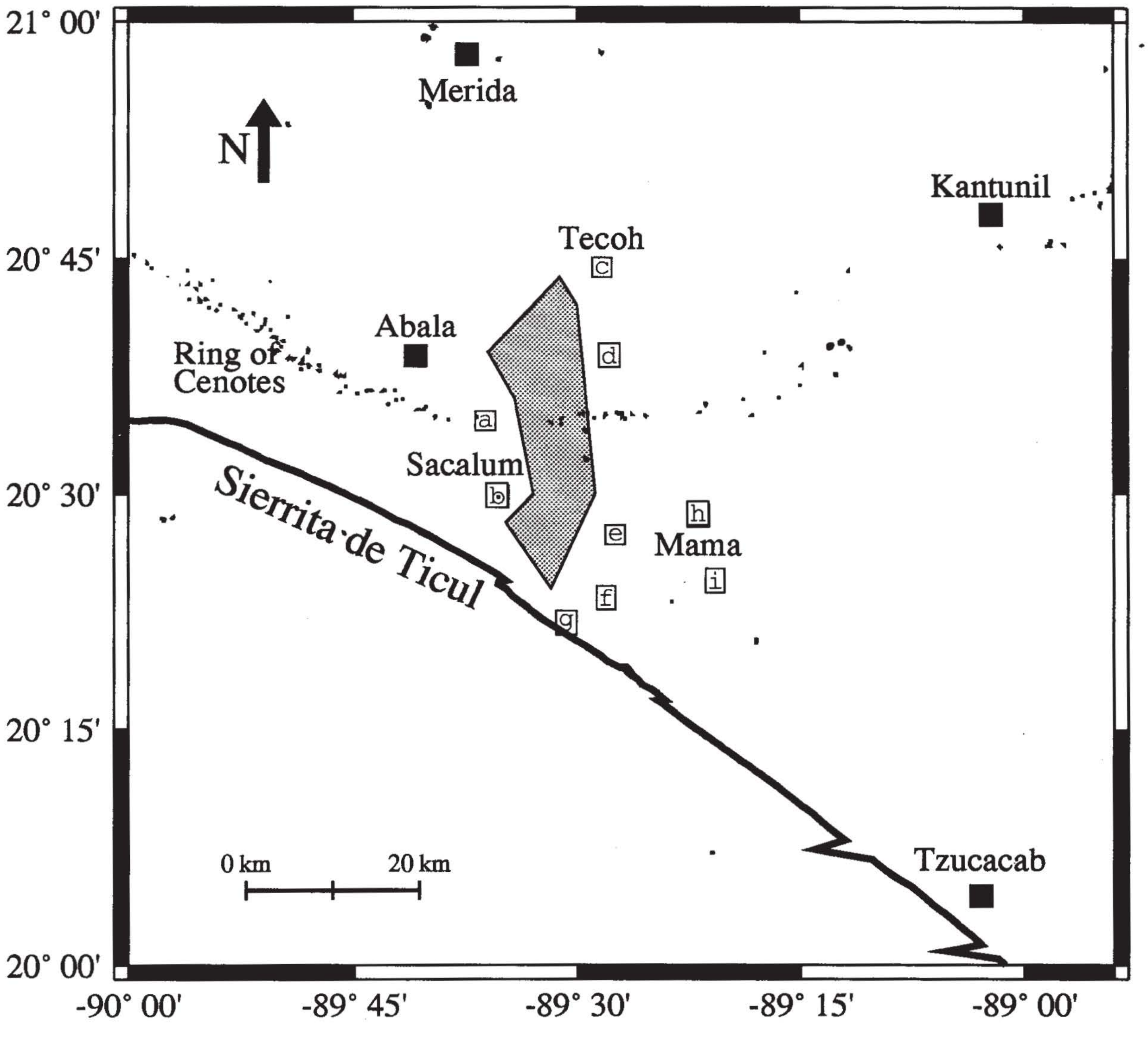

Fig. 3. Gray shaded area is the proposed location for the dividing zone as derived from hydrogeological data. [a] to [i] are the observation wells.

tio of SO_4/Cl greater than 300.0. In the first group SO_4/Cl is controlled primarily by mixing of the fresh water lens with the salt water intrusion. This group includes water from the area within the Ring and southeast of the Ring (Figure 4). Perry *et al.* (in review) present evidence that samples of the second group are mainly influenced by the contact with and dissolution of evaporites located in the southern part of the study area. Highest values extend in a zone about 20 km wide more or less parallel to the Sierrita de Ticul (Figure 4).

