CAVE-DRIP MONITORING AS A FOUNDATION FOR BETTER PALEOCLIMATE RECONSTRUCTION

Patricia A. Beddows
McMaster University
P.O. Box 25, 1280 Main St. West
Hamilton, ON L8S 1C0, Canada
beddows@mcmaster.ca
905-526-8637

Henry P. Schwarcz, Ren Zhang, and Derek C. Ford
School of Geography and Earth Science
McMaster University

Abstract

Many caves preserve high-resolution palaeoenvironmental records within stalagmites, from which an increasing number of records are being published. The dating of speleothem calcite and the analysis of stable isotopes is now routine and decreasing in cost. However there remains a need for greater confidence in how representative each stalagmite may be of environmental conditions on the local to regional scale. It is recommended that when studying younger and actively growing samples, that a suitable cave-drip-water monitoring program be undertaken to assess representativeness of key variables compared to adjacent and distant drips, and specifically to identify seasonality in the hydrological flows. Where drips become seasonally inactive, the corresponding stalagmite record will be seasonally biased, therefore requiring more careful interpretation. Drip monitoring results from 18 drips in six caves across North America will be used to illustrate the variability of drip waters within a cave passage, between caves in the same region, and across the continent. Study of modern cave-drip waters is very valuable in ensuring that only the most suitable speleothem samples form the basis of palaeoenvironmental reconstruction, in support of the unique role that speleothem-proxy records may play on a global scale.

Key words: speleothem dating, cave-drip water, paleoclimate, water chemistry

Introduction

The secular variations of isotopic and trace element compositions of speleothem calcite provide valuable continental based indices of paleoclimate change, with a spatial distribution complimentary to that of polar ice cap and marine core records. Paleoclimate studies often assume that the isotopic chemistry of the calcite broadly reflects that of the local meteoric precipitation. However, the epikarst and vadose zone above the cave is complex because of storage and mixing of fast and slow-flowing waters along different-sized fractures and conduits. Qualitative observations indicate that drip-water hydrochemistry may differ between closely spaced adjacent drips as shown by the distinct ability of some drips to form soda straws and corresponding stalagmites (Figure 1). Similarly, observations show seasonal variation in seepage rates, which suggests potential for seasonal variations in “upstream” calcite deposition and deposition on the speleothem itself, bias in the chemical and isotope composition of the water reaching the cave, and significant differences between adjacent drips and corresponding speleothem. A key research challenge presently at the forefront of paleoclimate reconstruction from speleothem records is developing an advanced understanding of hydrological processes in the karst vadose zone that control the surface climate components captured in individual speleothems, and how representative each speleothem is of the regional climate signal. The broader focus of this research effort is progress towards an integrated trans-North American study of the calcite-cave drip-climate system. Study sites include six caves, including three on the Pacific coast of Vancouver Island and one each in the Bow Valley of the Rocky Mountains, the Midwest (southern Indiana) and the northeastern U.S. (upstate New York; Figure 2).

A specific advantage of monitoring closely spaced drip points is the potential to quantify the common elements of the drip hydrology and hydrochemistry independent of confounding environmental factors such as infiltration through distinct geological units above the cave, differences in surface land cover and vegetation units, vadose zone thickness, and distance from the cave entrance. These environmental factors may give rise to complexities that are often suggested as explanations of significant inter-drip differences observed between monitored drips where longitudinal monitoring of distinct drip types along caves have been undertaken (Tooth & Fairchild, 2003; Vokal et al. 1999).

Figure 1 *Distinct hydrochemical characteristics of adjacent drips showing that only a limited number of drip points are competent at forming stalagmites.*

Methods

Custom drip monitoring stations were deployed late in 2004 through 2006 to provide high frequency 15-minute records of temperature, electrical conductivity as a proxy of total dissolved solids, and drip rate at three adjacent drips (<30 m distant) in each of the six caves, while monthly bulk water samples were captured for isotopic and chemical analysis (Figure 3). Water samples were isotopically analyzed at McMaster University using a Finnigan Delta XP^{PLUS} isotope-ratio mass-spectrometer coupled with a Thermo TCEA that was set at 1450°C. A redesigned glassy carbon reactor column combined with a redirected helium carrier gas flow system was employed to improve sample flush-

