An Explanation for the Lack of a Dilute Freshwater Lens in Unconfined Tropical Coastal Aquifers: Yucatan Example

Ronald K. Stoessell[1] and James G. Coke[2]

[1]Department of Earth and Environmental Sciences, University of New Orleans, New Orleans, LA 70148

[2]P.O. Box 8663, The Woodlands, TX 77387

ABSTRACT

Dilute brackish waters, not dilute freshwaters, form the groundwater lens above the halocline in the northern Yucatan Peninsula. The lens is fed by rainwater and the absence of dilute freshwater needs to be explained. The lens overlies modified seawater in the unconfined, surface carbonate aquifers of the northern Yucatan Peninsula and has a maximum thickness of about 230 ft (70 m) in the peninsula interior. The salt composition in the lens is generally uniform with depth with total dissolved solids generally greater than 1,000 mg/L. Temperature is often nearly constant with depth between the halocline and water table or the base of the thermocline (in open sinkholes). The salt content increases approaching the coasts.

Vertical heat flow upward from the warmer, saline water below the halocline is hypothesized to produce instability at the top of the halocline, causing slightly saline water to rise by buoyancy. The resulting convection process distributes small amounts of salt throughout the lens to produce a uniform brackish composition. The mixing also promotes a constant temperature from the top of the halocline up to water table or base of the thermocline (in open sinkholes). The process continues along the coastward flow path of the groundwater, explaining the gradual increase in salt content of the brackish waters.

INTRODUCTION

The northern Yucatan Peninsula (Fig. 1) covers an area of 25,000 mi^2 (65,000 km^2), and is bounded on the west by the Bay of Campeche, on the north by the Gulf of Mexico and on the east by the Caribbean Sea. This is a region of karst topography with numerous sinkholes and few surface streams or lakes (Back and Hanshaw, 1970). The surface is formed from unconfined Quaternary, Neogene and Paleogene limestone aquifers (Lopez, 1973).

Within the carbonate rocks, high-Mg calcite has dissolved or been replaced by low-Mg calcite; dissolution of aragonite is an on-going process, and mixing-zone dolomitization has occurred within the saline portion of the halocline (Ward and Halley, 1985; Stoessell *et al.*, 1989). The sinkholes (called *cenotes*) collect organic matter and usually show evidence of sulfate reduction and sulfide oxidation where the sinkhole floor is below the halocline (Socki, 1984; Stoessell *et al.*, 1993). The southern portion of the region, between Lagunas Chichankanab and Esmeralda and Cenotes Azul and Angelita (see Figure 1) has brackish groundwaters enriched in sulfate due to the apparent dissolution of gypsum (Perry *et al.*, 2002).

Stoessell, R. K., and J. G. Coke, 2006, An explanation for the lack of a dilute freshwater lens in unconfined tropical coastal aquifers: Yucatan example: Gulf Coast Association of Geological Societies Transactions, v. 56, p. 785-792.

