PALEOC LIMATE INFORMATION FROM SPELEOTHEMS: THE PRESENT AS A GUIDE TO THE PAST

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1. INTRODUCTION

Speleothems are the secondary mineral deposits formed in caves. The most common type of speleothems are the calcium carbonate (CaCO₃) stalactites, stalagmites, and flowstones which are a ubiquitous feature of caves worldwide. Variations in the $^{18}$O/$^{16}$O and $^{13}$C/$^{12}$C ratios in calcite speleothems can provide important information about terrestrial paleoclimate, if deposition occurred under equilibrium conditions because (i) they contain a well-defined internal stratigraphy, (ii) their absolute age of deposition can be determined accurately with high precision through mass spectrometric U-series disequilibrium geochronology (Edwards et al., 1987; Li et al., 1989), (iii) variations in their internal chemical and isotopic composition are determined by the environmental conditions at the time of deposition, (iv) they may trap surface-derived dust, pollen, and organic acids as the calcite layers are sequentially deposited and (v) they tend to behave as geochemically closed systems (see e.g. Schwarz, 1986; Gascoyne, 1992).

The temperature dependence of equilibrium isotope exchange in the calcite-water system has been intensively studied since Urey (1947) first suggested that the paleotemperature of the ancient oceans could be estimated by the O-isotope distribution between seawater and the calcium carbonate precipitated from it. Urey et al. (1951) argued that O-isotope equilibrium between seawater and CaCO₃ was likely and support for this idea has come from the close agreement between the CaCO₃-H₂O isotopic fractionation observed in natural systems and those derived from both thermodynamic calculations and laboratory experiments (e.g. Epstein et al., 1951, 1953; Emiliani, 1955; O'Neil et al., 1969; O'Neil et al., 1975).

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Some three decades ago, researchers in New Zealand (Hendy and Wilson, 1968) and Europe (Galimov et al., 1965; Labeyrie et al., 1967; Duplessy et al., 1970; Fantidis and Ehhalt, 1970) called attention to the fact that changes in terrestrial climate might be recorded in the O- and C-isotope compositions of speleothems. Subsequently Hendy (1971) geochemically modeled the isotope effects which accompany different modes of speleothem deposition. These earliest studies recognized that:

(i) records of past climate fluctuation can only be obtained from stable isotope ratio (i.e. speleothems that formed in isotopic equilibrium with parent seepage water and subsequently have remained closed to isotopic re-equilibration, and
(ii) paleotemperatures could not be directly inferred from speleothem $^{18}O/^{16}O$ ratio variations because the calcite O-isotope signal was a function of several different factors that could not be explicitly determined.

Subsequent research at McMaster University over the period 1970-1985 (Thompson et al., 1974, 1976; Schwarcz et al., 1976; Harmon et al., 1977, 1978a,b, 1979a,b; Harmon and Schwarcz, 1981; Gascoyne et al., 1980, 1981; Gascoyne, 1983; Schwarcz and Yonge, 1983; Yonge et al., 1985; Gascoyne, 1992) examined different aspects of speleothem deposition across a spectrum of climates. These studies made several important observations:

(i) speleothem deposition frequently occurs under conditions of isotopic equilibrium, but not always,
(ii) cave seepage waters in temperate climates tend to be representative of meteoric precipitation on the surface above the cave,
(iii) the fluid inclusions present in speleothems are a relict sample of the parent seepage water from which the speleothem was deposited, and
(iv) the effect of temperature change on isotopic fractionation between water and calcite is not necessarily the primary cause of O-isotope variation in speleothems.

During the last decade, there has been a renewed interest in speleothem paleoclimatology which has produced some very exciting and, in some instances, contradictory interpretations (Lauritzen et al., 1990; Dorale et al., 1992; 1998; Lauritzen, 1995; Goede et al., 1996; Baker et al., 1997; Bar Matthews et al., 1996, 1997; Burns et al., 1998; Hellstrom et al., 1998; Holmgren et al., 1995; Frumkin et al., 1999; Lauritzen and Onac, 1999). However, not all of these recent studies have given the necessary attention either to demonstrating speleothem equilibrium deposition or to placing the paleoclimate interpretations within the context of the modern depositional setting. A major purpose of this contribution is to illustrate the importance of understanding the modern depositional environment when conducting paleoclimate studies on speleothems.

In this paper, we will examine the physiochemical processes that act in concert to determine the isotopic composition of speleothem calcite and, based upon a worldwide data compilation, argue that it is important to base any speleothem paleoclimatology study upon as thorough an understanding of the modern cave depositional environment as is possible. The focus of the discussion will be on oxygen isotopes, but we also will discuss carbon isotopes to a limited extent. Our observations and comments are based upon a comprehensive isotopic database compiled for precipitation, cave seepage water,