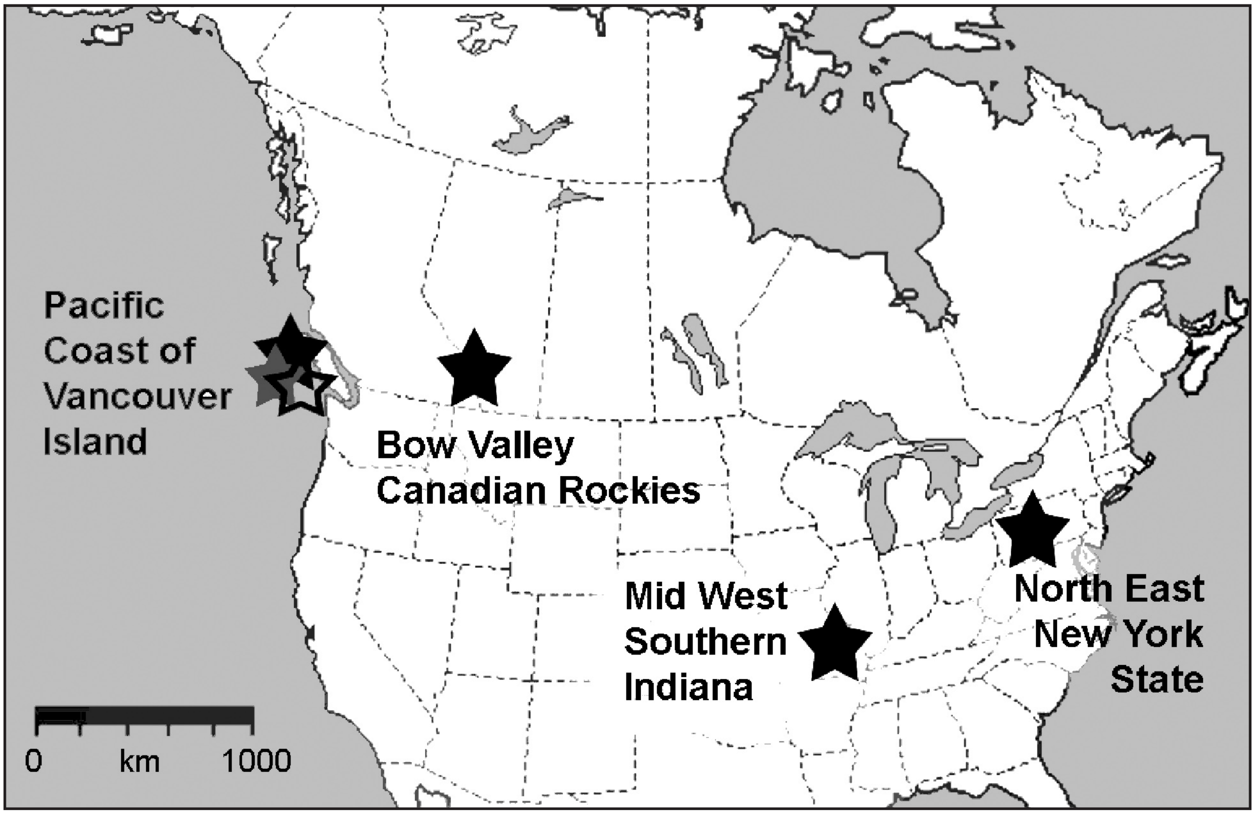

Figure 2 *Location map for 6 caves across North America with drip monitoring networks.*

ing through the system as described by Gehre et al. (2004). In each analysis, 0.8 µL of sample was manually injected via a septum into the top of the glassy carbon column. The data was normalized to the VSMOW scale in ‰ using bracketed initial and final runs of DTAP (internal lab standard) and IAEA accepted standard (VSMOW, GISP, or SLAP) on each analysis day.

Upon decommissioning of the drip monitoring sites in 2006, pre-weighed, acid-cleaned, frosted glass plates were positioned under each drip site on which calcite was growing. These glass plates will be returned to the lab where the modern calcite will be micro milled and analyzed for $\delta^{18}O$ and $\delta^{13}C$, with the resulting data interpreted within the context of the broad chemical and isotopic characteristics of the drip site.