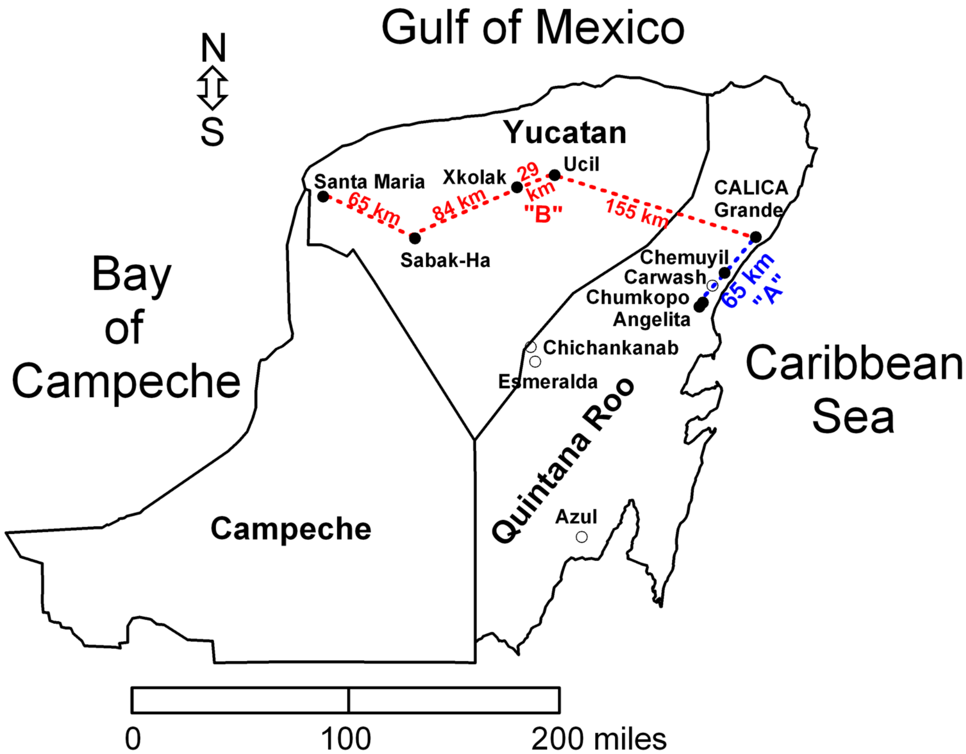

Figure 1. Yucatan Peninsula site locations for depth profiles shown in Figures 5 and 6, respectively, for traverses "A" and "B." Open circles denote locations where only groundwater above the halocline was sampled.

The mean annual recharge of freshwater for the Yucatan Peninsula has been estimated by Hanshaw and Back (1980) to be 5.9 in./yr (15 cm/yr), their estimate of the average difference between rainfall and evapotranspiration. The resulting groundwater lens above the halocline approaches 230 ft (70 m) thickness in the center of the northern Yucatan Peninsula and is characterized by low hydraulic heads with rapid recharge and high flow velocities (Back and Hanshaw, 1970). Inland from the Caribbean coast, Stoessell *et al*. (1993) showed the compositions of the saline water below the halocline to be modified seawater. Back and Hanshaw (1970) used brackish water compositions above the halocline to reach a similar conclusion for the underlying saline water in the peninsula interior.

The lens near the Caribbean coast is thinner than predicted by either the static Ghyben-Herzberg model or the non-static Hubbert freshwater model (Moore *et al*., 1992). The coastal halocline is often only a few meters thick, forming a stable density-stratified layer that has been reproduced by modeling its formation as a diffusion boundary between layers of seawater and freshwater (Stoessell, 1995). Moore *et al*. (1992) and Soteres (2000) measured flow velocities within the saline water under the halocline near the coast on the order of 0.004 in./sec (0.01 cm/sec) in the porous medium and fracture regimes. A temperature spike is often observed within the top of the halocline and has been explained as due to the coastward movement of the return arm of local seawater water thermal convection cells (Stoessell *et al*., 2002).

This paper provides an explanation for the dilute brackish composition of the groundwater lens above the halocline in the carbonate aquifers in the center of the northern Yucatan Peninsula. The brackish compositions contrast with the freshwater compositions of groundwaters in carbonate aquifers in the Florida Peninsula (Back and Hanshaw, 1970, their Table 3). Vertical profiles in this study shows the lens is characterized at individual sites by brackish waters of nearly constant total dissolved solids. Similarly, depth profiles of groundwater temperatures at individual sites are often nearly constant through all or part of the Yucatan lens. The absence of dilute freshwater in the center of such a large peninsula (25,000 mi^2; 65,000 km^2) is unexpected for a groundwater thickness of up to 230 ft with an average rainwater recharge rate of 5.9 in./yr.

METHODS

Total dissolved solids (tds) of water samples from near the water table are plotted in Figure 2 from sites across the Yucatan. The data include samples from this study, from Perry *et al*. (2002), Stoessell *et al*. (1993), and unpublished data in 1994 by R. K. Stoessell from Cenote Chemuyil (location in Figure 1). Total dissolved solids were computed from the measured concentrations of cations, anions, and aqueous silicon dioxide. Samples taken by Stoessell and co-workers in previous studies (prior to 1997) were taken and analyzed as described in Stoessell *et al*. (1993). Cation and anion (other than bicarbonate measured by alkalinity titration) concentrations in samples taken during this study were measured using a Dionex 100 Ion Chromatograph. A compilation of the complete analyses of all Yucatan samples and locations can be obtained by request from the senior author and on the world-wide web (Stoessell, 2006).

