Performing Multiprobe Profiles and Hydrographic Description of the Water column in an Anchialine Cave in Quintana Roo

Olmo Torres Talamante [1,2]*, Elva Escobar [3]*, Patricia A. Beddows [4]* and Jill Yager[5]

[1] Posgrado en Ciencias del Mar y Limnología, Instituto de Ciencias del Mar y Limnología, UNAM, Ciudad Universitaria, 04510, Mexico City, ulmusacuaticus@gmail.com
[2] Federación Mexicana de Actividades Subacuáticas. Av. Rio Churubusco Puerta 9, Cuidad Deportiva 08010, Mexico City
[3] Universidad Nacional Autónoma de México, Instituto de Ciencias del Mar y Limnología, A.P. 70-305 Ciudad Universitaria, 04510, Mexico City, escobri@mar.icmyl.unam.mx
[4] School of Geography and Earth Sciences, McMaster University, Hamilton ON L8S 4KI, Canada. patricia.beddows@gmail.com
[5] Department of Environmental and Biological Sciences, Antioch College, Antioch OH, 45387 USA. jill.yager@gmail.com
* corresponding author

Abstract

In anchialine coastal caves, the underlying marine water layer beneath the density interface is hypoxic and food limited due to the absence of light and reduced transport of material from the sinkholes. Cave fauna survive under these conditions displaying great adaptation. This study describes the use of multiprobe data loggers (e.g., Hydrolab DS3) to generate high-resolution profiles of environmental factors in the anchialine cave system Crustacea in Quintana Roo, Mexico. Cave diving techniques, advanced Nitrox and decompression procedures were required to achieve the goals of this study over the course of twelve dives and approximately 26 h of observations and underwater work. Salinity profiles show the strong stratification with a brackish upper water lens, a bottom marine water zone and a mixing zone or halocline between those. There is a thermal inversion with the bottom marine water warmer than the upper brackish lens. The water column within the cave is hypoxic (2.54 to 0.2 mg·L^{-1}). The suitable use of an internally logging multiprobe is shown to be of great value in the collection of detailed environmental data which then contributes to the understanding of coastal groundwater habitats and helps strengthen conservation policies through ecological information.

Keywords: groundwater, halocline, hypoxia, Mexican Caribbean coast, thermal inversion

Introduction

A distinct feature of coastal anchialine aquifer systems is the presence of freshwater overlying denser salt water, with a density interface separating the two which acts as a physico-chemical boundary. Karst cave systems form along carbonate coastlines from dissolution driven by hydrogeochemical and biogeochemical process. The dissolution produces organized and interconnected voids that efficiently drain meteoric water to the coast. The term anchialine is used herein to define the coastal cave systems with an inland opening and subsurface connections to the sea.

Anchialine groundwater ecology is a relevant domain of research. Many anchialine systems are known to host rich fauna (Stock et al., 1986), mainly crustaceans of marine ancestry (Iliffe, 2000), and these ecologies remain poorly documented similar to those of the deep seas (Glover and Earle, 2004). Of particular note, the underlying marine water in anchialine limestone caves is usually

177

hypoxic (3 to <1 mg·L^{-1}) (Yager, 1994; Yager and Humphreys, 1996; Iliffe, 2000) seriously limiting the presence of most fauna.

There is also a pressing demand for research on groundwater ecology since much of the world's population depends on groundwater resources, of which ~25% of the world's population is specifically reliant on karst aquifers (World Water Assessment Program, 2006). In the state of Quintana Roo along the Caribbean coast of the Yucatan Peninsula, the freshwater layer is frequently of drinking water quality (salinity less than 1 mg·L^{-1}) and the inhabitants are almost solely reliant on groundwater for the daily basic activities (Doehring and Butler, 1974; Marín and Perry, 1994).