Results and Discussion

The drips selected for monitoring all appeared to be actively precipitating calcite. Within the classification scheme for karst waters of Smart and Friedrich (1987) all had very low drip rates, with many plotting below the minimum boundary of the original classification scheme, while the coefficient of variation (COV = average / standard deviation, also known as RSD) spanned several orders of magnitude, but for most sites was relatively low (Figure 4). Previous studies on karst waters focused on larger scale hydrogeology with implications for water supplies and contaminant transport through karst aquifers. In comparison we have focused on year-round, active, cave-drip waters and more specifically, those that are apparently forming stalagmites. We found that calcite deposition is associated with slower drip rates in general. This observation is consistent with the conceptualization of slow-flowing seepage waters being sourced principally by longer-residence-time storage water in the smaller flow paths of the vadose zone. The physic0-chemical aspects of these waters should therefore be decoupled from the day-to-day weather components affecting the surface, and instead be modulated, and damped, reflecting broad climatological aspects.

Qualitative observations in caves indicate that many drips are indeed responsive, with increased drip rates during surface recharge events such as rainfall or snow melt. In the high resolution elec-

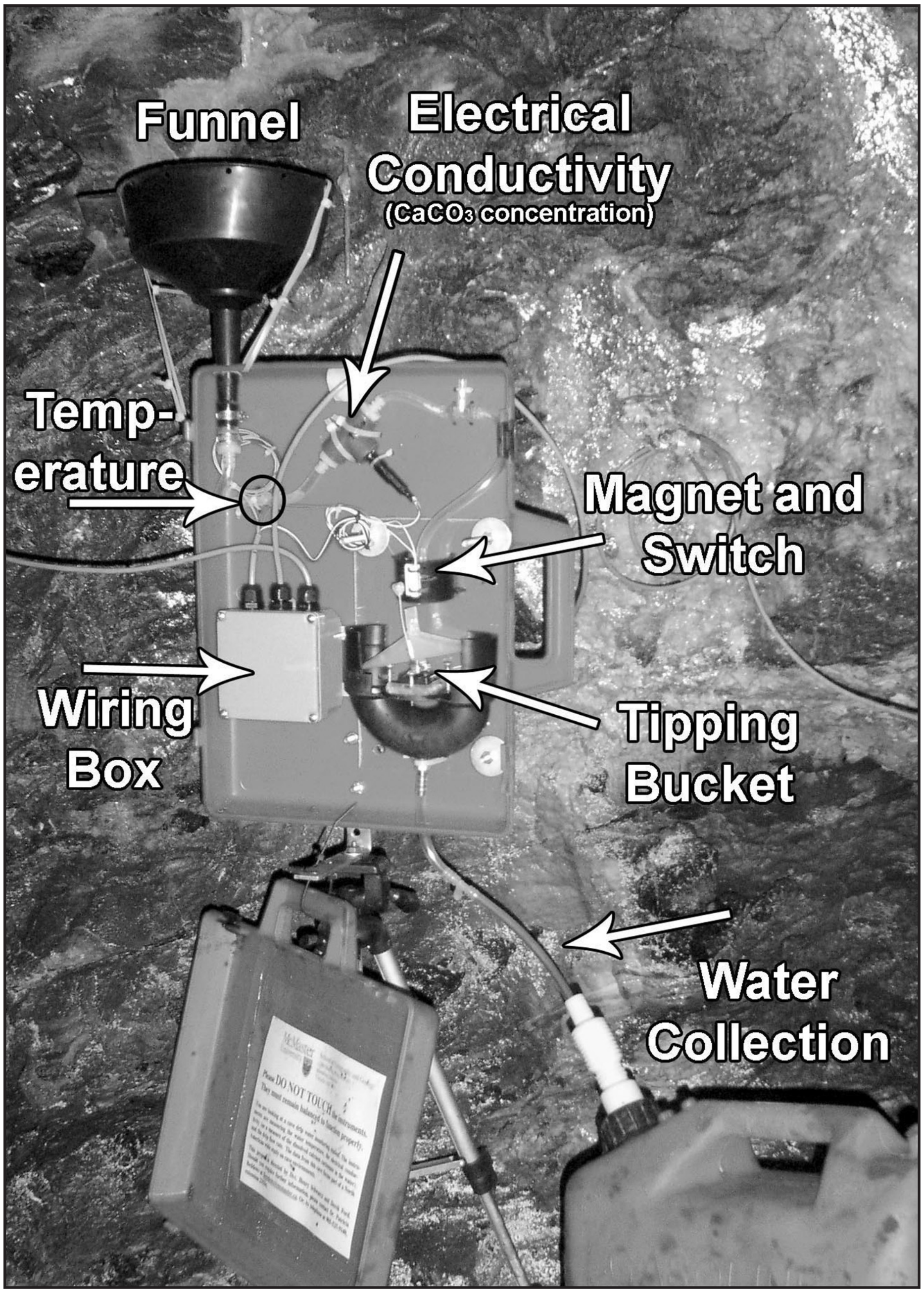

Figure 3 Custom cave-drip-water monitoring station.

concurrent between drip sources located tens of meters apart in the same cave, while at other times each drip may display independent hydrological characteristics.