The highest ratio of SO_4/Cl (1095.5) is found in the southeastern part of the study area at Tzucacab (-89.05 west, 20.08 north, Figure 4). We may assume in this zone an evaporite source of sulfate in or above the fresh water lens; we are unable to locate this source more precisely because none of these waters is near saturation with respect to gypsum. There is a gradual decrease of SO_4/Cl toward the north of the evaporite zone. The preferred flow direction of the sulfate-enriched water from the evaporite zone is problably towards the west coast. As shown by Perry *et al.* (1995) the water from the Celestun water works (near the east coast, Figure 1) has a SO_4/Cl ratio similar to that at Kopoma. The same ground water flow direction was also proposed by Steinich and Marín (in press(b)).

Within the shaded area in Figure 4, bounded by Abala, Tecoh, Sacalum and Mama, the contours of SO_4/Cl cross the Ring of Cenotes at a sharp angle. In contrast, the SO_4/Cl ratio decreases gradually northward in the western part of the study area as has already been mentioned.

(c) Location of the ground water divide

The hydrogeological data (Figure 3) and the geochemical data (Figure 4 and Table 1) show good agreement be–

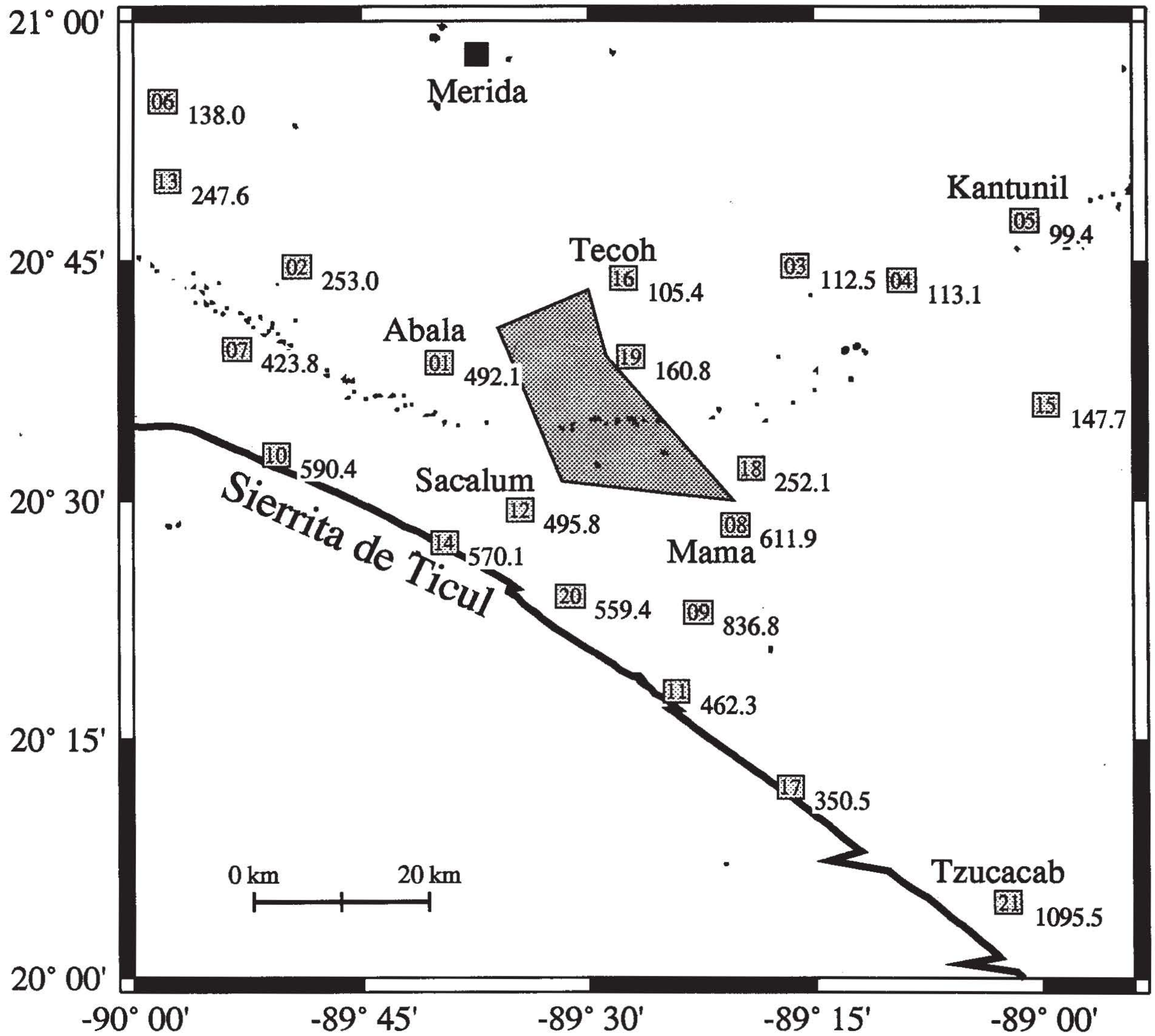

Fig. 4 (SO_4/Cl) x 1000 for 21 ground water samples. Sample site locations are shown as small numbered rectangles (numbers refer to Table 1).

tween the location of the proposed dividing zone and the sharp decrease of the SO_4/Cl ratio. We propose that this is a ground water divide. Thus, sulfate-enriched water from the evaporite zone near Tzucacab would initially flow to the north, but then the flow is deviated towards the west on a path between the Sierrita de Ticul and the western segment of the Ring of Cenotes. Sulfate-enriched water from Tzucacab does not cross the Ring of Cenotes to sites like Tecoh (well 16) and Telchaquillo (well 19) (Figure 4, Table 1).

Based on these results, we propose that the ground water divide is located on a line east of Abala (well 01) and west of Tecoh and Telchaquillo (sampling sites 16 and 19). The divide intersects the Ring of Cenotes west of Tekit and northeast of Sacalum (sampling sites 18, and 12). The proposed ground water divide is shown in Figure 4 as a gray shaded area. To the east, we lack sufficient geochemical data to trace the sulfate-enriched plume.

(d) Low permeability zone near Abala