The aim of this paper is to describe the use of a self-contained multiprobe in generating profiles of the stratified water column within an anchialine system, and the data resulting from that exercise. The anchialine cave system Crustacea was chosen for a broader study due to the increasing stress on the site from urban expansion and tourism. A segment of the explored cave conduit was selected for profiling of the water column with four stations along a 289 m transect running nearly parallel to the coast at depth of 9-19 m. Crustacea is located at 0.5 km inland from the coastline in the NE Yucatan Peninsula, Mexico. The flooded cave links three sinkholes, and has a total surveyed length of 3,626 m (Quintana Roo Speleological Survey, 2008).

Methods

Cave Diving

Full cave diving, advanced Nitrox and decompression procedures were required to achieve the study goals. The dives were performed by a team of two divers using back mounted double manifolded aluminum 80 tanks with Hogarthian cave diving configuration and a third aluminum 80 tank mounted as a stage bottle using a EANx32 gas mix. Equivalent air depth (EAD) at 19 m using EANx 32 is 15 m, no decompression limit is 75 min on Bühlmann's ZHL-16 Dive Tables, and most of the dives were over 120 min bottom time so decompression was mandatory. A distinctly marked and cleaned tank with 100% oxygen was clipped to the primary reel line at 6 m depth within the open sinkhole water pool at the entrance of the anchialine system for shared decompression as nitrogen release, as an added safety margin given the physical labor and task loading on these dives, their duration, moderately deep depth, and the many sequential days of diving.

Multiprobe Use

In situ profiles in four selected sampling stations (A,B,C,D) were performed with a Hydrolab DS3 data logger to record depth, conductivity which is equated to salinity, temperature, and dissolved oxygen. The multiprobe was programmed to the maximum instrumental frequency of 0.2 Hz, or once every five seconds to achieve the best description of the stratified hydrographic structure of the water column. The 1.2 m long multiprobe was clipped D-rings at the hip and upper chest on the cave diving 5-point harness during travel and unclipped for hand-held use at each station to generate the profiles. The diver rose to the ceiling and achieved a mean descent rate of 2.3 cm/sec principally using breath hold buoyancy, and thus allowing the sensors to thermally compensate and stabilize the readings particularly while crossing through the salinity and thermal stratification zone. It is recommended to read the operating manual for parameter specifications prior to use of any multiprobe data logger (Table 1). The data sets from the Hydrolab DS3 multiprobe were downloaded after each dive, compiled, plotted and compared against the use of another multiprobe by Yager and Madden (Yager and Madden, 2002) in the same cave system.

178

Table 1. Hydrolab DS3 parameter specifications (Hydrolab, 1991)

Parameter	Range	Accuracy	Resolution	Response time
Temperature	-5 to 50°C	±0.15°C	0.01°C	<1 min
Conductivity	0 to 100 mS·cm^{-1}	±1% of range	4 digits	<1 min
Salinity	0 to 70 ppt	± 0.2 ppt	0.1 ppt	<1 min
Dissolved O_2	0 to 20 mg·L^{-1}	±0.2 mg·L^{-1}	0.01 mg·L^{-1}	<1 min