A paradoxical relationship exists between the isotopic and chemical responses of drips to seasonal driving forces, and the observed hydrological response. Drips with nonseasonal hydrology, such as the nine monitored drips in the three caves on Vancouver Island, may have equally nonseasonal response in the specific electrical conductivity and the solute flux through the system (Figure 6). However, the hydrogen and oxygen isotopes are clearly seasonal for these drips (Figure 7). In contrast, drips with seasonal hydrological cycles, such as at Marengo Cave, may also have corresponding seasonality in specific electrical conductivity, yet the isotope chemistry of these drips is temporally invariate over the course of the year (not shown). In Howe Caverns, New York, the three monitored drips have parallel patterns in specific electrical conductivity, however the hydrological response is varied and clearly inverse between the two drips with higher drip rates (Figure 7). For Howe Caverns, similar to Marengo Cave, which is the other mid-continent site in this study, the drips are isotopically nonseasonal, although the drip with the lowest drip rate has a step-wise change in isotopic values.

Some of the assumptions made in palaeoenvi-

tronic data, hydrological events are evident (Figure 5) even though, as noted, the month-to-month bulk water rate is low and relatively constant (COV<50) for most drips. Perhaps the constancy in drip rate observed in this study is a function of targeted monitoring of drips forming speleothem calcite, while adjacent drips without calcite formation may be the ones observed qualitatively to respond most dramatically to recharge. Furthermore, the hydrological data show that temporal variations in hydrological parameters are sometimes

