WATER COLUMN VARIABILITY IN A COASTAL TOURIST CAVE IN MALLORCA, SPAIN

Liana M. Boop  
Department of Geology  
University of South Florida  
4202 E. Fowler Ave., SCA 528  
Tampa, Florida, 33620, USA  
lianaboop@mail.usf.edu

Joan J. Fornós  
Departament de Ciències de la Terra  
Universitat de les Illes Balears  
Ctra. Valldemossa, km 7.5  
07122 Palma de Mallorca, Spain,  
joan.fornos@uib.es

Bogdan P. Onac  
Department of Geology  
University of South Florida  
4202 E. Fowler Ave., SCA 528  
Tampa, Florida, 33620, USA  
bonac@usf.edu

Marta Rodríguez-Homar  
Departament de Ciències de la Terra  
Universitat de les Illes Balears  
Ctra. Valldemossa, km 7.5  
07122 Palma de Mallorca, Spain,  
marta.rodriguez@geografos.org  
wynnj@usf.edu

Jonathan G. Wynn  
Department of Geology  
University of South Florida  
4202 E. Fowler Ave., SCA 528  
Tampa, Florida, 33620, USA

Abstract  
Coves del Drac is visited by more than 1 million tourists annually and has been a tourist destination in the western Mediterranean for over 100 years. All areas of the cave are developed with historic or current tour route infrastructure, including walkways, handrails, and electric lighting. This study compares one vertical water profile collected along the current tour path with two other profiles from historic tour route locations. Differences in freshwater and organic inputs, as well as direct anthropogenic impacts, are clearly observed in the aquatic parameters and stable isotopes collected in the profiles. Anthropogenically-driven undersaturation in the cave pools, as well as rising sea level, may threaten the unique speleothem encrustations that are formed at the air-water interface within the cave.

Introduction  
Mallorca, the largest island of the Balearic Archipelago, is located in the western Mediterranean. Tourists enjoy Mallorca’s natural beauty; five show caves currently operate in Mallorca (Ginés and Ginés, 2011). Coves del Drac (Drac) is the most visited show cave in Mallorca, documented by over 1 million annual ticket sales, making it the most visited cave in Europe (Robledo and Durán, 2010). Recent and ongoing research focus on the unique speleothem encrustations within Drac and other littoral caves in Mallorca. These phreatic overgrowths on speleothems (POS) are carbonate encrustations on pre-existing carbonate supports, and form at the air-water interface in brackish phreatic pools. Since the water table is coincident with sea level, POS are strong proxies for sea level reconstruction (Dorale et al., 2010; Ginés et al., 2012).

Both calcite and aragonite POS are observed in Mallorca’s caves. Some caves contain POS bands of both minerals, where bands at different elevations correspond to different sea level elevations. The mineralogy of a POS band does not change for any given sea level stand, suggesting a relatively stable geochemical environment during each sea level stand. To date, only calcite POS have been documented in Drac.

Previous work on Mallorca’s POS by Csoma et al. (2006) found that proximity to the surface of the water promotes degassing of CO$_2$, which in turn controls the precipitation of POS.

This study compares aquatic parameters and stable isotopes in a vertical water profile from the current tour route with two profiles collected proximal to the historic
trail in Drac. The objective of this study is to delineate variations in geochemistry throughout Drac in an effort to further understand the dynamic of POS precipitation at the air-water interface.

**Study Area**

Drac is located in the village of Porto Cristo, on the eastern coast of Mallorca (Figure 1). The land above the cave is developed to support the cave’s tourism, including parking lots, cafes, and shops, surrounded by scrub vegetation. Drac is a typical mixing-zone cave, reflected by its large, randomly oriented rooms connected by small breakdown passages (Ginés and Ginés, 2007). The cave is developed in Upper Miocene reef carbonates and the current survey documents a mapped extent of over 2,300 m (Fornós et al., 2012), though ongoing cave diving expeditions add previously unexplored flooded passages to the known cave size.

Tourists enter the cave through an artificial entrance and observe the numerous speleothems as they descend to the water table at Llac Martel (Martel). Once seated in a large room that can hold tour groups of several hundred people, tourists listen to a short narrative about the cave, and then enjoy a short classical music concert, played from three rowboats that enter and exit the gallery from out of sight. When the concert is finished, tourists may continue the remainder of the tour route entirely on foot, or by boarding a rowboat for a portion of the exit path. One profile was collected in the area where tourists disembark from the boats on Martel (Figure 2).

All tourists exit the cave through its natural entrance, an obvious collapse feature.