Results

Data Record and the Diving Descent Rate

Extended bottom time was necessary to perform slow and controlled vertical profiles from which detailed hydrographic description of the water column could be obtained (Figure 1 and 3, Table 3). Ceiling-to-floor profiles were initiated with a pause for ~30 sec near the ceiling (Figure 1) allowing the probe to thermally equilibrate and for the diver to stabilize themselves. This was followed by a slow and constant mean descent rate of 2.3±0.2 cm·s^{-1} which should allow the sensors to compensate and stabilize the readings while crossing through the stratification zone. In this example, the slowest descent rate was attained at Station D which was the final profile conducted on this dive, whereas the highest occurred at station A which was the first profile captured (Figure 1). Due to cave's geomorphology, it was possible to reach the shallowest profiling depth of ~9 m at the ceiling of station A, whereas the cave ceiling was deeper at stations B, C and D. Station A profile is the longest simply due to the greater accessible depth of water column, while the upper water layer was not as well represented in the data recorded at Stations B-D (Table 2).
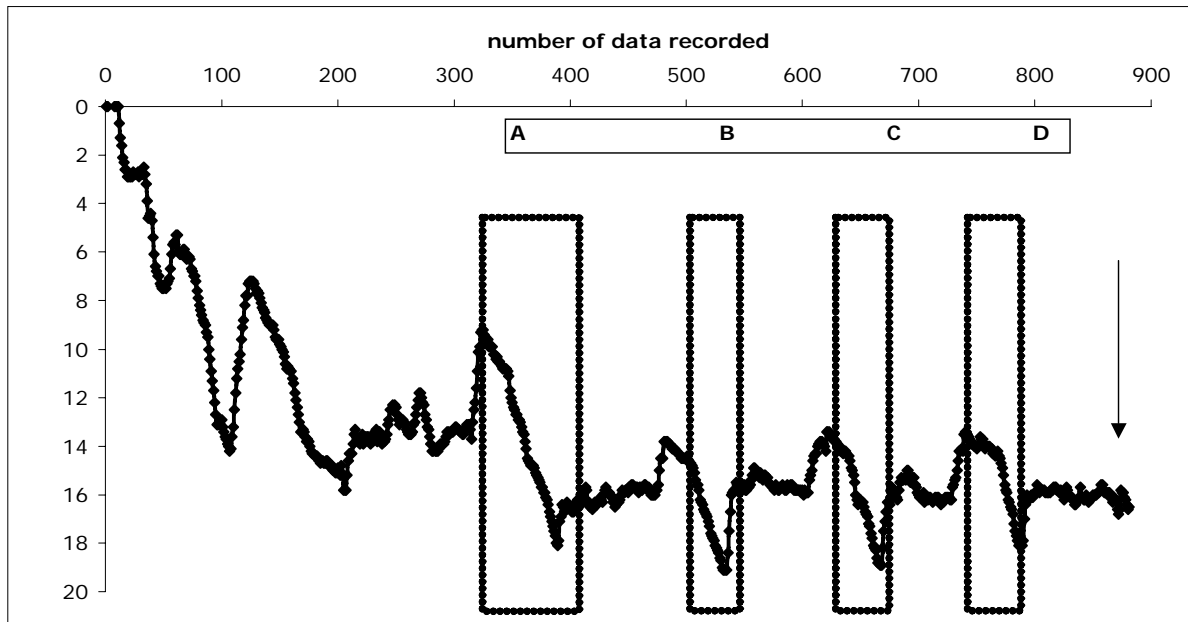

Figure 1. Dive profile, vertical profiles at sampling stations with data record every five seconds, arrow indicate mid-point in the dive at the point of furthest penetration into the cave system Crustacea
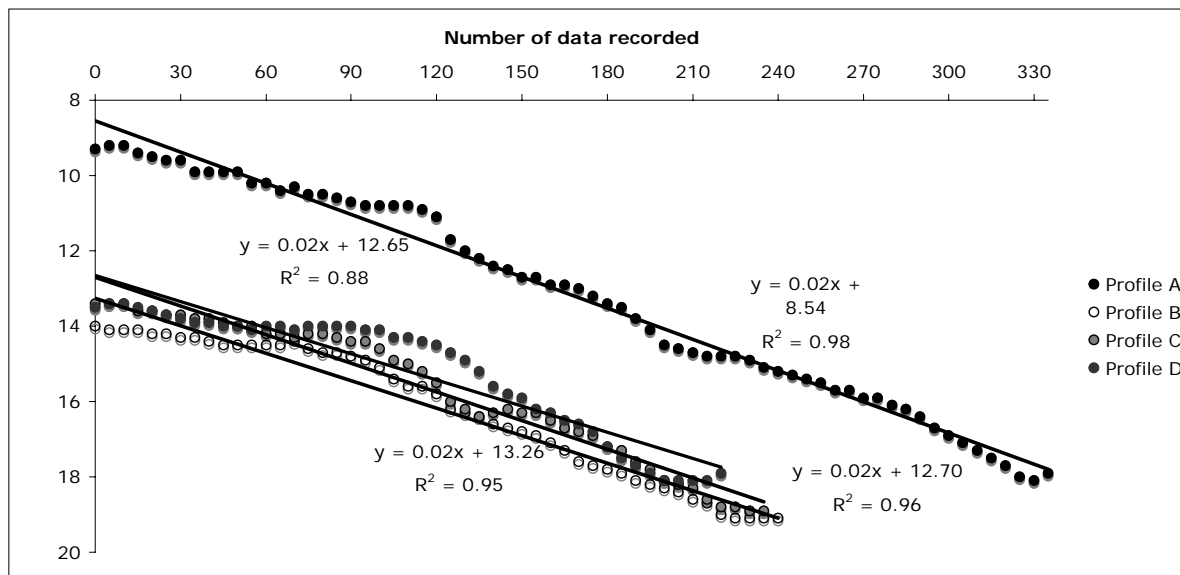
Figure 2. Similar slopes between profiled station show slow and constant descent rate, data record every five seconds