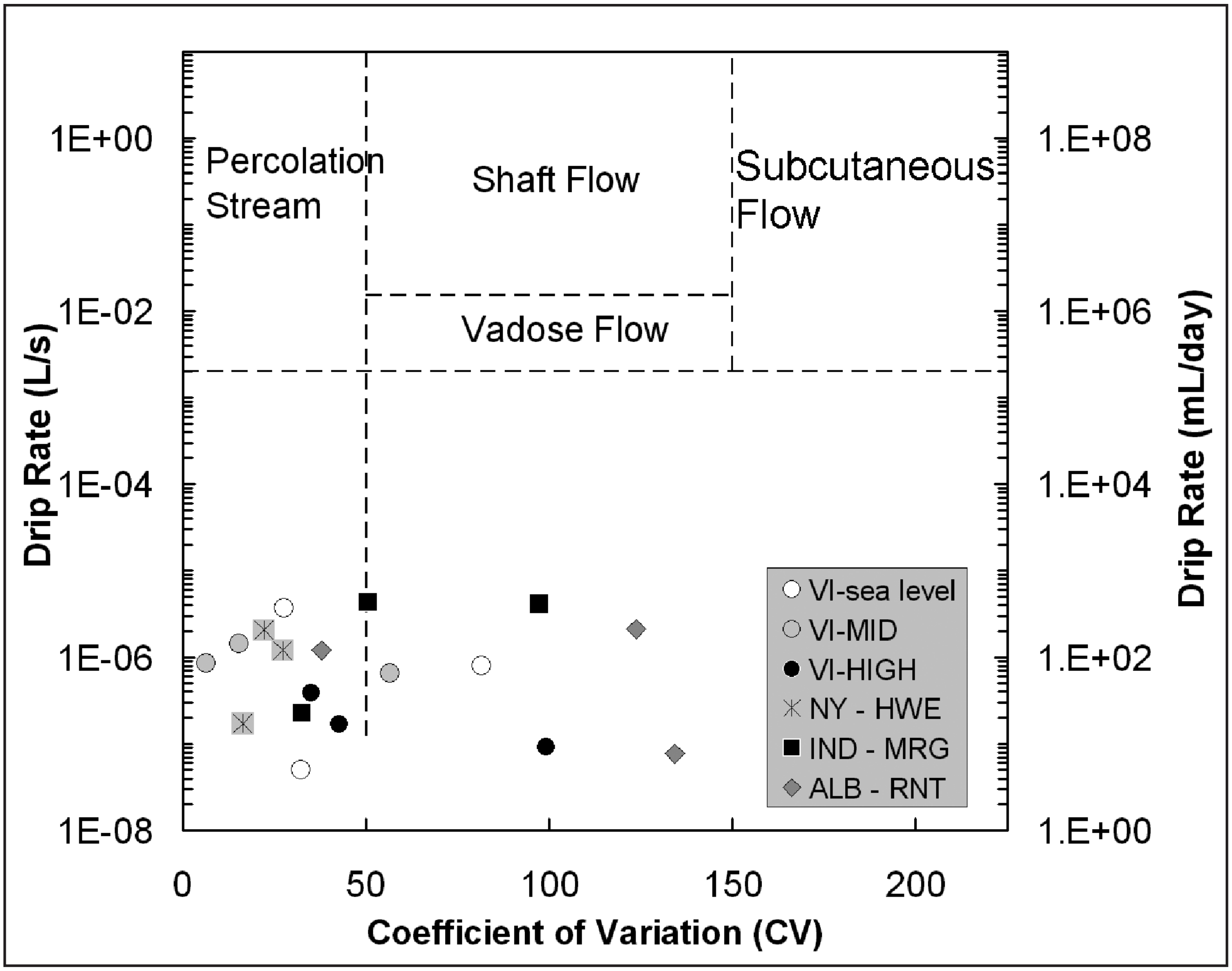

Figure 4 *Plot of drip rate based on daily average from monthly bulk water collected versus the inter-monthly variability measured as the coefficient of variation (standard deviation divided by mean value, expressed as a percentage) within the Smart and Friedrich karst water classification scheme (1987).*

ronmental reconstruction from speleothems is that the calcite is precipitated continuously throughout the year so that there is no seasonal bias, and that the isotopes in the speleothem calcite will broadly reflect that of the mean annual precipitation and temperature above the cave, and that each speleothem is equally good at recording conditions above the cave. Within this dataset, drips with seasonal drip rates tend not to have isotopic seasonality, while hydrologically stationary drips exhibit significant isotopic seasonality, thereby undermining some of the assumptions. This result is consistent with the general knowledge that some speleothems have annual bands because of seasonality in aspects of the drip waters, while other speleothems are not banded at all, potentially because of a constant drip water chemistry and supply. Also, there are examples of significant differences between adjacent drips in the monitored caves in all variables examined, and this is consistent with other recent reports of differences between coeval speleothem records from the same cave: two coeval and adjacent speleothems from South Dakota were found to have a 4‰ offset in $\delta^{18}O$ although their secular variations still revealed the same important climate events (Serefiddin et al. 2004).

Cave-drip monitoring is a valuable method in characterizing the hydrochemical response to seasonal climate forcing at individual drip points. Ultimately, cave-drip monitoring will help determine which corresponding speleothems may provide intra-annually unbiased records of long-term change, as opposed to those speleothems with signals dominated by responses to sub-annual events.