The other portions of Drac are historic tour routes, and are similarly developed with concrete walkways (in various stages of disrepair), metal railings, and electric lights. The entrance and exit for the historic pathway is at the current tour route exit. Profiles collected at Llac Negre (Negre) and Llac de les Delícies (Delícies) are located in separate rooms. Negre represents the most distal expression of the water table with regard to the coast of the Mediterranean Sea, and is also the location of ongoing cave diving exploration. Calcite rafts float at the surface of both Negre and Delícies. POS are present at the air-water interface at all three sample sites (Figure 3).

**Methods**

In March 2013, vertical water column profiles were collected starting from the surface and ending at depths of 2.8, 2.6 and 2.6 m in Martel, Negre, and Delícies, respectively. Using a recently calibrated Hanna Instruments® 9828 Multiparameter Meter that was slowly lowered through the water column, temperature, pH, oxidative-reductive potential, dissolved oxygen, specific conductivity, total dissolved solids, and salinity were collected at 20-cm increments from the surface to the bottom at each profile location. Water samples for stable isotope analyses were collected at 50-cm increments using a 1-liter capacity LaMotte® Water Sampler. $\delta^{18}$O and $\delta^{13}$C were analyzed at the University of South Florida Department of Geology Stable Isotope Lab using a Thermo Fisher Scientific (Finnigan) Delta V Isotope Ratio Mass Spectrometer; results are reported...
with respect to international standards VSMOW and VPDB, respectively, and analytical error is ±0.1‰.

**Results and Discussion**

Aquatic parameters show the greatest variability in Negre, and the least variability in the pool proximal to the tourist route, Martel. The profiles appear to trend toward convergence at depths exceeding 2 m (Figure 4).

The most consistent (least variability) values in all parameters are observed at Martel. This profile was collected at the location where tourists exit the boats, so homogenization is expected in at least the shallower depths. The warmest temperatures were observed at Martel.

Delícies had slightly lower temperatures than Martel, and similar consistency throughout the profile. Decreasing pH was observed with depth in the profile, and dissolved oxygen had an overall increasing trend with depth, but...
included negative excursions. The specific conductivity values increased with depth and converged with those of Martel at depths exceeding 2 m.

Negre is the most distal profile from the Mediterranean Sea. Water temperature and specific conductivity are considerably lower at Negre compared to the other two locations, suggesting an input of cooler freshwater to this location. The specific conductivity increases from 10,530 μS/cm at -1.4 m to 16,530 μS/cm at -1.8 m. The dissolved oxygen decreases from the surface value of 4.36 to 0 mg/L at -0.4 m, returning to oxic conditions at -1.8 m. It is likely that organic matter enters Negre with the cooler, fresher water, and is trapped by a density difference as exhibited in the specific conductivity profile. pH is highest at the surface (7.62), decreases to a minimum of 6.94 at -1.2 and -1.4 m, and converges with the other profiles at -2 m. The lowest pH values were recorded within the anoxic zone, attesting to respiration of the organic matter.

δ¹⁸O values in Negre show an excursion toward more negative values in this anoxic zone as well, further supporting microbial respiration at the density difference indicated by specific conductivity (Figure 5A). δ¹³C (Figure 5B) is similar to pH, with more positive values observed in the surface of Delícies and Negre. These more positive values are the result of CO₂ degassing, leaving the heavier isotope in the water. Combined, pH and δ¹³C confirm that these pools act as a CO₂ source.

**Future Directions**

Recently, a POS from the current precipitation band in Delícies was recovered. This speleothem featured well-developed calcite crystals at the top of the encrustation, grading to corroded crystals at its bottom, attesting to undersaturated conditions existing immediately below a supersaturated horizon.

Carey et al. (2001) and Martínez-Taberner et al. (2000) report depleted dissolved oxygen concentrations at the halocline in caves closer to Mallorca’s coast due to microbial respiration of organic material. Several authors report that the bottoms of Mallorca’s brackish littoral cave pools are undersaturated with respect to carbonate minerals, causing the recycling of rafts that grow too large to be supported by surface tension (Ginés et al., 1981; Csoma et al., 2006). Thus, a saturation index gradient may exist where supersaturation and precipitation of POS is controlled by degassing of CO₂ from the surface of the water, whereas undersaturation exists deeper within the water column, possibly facilitated by microbial processes. In the context of a changing climate, the current POS band may be jeopardized by rising sea levels elevating the undersaturated portion of the water column.

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References


Biography

Liana M. Boop is a doctoral candidate at the University of South Florida in Tampa, Florida. Liana received her BS in Environmental Science from the University of Connecticut in 2007. Liana’s dissertation research focuses on the geochemistry of brackish pools that precipitate phreatic overgrowths on speleothems within Mallorca’s caves. Her professional and personal interests are inspired by her passion for caves and karst.