Br versus Cl concentration and Na versus Cl concentration are plotted, respectively, for Yucatan groundwater in Figures 3 and 4. The Br versus Cl concentration plot used only samples from this study (taken when the depth profiles were measured) because other studies did not include measuring Br concentrations. The Na versus Cl concentration plot also included previous data from the Caribbean Coast reported in Stoessell *et al*. (1993) and unpublished data in 1994 from R. K. Stoessell at Cenote Chemuyil. In all cases, samples were collected by lowering an open one-liter plastic tube container on a cable and then dropping a metal messenger to seal the container at the sample depth.

Temperature and salinity versus depth profiles in sinkholes (*cenotes*) in the northern Yucatan Peninsula are shown in Figures 5 and 6. With two exceptions, the depth profiles were made with a Quanta G Hydrolab Probe. The exceptions are the profiles at Cenotes Chemuyil and Angelita (locations in Figure 1) that were taken with a modified YSI 3000 Probe.

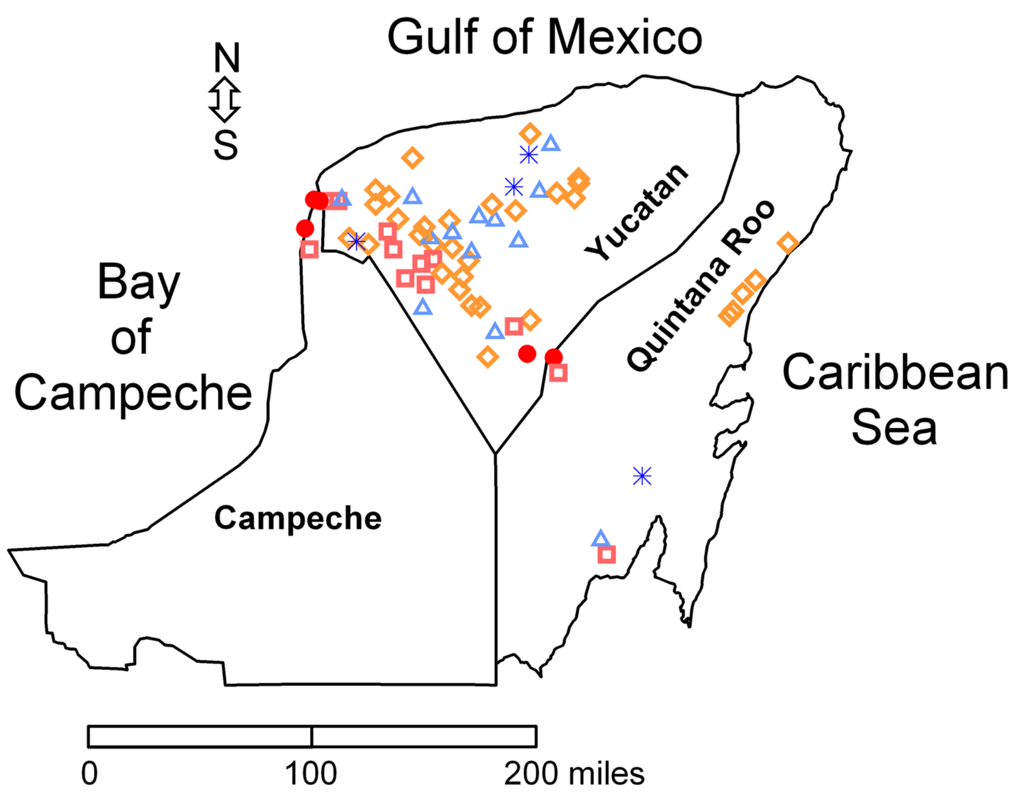

Figure 2. Total dissolved solids (mg/L) in groundwater near water table. See text for sources of data. Asterisk, >400-800 mg/L; triangle, >800-1,000 mg/L; diamond, >1,000-2,000 mg/L; square, >2,000-3,000 mg/L; circle, >3,000 mg/L.