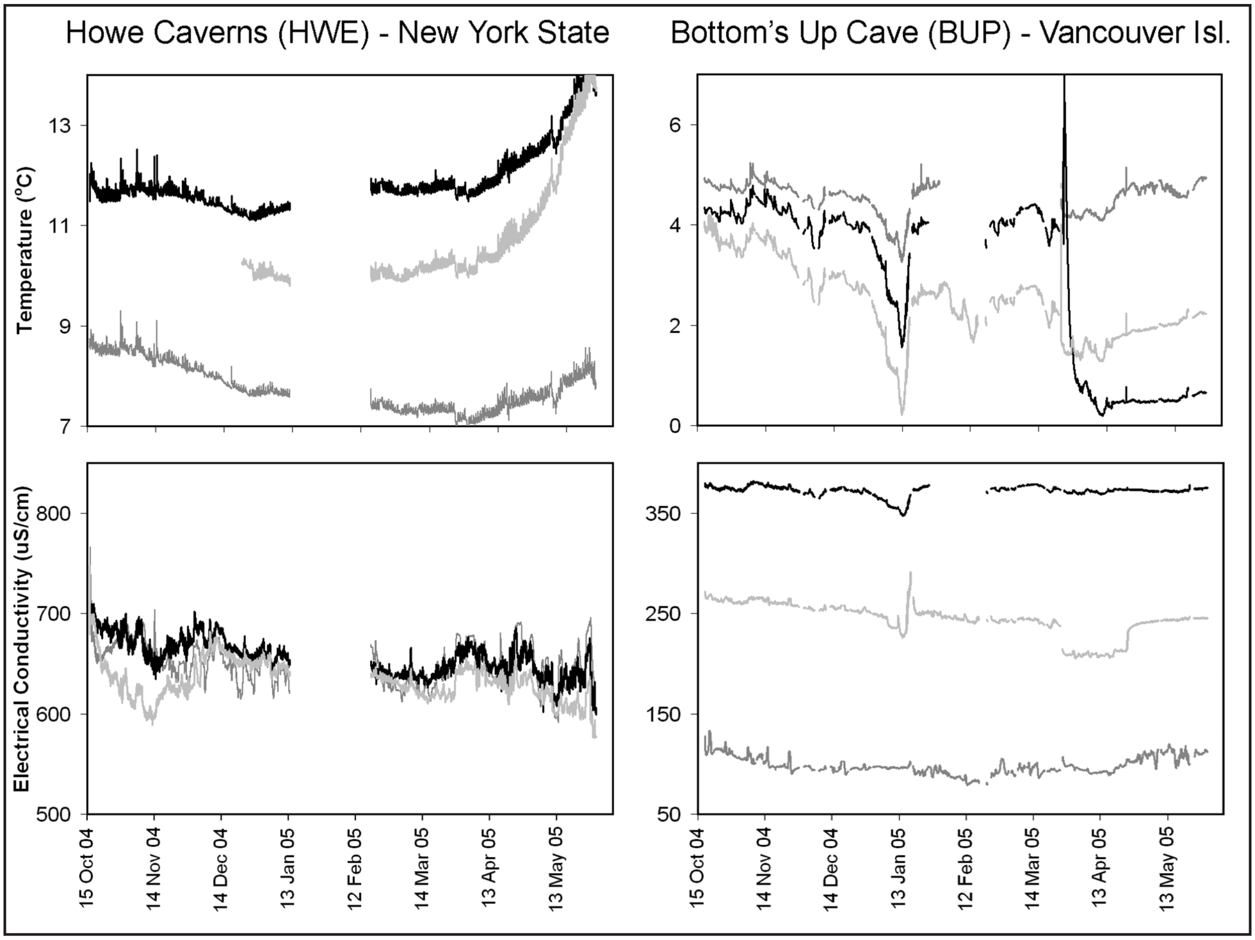

Figure 5 *Cave-drip water specific electrical conductivity (top row) and temperature (bottom row) in Bottom's Up Cave at 550 m ASL mid elevation on Vancouver Island (left) and Howe Caverns in upstate New York (right).*

This study focuses on drips actively forming calcite, and therefore this approach is inherently limited to palaeoenvironmental studies focused on the Holocene, since the drip points of older speleothems are often now inactive. Given the distinct hydrochemical response observed at individual drip points, the sampling of more than one coeval speleothems may be required to provide robust palaeoenvironmental records.