The only sample north of the Ring of Cenotes having a high SO_4/Cl ratio is at Abala (Figure 4). This apparently contradicts the ground water divide hypothesis above. Steinich and Marín (in press(a)) showed that there is a zone of relatively low permeability near the village of Abala. Peak values of water level with respect to mean sea level were found in the same area (Steinich and Marín, in press(b)).

There are two possible explanations for high tracer values north of the Ring of Cenotes. (1) the high content of SO_4 is due to sulfate-enriched ground water flowing from south to north, or (2) there is a source of SO_4 near the area of Abala.

Steinich and Marín (in press(b)) showed that ground water may cross the Ring from southeast to northwest in the segment between the low-permeability zone and Kantunil. This flow is assumed to follow a flow path along a system of aligned fractures having the same direction (Steinich and Marín, in press(b)). As we have seen, this flow must occur east of the dividing zone. If sulfate-enriched ground water reaches the area near Abala, the dividing zone must be interrupted somewhere and a hydraulic gradient from east to west must be present. Measured peak values of the water level in different periods of the year (Steinich and Marín, in press(b)) seem to contradict this hypothesis. However, a temporary reversal in hydraulic gradient cannot be ruled out in such a highly permeable karstic aquifer.

6. CONCLUSIONS

Integration of hydrogeological and geochemical data was used to identify the ground water divide in the aquifer of northwestern Yucatán. The proposed location is based on: (1) results of hydrogeological data which made it possible to identify a zone dividing the aquifer into two subzones. Water of either of the subzones is unlikely to reach the other subzone. (2) Geochemical analysis of twenty-two ground water samples taken in the study area show that the ground water in the aquifer can be divided into two families, one in contact with an evaporite body located in the southern part of the study area and subject to enrichment with sulfate, and another family which is relatively poor in sulfate and can be assumed not to be in contact with evaporites. The sulfate-enriched water may be used as a natural tracer to allow determination of local flow directions of the ground water and the location of the ground water divide within the aquifer. The proposed ground water divide has a southeast to northwest direction and is located between Abala and Sacalum on the west and Tecoh and Mama on the east side.

7. ACKNOWLEDGMENTS

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