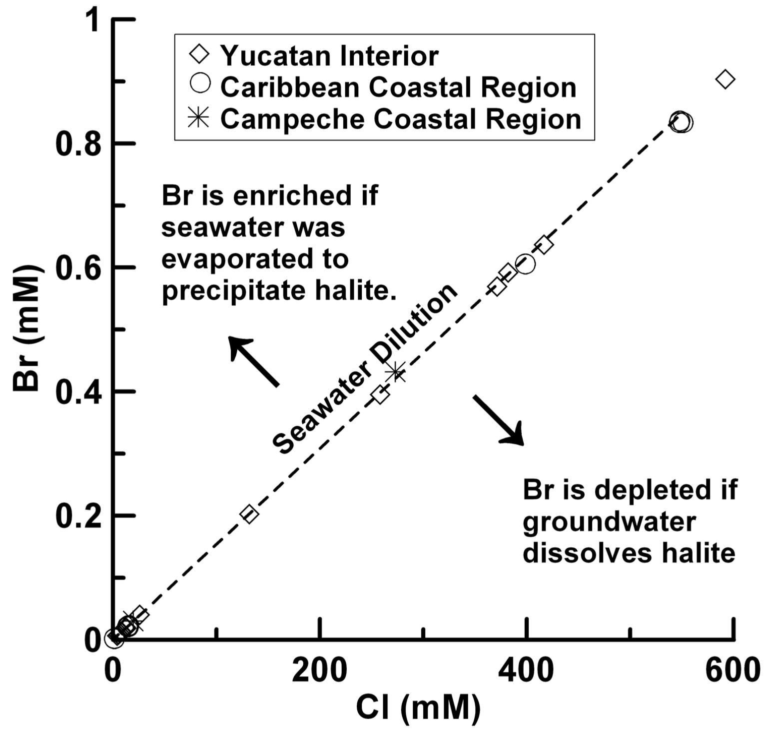

Figure 3. Br vs. Cl mmolarities in Yucatan groundwaters with a seawater – distilled water mixing line.

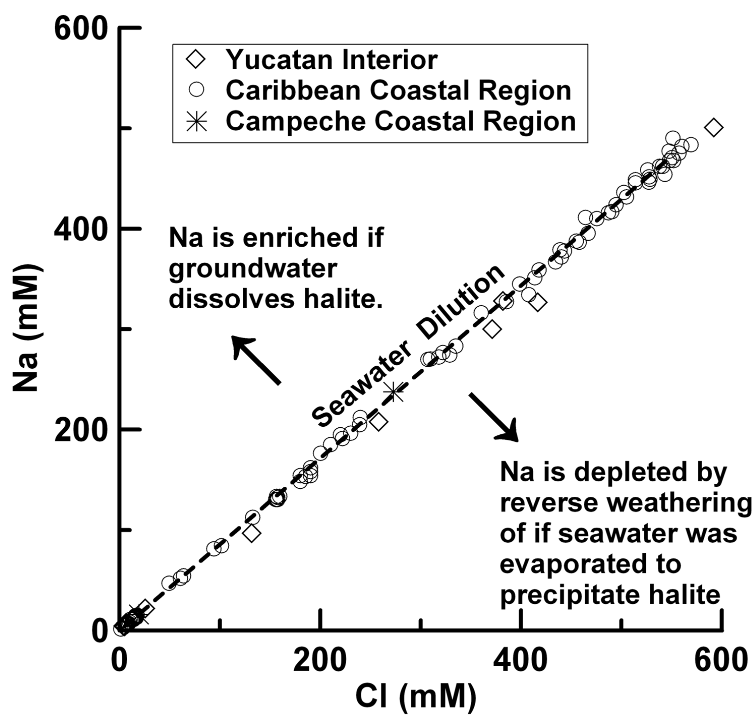

Figure 4. Na vs. Cl mmolarities in Yucatan groundwaters with a seawater – distilled water mixing line.