Acknowledgments

This study was supported by a grant from the Canadian Foundation for Climate and Atmosphere Sciences (CFCAS Grant No. GR-421) to HPS and DCF and a grant to HPS from the Natural Sciences and Engineering Research Council of Canada (NSERC). Site access and logistical support for the monthly drip monitoring was provided by Gordon Smith and Steve Calhoun at Marengo Caverns (Indiana), John Sagendorf of Howe Caverns and Art and Peggy Palmer (New York), Chas Yonge at Rats Nest Cave (Alberta), and Brian Bischoff and Paul Griffiths for three caves in Tahsis Inlet, Vancouver Island, and coordination of the research effort with the British Columbia Ministry of Forests. Invaluable technical support was received from Kenrick Chin of the Nuclear Reactor Facility, McMaster University

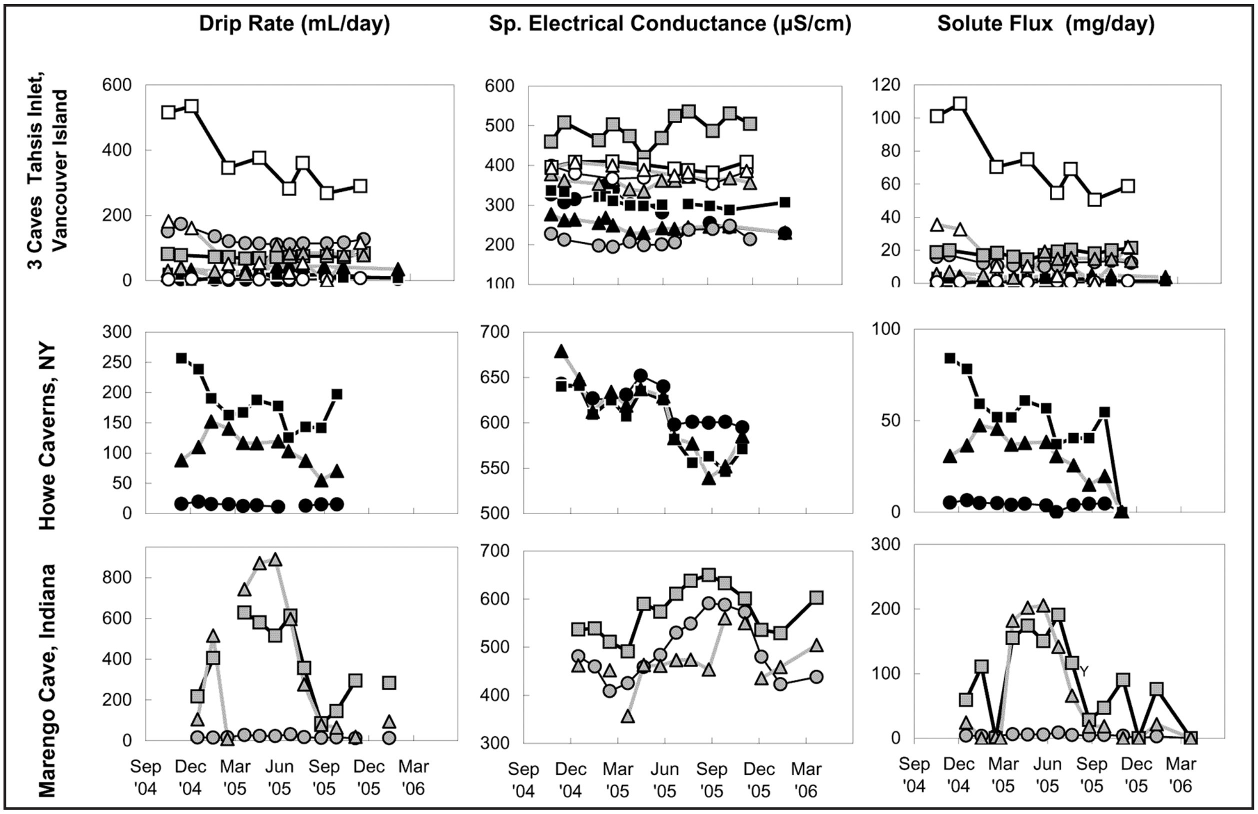

Figure 6 *Data matrix for drip water data from different cave regions (each row) for the three parameters of drip rate (left), specific electrical conductivity (SpC; middle), and solute flux (right) which was calculated by using Equation 19 of Krawczyk and Ford (2006) for nonpolluted karst waters.*