Table 2. Data recorded summary of water column profiles in four sampling stations

Station	Number of data recorded	Profile length cm	Descent speed cm·s^{-1}	Number of data recorded		
				Upper water lens	Intermediate water lens	Bottom water lens
A	68	880	2.62	42	11	15
B	49	510	2.12	6	14	29
C	48	550	2.34	10	11	24
D	45	460	2.13	7	17	19

Hydrographic Description of the Water Column

General salinity data of the cave shows a strong stratification with three water masses (Figure 3). The first water mass is fresh (<3 g·L^{-1}) from the surface to 6 m depth, the second is brackish ~10 g·L^{-1} from 9.4 to 14.6, and the third is marine ~35 g·L^{-1} from 15.9 to bottom. Steep salinity gradients or haloclines are present between the water masses. Salinity data from profiles at stations A,B,C and D show strata depth variation, the brackish upper water lens or epicline extends from 9.2 to 14.2 m depth, intermediate water lens or cline from 13.9 to 16.3 m depth, and bottom water or hypocline from 14.7 to bottom (Table 3). Temperature increases at ~14 m depth such that the bottom marine water is warmer than the upper brackish lens (Figure 3B). There is a temperature maximum at ~15.5 m which is immediately below the lower inflection of the halocline as seen in the salinity profile (Figure 3). Dissolved oxygen in the four profiles was hypoxic (2.54 to 0.2 mg·L^{-1}; Table 3).
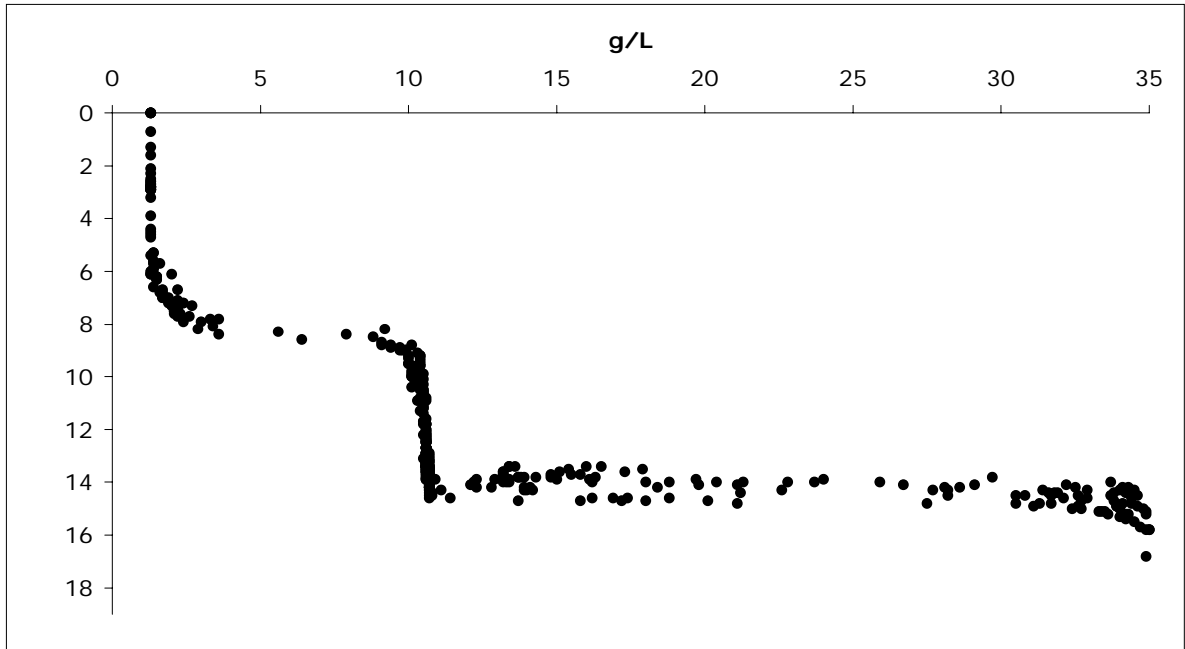
Figure 3. Salinity record along the dive data record every five seconds from the cave system Crustacea
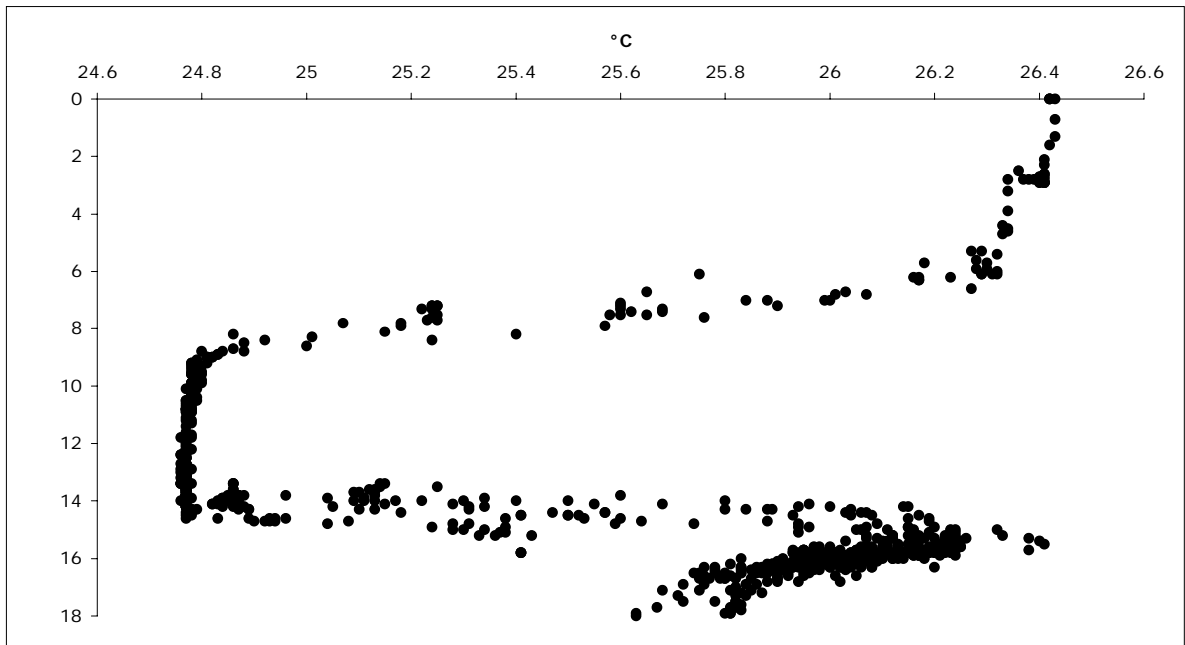