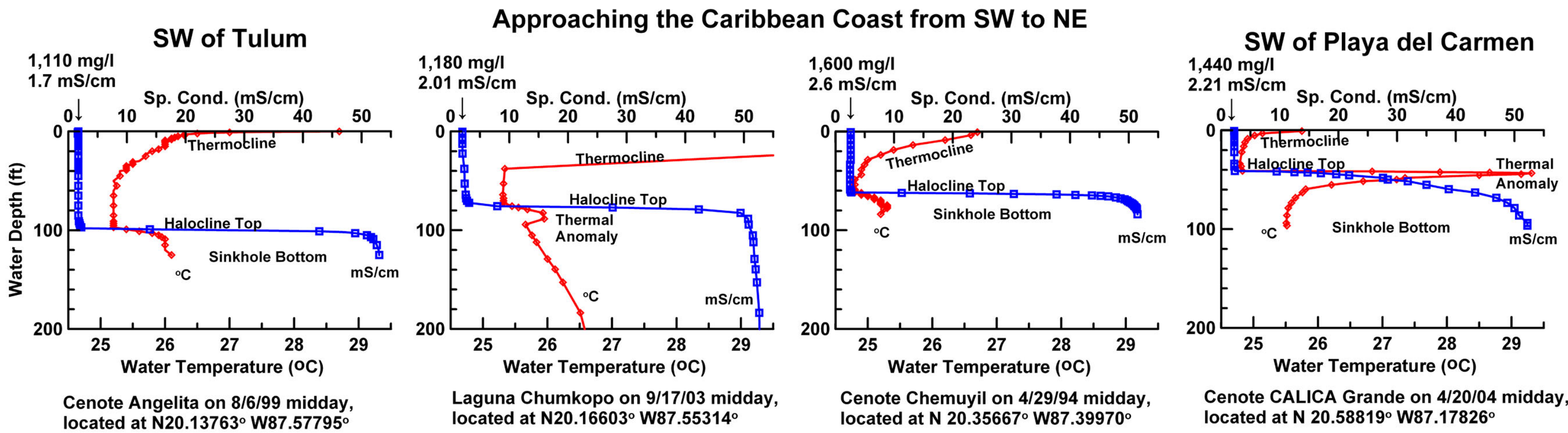

Figure 5. Temperature (red diamonds) and specific conductivity (blue squares) vs. depth in four sinkholes near Caribbean Coast along traverse "A" in Figure 1.

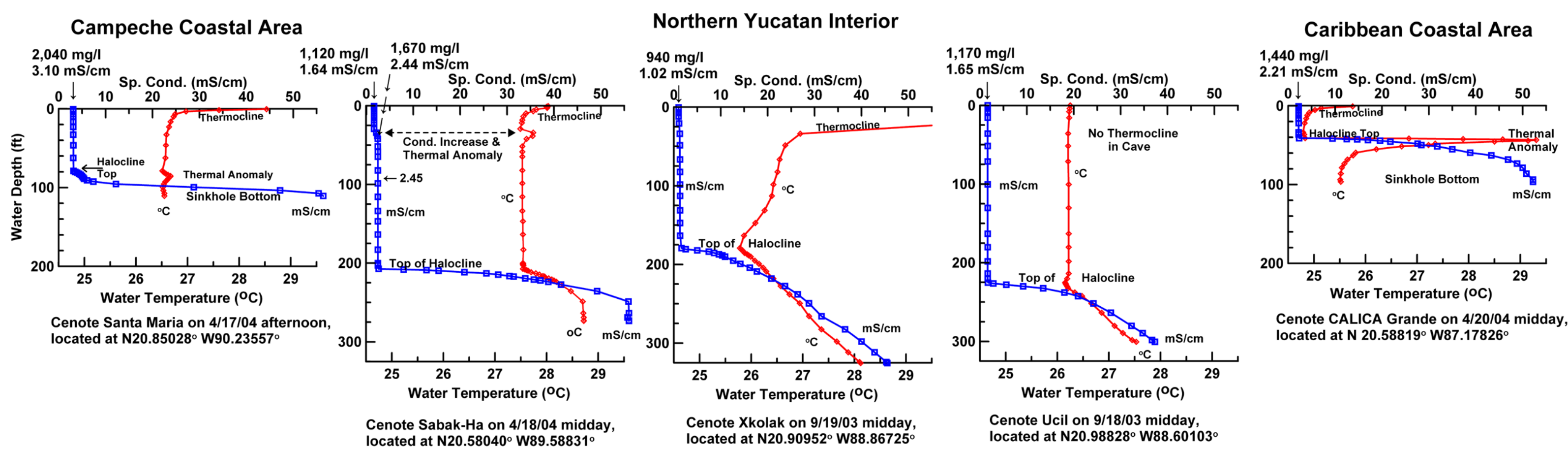

Figure 6. Temperature (red diamonds) and specific conductivity (blue squares) vs. depth in northern Yucatan along traverse "B" in Figure 1.

RESULTS AND DISCUSSION

The general brackish nature of the groundwater near the water table in the northern Yucatan Peninsula is shown by the tds data in Figure 2. Twelve of the samples were taken just below the water surface in sinkholes by Stoessell and co-workers (sources given above in Methods). The remaining 54 samples are from Perry *et al*. (2002) and are predominantly samples of groundwater used by municipalities. Of the 66 samples in Figure 2, the tds is from 400 to 800 mg/L in 4 samples, between 800 and 1,000 mg/L in 13 samples, and greater than 1,000 mg/L in the remaining 49 samples.