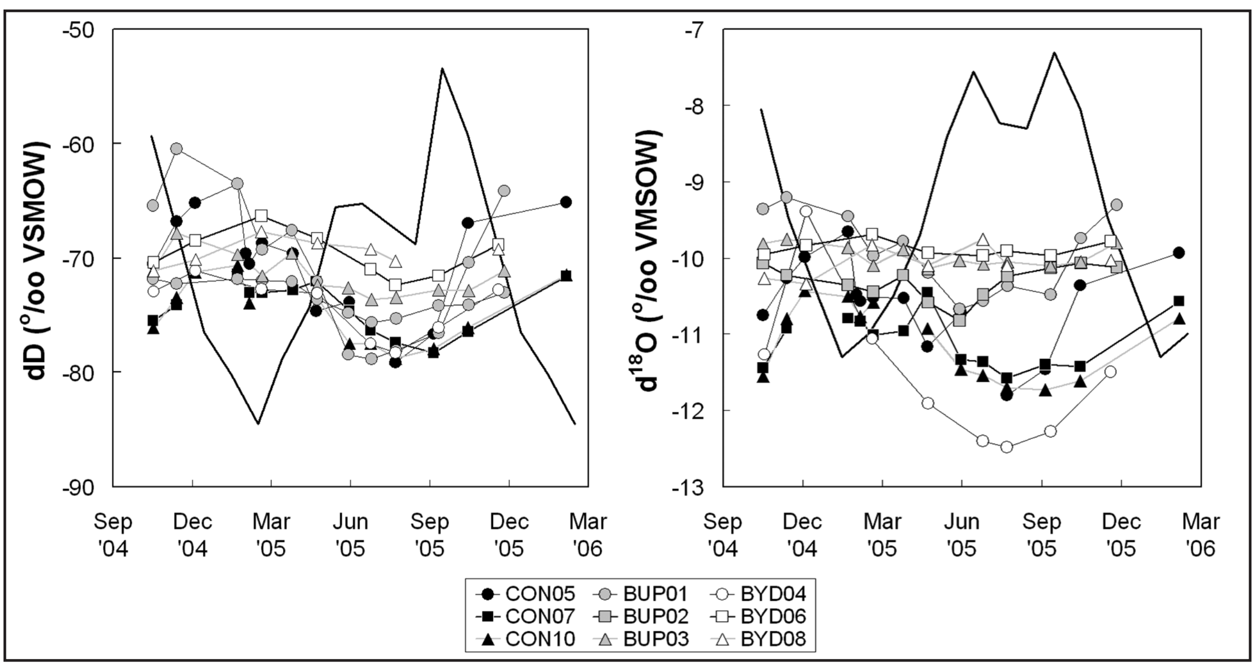

Figure 7 *Deuterium (δD) and oxygen ($\delta^{18}O$) isotopic values of drip waters from 3 caves, Tahsis Inlet, Vancouver Island.*

Literature Cited

Gehre, M., Geilmann, H., Richter, J., Werner, R.A., Brand, W.A., 2004. Continuous flow $^{2}H/^{1}H$ and $^{18}O/^{16}O$ analysis of water samples with dual inlet precision. *Rapid Communications in Mass Spectrometry* 18(22):2650-2660.

Krawczyk, W.E. & Ford, D.C., 2006. Correlating specific conductivity and total hardness in limestone and dolomite karst waters. *Earth Surface Processes and Landforms*. 31(2):221-234.

Serefiddin, F., Schwarcz, H.P., Ford, D.C. and Baldwin, S., 2004. Late Pleistocene paleoclimate in the Black Hills of South Dakota from isotope records in speleothems. *Palaeogeography, Palaeoclimatolog,y Palaeoecology,* 203(1-2):1-17.

Smart, P. L. and Friedrich, H., 1987. Water movement and storage in the unsaturated zone of a maturely karstified aquifer, Mendip Hills, England, *Proceedings of the Conference on Environmental Problems in Karst Terrains and Their Solution*, Bowling Green, Kentucky. National Water Well Association, pp. 57-87.

Tooth, A. and Fairchild, I., 2003. Soil and karst aquifer hydrological controls on the geochemical evolution of speleothem-forming drip waters, Crag Cave, southwest Ireland. *Journal of Hydrology*. 273(1-4):51-68

Vokal, B., Obelic, B., Genty, D., and Kobal, I., 1999. Chemistry measurements of dripping water in Postojna Cave. *Acta Carsologica* 28(1):305-321.