Figure 4. Thermal record along the dive data record every five seconds from the cave system Crustacea

Table 3. Values for salinity, temperature and dissolved oxygen profiles
by stations and depth range in Crustacea

		Depth m	Salinity $g \cdot L^{-1}$	Temperature ^{o}C	Dissolved. O_2 $mg \cdot L^{-1}$
Station A	Epi	9.2 - 14.6	10.52 ± 0.11	24.77 ± 0.00	0.13 ± 0.07
	Cline	14.6 - 16.3	31.09 ± 5.5	26.07 ± 0.44	0.08 ± 0.07
	Hypo	16.3 - 18.9	35.46 ± 0.09	25.8 ± 0.18	0.01 ± 0.00
Station B	Epi	13.9 - 14.2	12.30 ± 0.25	24.8 ± 0.01	0.16 ± 0.02
	Cline	14.2 - 14.7	28.71 ± 7.03	25.47 ± 0.32	0.32 ± 0.10
	Hypo	14.7 - 18.9	35.49 ± 0.18	25.86 ± 0.11	0.03 ± 0.06
Station C	Epi	13.9 - 14.2	13.27 ± 0.13	24.85 ± 0.00	0.2 ± 0.03
	Cline	14.2 - 15.2	26.50 ± 7.66	25.39 ± 0.40	0.27 ± 0.07
	Hypo	15.2 - 18.9	35.61 ± 0.10	25.89 ± 0.11	0.04 ± 0.02
Station D	Epi	13.4 - 13.9	15.68 ± 1.07	25.14 ± 0.04	1.83 ± 0.81
	Cline	13.9 - 14.7	24.29 ± 6.22	25.44 ± 0.35	0.92 ± 0.67
	Hypo	14.7 - 18.9	35.55 ± 0.18	25.94 ± 0.14	0.03 ± 0.01

Discussion

Data Record and the Diving Descent Rate

The plotting and interpretation of data allows for the description of the hydrographic structure and discrimination of boundaries within the system. These results were compared and differences described against different methods of usage of other multiprobe (Yager and Madden, 2002) in the same cave system. It is notable that the work of Yager and Madden (2002) was a pioneering assessment for Crustacea focusing on the biology and that preliminary effort set the baseline for other studies such as this one.