If the source of the dissolved salt in the brackish groundwater is the saline water below the halocline, the ratios of conserved components will be the same above and below the halocline. Br versus Cl concentrations are plotted in Figure 3 and Na versus Cl concentrations are plotted in Figure 4. These are conserved components and their concentrations fit a linear mixing line corresponding to seawater dilution, fingerprinting the saline water to be originally seawater and to be the main salinity source of NaCl-rich brackish waters above the halocline. Additional salinity sources can exist, *e.g*., gypsum dissolution to produce the sulfate-rich brackish waters in the area from Cenotes Azul and Angelita to Lagunas Esmeralda and Chichankanab (Perry *et al*. 2002). The plots also indicate the saline water has not dissolved halite, which would have increased the Na:Cl aqueous ratio and decreased the Br:Cl aqueous ratio. Apparently seawater enters the Peninsula at various depths along the coast and crosses the interior, moving through the fractured carbonate aquifers. The heat source for the saline water is the geothermal gradient. The authors think the saline water under the halocline is returning to the coasts as the return arm of saline convection cells, driven by freshwater loading through rainwater infiltration causing temporary mounding of the water table (Stoessell and Coke, 2004).

Two traverses of specific conductivity and temperature versus depth profiles for sinkholes are shown in Figures 5 and 6, respectively. The profile point locations are shown in Figure 1. Traverse A in Figure 5 is 37.3 mi (60 km) long and starts at Cenote Angelita, 7.5 mi (12 km) inland and southwest of Tulum, and runs northeast to Laguna Chumkopo, then to Cenote Chemuyil, and ends at Cenote CALICA Grande near Playa del Carmen, 3.1 mi (5 km) inland from the Caribbean Sea. Traverse B in Figure 6 runs for 199 mi (320 km) across the interior of the peninsula, starting at Cenote Santa Maria, about 10.6 mi (17 km) inland from Celestun on the Bay of Campeche, and running southeast to Cenote Sabak-Ha, then northeast to Cenote Xkolak, and northeast to Cenote Ucil, and then southeast to Cenote CALICA Grande near Playa del Carmen.

The groundwater lens above the halocline in the sinkholes has a maximum thickness of 230 ft (70 m) at Cenote Ucil and (as expected) thins coastward in Figures 5 and 6. The minimum specific conductivity at the water surface in any of the sinkholes was 1.02 microSiemens per cm (mS/cm) (940 mg/L total dissolved solids) at Cenote Xkolak where the groundwater lens was only 180 ft (55 m) thick.

A nearly constant specific conductivity in the brackish lens occurs from the top of the halocline to the water surface in all of the profiles. The difference in specific conductivity throughout each lens is within 0.05 mS/cm in all profiles except in Chumkopo, Xkolak, and Sabak-Ha. Small, linear increases in specific conductivity occur with increasing depth in Xkolak and Chumkopo, producing conductivity differences of 0.3 and 0.7 mS/cm between the top and bottom of the lens. Sabak-Ha has two distinct brackish water bodies: a thin upper layer and a thick lower layer with specific conductivities, respectively of 1.64 and 2.44 mS/cm. Both layers have constant conductivities within 0.05 mS/cm.

All of the sites in the traverses are open sinkholes except Cenote Ucil which opens within a cave. Consequently, all of the sinkholes have thermoclines at the top of the water column except for Ucil. The thermoclines are a temporary feature within the coastward-moving brackish water. The portion of the temperature-depth profiles below the thermocline is representative of the groundwater within the closed fractures, outside of the open sinkholes.

The temperature-depth profiles extending up from the top of the halocline show constant temperatures with decreasing depth at Ucil, Sabak-Ha, Angelita, and Chumkopo, nearly constant temperature at Santa Maria, and nonlinear increases at Xkolak, Chemuyil, and CALICA Grande. Thermal anomalies exist in the halocline of all of the coastal sinkholes but not in the interior sinkholes. In Sabak-Ha, a thermal anomaly separates the two brackish groundwater layers above the halocline. The temperature below the halocline is warmer by a degree Centigrade or more in all of the sinkholes except Santa Maria which bottomed out at the base of the halocline, preventing the measurements of deeper saline groundwater temperatures.

The warmer temperature of the saline water below the halocline is a heat source for convection above the halocline. The most representative depth profile for the Yucatan groundwater is probably that at Ucil, which has the thickest brackish water lens (70 m) and lacks a thermocline. Both the temperature and dissolved salt content are constant throughout the lens at Ucil, indicating mixing. The Br to Cl and Na to Cl ratios of the Yucatan brackish groundwaters indicate the salt source is the saline water below the halocline.

CONCLUSIONS

Vertical advection induced by heat flow up through the halocline is a reasonable explanation for this well-mixed dilute brackish lens. The heat flow warms the slightly saline water just above the top of the halocline, making it less dense than the overlying, less saline but colder water. The water rises by buoyancy, bringing salt and inducing mixing within the lens. The process continues as the groundwater flows coastward, which gradually increases the salt content of the brackish waters.

ACKNOWLEDGMENTS

John Clark of Vulcan and Marie Carmen Cerda, Jorge Rodriguez, and Lourdes Rodriguez of CALICA gave us access to the CALICA sinkholes. Charles Shaw of Centro Ecologico Akumal and William Ward of the University of New Orleans provided valuable insight into the geology and hydrology of the Yucatan. Eugene Perry provided access to data collected by him and his coworkers. R. K. Stoessell wishes to thank his wife, Londi Moore, for her sacrifice of untold hours of "quality time."

REFERENCES CITED

Back, W., and B. B. Hanshaw, 1970, Comparison of chemical hydrogeology of the carbonate peninsulas of Florida and Yucatan: Journal of Hydrology, v. 10, p. 330-368.

Hanshaw, B. B., and W. Back, 1980, Chemical mass-wasting of the northern Yucatan Peninsula by groundwater dissolution: Geology, v. 8, p. 222-224.

Lopez, R. E., 1973, *Estudio geologico de la Peninsula de Yucatan: Association Mexicana de Geologos Petroleros Boletin*, v. 25, p. 23-76.

Moore, Y. H., R. K. Stoessell, and D. H. Easley, 1992, Ground-water flow along the northeastern coast of the Yucatan Peninsula: Ground Water, v. 30, p. 343-350.

Perry, E. C., G. Velazquez-Oliman, and L. E. Marin, 2002, The hydrogeochemistry of the karst aquifer system of the northern Yucatan Peninsula, Mexico: International Geology Review, v. 44, p. 191-221.

Socki, R. A., 1984, A chemical and isotopic study of groundwater from northwestern Yucatan, Mexico: M.S. thesis, Northern Illinois University, DeKalb, Illinois, 61 p.

Soteres, A. D., 2000, Groundwater model of freshwater/salt-water lens in the northeastern Yucatan Peninsula: M.S. thesis, University of New Orleans, New Orleans, Louisiana, 70 p.

Stoessell, R. K., 1995, Dampening of transverse dispersion in the halocline in karst limestone in the northeastern Yucatan Peninsula: Ground Water, v. 32, p. 366-371.

Stoessell, R. K., 2006, Yucatan Caribbean data 1980s and 1990s, <http://www.ronstoessell.org/Stoessell_Yucatan.pdf> Accessed June 16, 2006.

Stoessell, R. K., and J. G. Coke, 2004, Hydrological and chemical processes in groundwater within Yucatan karst: Geological Society of America Abstracts with Programs, v. 36, no. 5, p. 258.

Stoessell, R. K., W. C. Ward, B. H. Ford, and J. D. Schuffert, 1989, Water chemistry and $CaCO_3$ dissolution in the saline portion of an open-flow mixing zone, coastal Yucatan Peninsula, Mexico: Geological Society of America Bulletin, v. 101, p. 159-169.

Stoessell, R. K., Y. H. Moore, and J. G. Coke, 1993, The occurrence and effect of sulfate reduction and sulfide oxidation on coastal limestone dissolution in Yucatan *cenotes*: Ground Water, v. 31, p. 566-575.

Stoessell, R. K., J. G. Coke, and D. H. Easley, 2002, Localized thermal anomalies in haloclines of coastal Yucatan sinkholes: Ground Water, v. 40, p. 416-424.

Ward, W. C., and R. B. Halley, 1985, Dolomitization in a mixing zone of near-seawater composition, late Pleistocene, northeastern Yucatan Peninsula: Journal of Sedimentary Petrology, v. 55, p. 407-420.