Yager and Madden (2002) obtained whole dive data by fixing the multiprobe in between the manifolded tanks throughout the dive with the instrument set to a one minute sampling interval (Figure 5). In contrast, we clipped the multiprobe to accessible D-rings and thus were able to detach it for profiling use at selected stations, while the sampling interval was every five seconds (Figure 1). Salinity profiles from both data sets (Figures 3 and 6) show the stratification with a fresh to brackish upper water lens, a mixing zone or halocline, and bottom marine water zone. However only with the targeting profiling and higher sampling rate is it possible to see the finer structure of the water column, notably the two distinct stepwise increases in salinity through the halocline. It is notable that Figure 1 does not show the return to the surface since the instrument memory reached capacity prior to the end of the dive (in this case, with 881 records or 73 min). Handling the multiprobe during the dive give us the chance to perform vertical profiles in selected sampling station, while attaching the probe to the tanks is a viable approach for broad scale assessments.
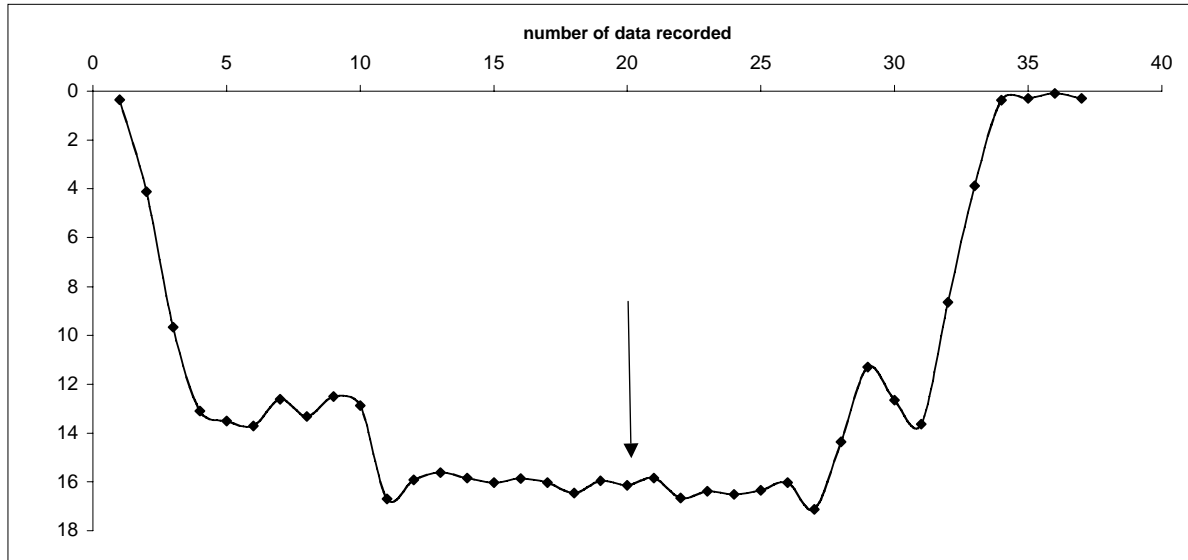
Figure 5. Dive profile and data record at one minute interval, arrow indicate mid-point in the dive at the point of furthest penetration into the cave system Crustacea (Yager and Madden, 2002)
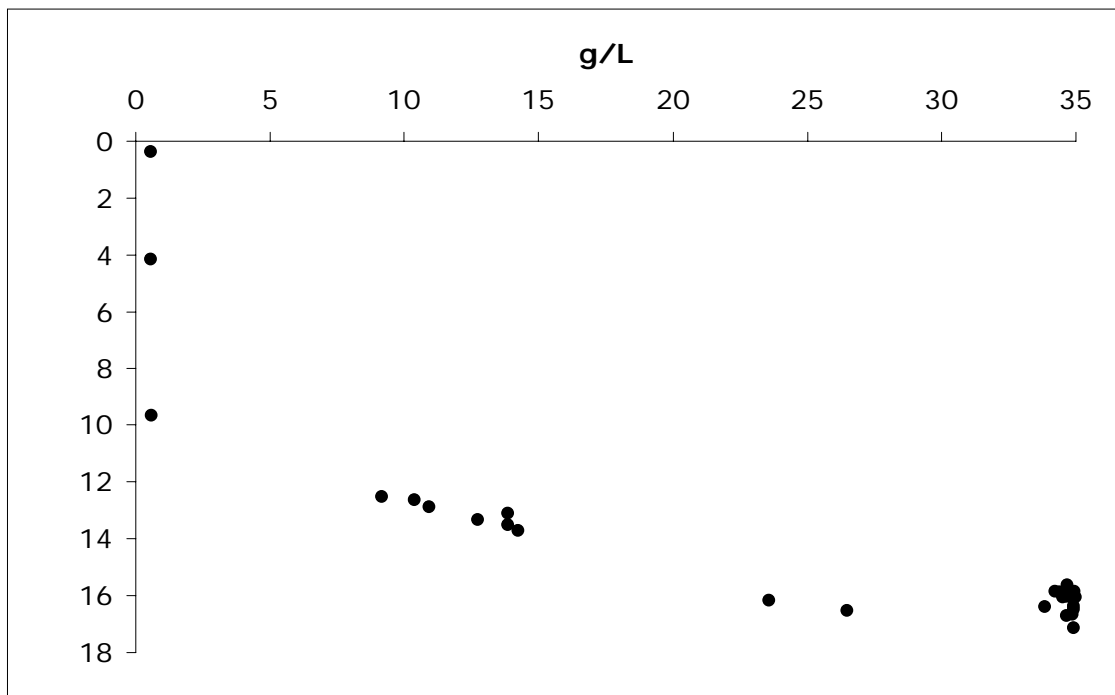

Figure 6. Salinity record along the dive data record at one minute interval from cave system Crustacea (Yager and Madden, 2002)

Table 4. Comparison of data set Yager and Madden (2002) and this study

	Yager and Madden (2002)	This study
Bottom time in minutes	37	>120
Number of data points	37	881
Number of data points within interface	9	792
Profiles	0	4
Descent speed at interface cm·s^{-1}	~5	2.3
Slope	0.16	0.02

Hydrographic Description of the Water Column

Temperature maxima within and below the halocline as observed in this data (Figure 3B) have been described for sites in the Yucatan (Beddows et al., 2002; Stoessell et al., 2002; Beddows, 2004) and for a site in the Bahamas (Schwabe and Herbert, 2004), with examples including both open water and overhead anchialine systems. Stoessell et al. (2002) review three possible explanations for thermal anomalies also called thermal excursions: biological activity by microorganisms, solar heating and geothermal convective cells. It must be noticed that the three processes are of very different scale, from 10^2-10^4 for geothermal convective cells to 10^{-2} to 10^{-4} for microorganisms, and could be complementary rather than exclusive. Stoessell et al. (2002) suggest a geothermal convective cell as the main explanation for such temperature maxima. However Beddows et al. (2002) and Beddows (2004) discriminates between thermal maxima contained within the halocline in open sites which is ascribed to heliothermic heating, thermal maxima immediately below the halocline as is the case here in Crustacea which is ascribed to rapid shuttling of warm marine water through the coastal caves, while she assigns importance to geothermal convective cells only in much deeper saline water circulation.

Biological activity has been explained in two ways. Stoessell considers that the heat is generated *in situ* by exothermic chemical reactions like sulfate reduction or sulfide oxidation in bacteria at the halocline, while Schwabe and Herbert (2004) working in open water Black Holes argue a explanation based on Pfennig (1967) and Culver and Brunskill (1969) where massive anoxigenic phototrophic bacterial production at halocline dissipate light energy absorbed by photosynthetic pigments as heat. This latter explanation cannot be applicable in the case of the Crustacea data since the profiles are from inside the cave where there is no incident sunlight.

In Crustacea the water column is hypoxic (2.54 to <1 mg·L^{-1}) as had been reported for other anchialine caves (Yager, 1994; Yager and Humphreys, 1996; Yager and Carpenter, 1999; Iliffe, 2000). Meteoric and marine water are two sources of dissolved oxygen for the water in anchialine caves. The diminished dissolved oxygen (DO) content in water is attributed to a lack of contact with the atmosphere, the absence of photosynthetic activity, organic matter remineralization, and zooplankton and nekton respiration. Quantification and characterization of organic matter from anchialine caves has rarely been undertaken. Biological oxygen demand of anchialine cave water in Bermuda is very low <0.25 mg O_2·L^{-1} but increases at the halocline (Iliffe, 2000). In Danube wetlands groundwater ecosystems DO is strongly dependent on the atmospheric temperature and total organic carbon (Danielopol et al., 2000). When meteoric or shallow marine water enters in the cave, we can assume that the DO is close to 100% saturation. Therefore once inside the cave, the dissolved oxygen must be consumed by respiration by microorganisms and stygobitic fauna. It is clear that ongoing

184

work with simple dissolved oxygen profiles may provide significant insight to organic matter content and water column-sediment respiration rates and how these relate to cycling of nutrients and the overall functioning of groundwater ecosystems (Stigebrand et al., 1996).

The method development for obtaining detailed water column profiles of multiple parameters and the results of those profiles contribute to the Mexican anchialine cave research program in order to advance the overall understanding of coastal groundwater habitats, pinpoint gaps in knowledge and encourage further integrative studies to set a baseline of solid ecological information and help strengthen conservation policies for decision makers.

Acknowledgments

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