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The use of oxygen isotope variation in shells of estuarine mollusks as a quantitative record of seasonal and annual Colorado River discharge

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Abstract—We describe a new method for the calculation of river flow that uses the oxygen isotope composition of bivalve mollusk shells that grew in the river-water/seawater mixing zone of the Colorado River estuary. Sclerochronological techniques are used to identify tidally-induced, fortnight-scale bundles of daily growth increments within shell cross-sections. These fortnightly markers are used to establish a chronology for samples taken for $\delta^{18}O$ analysis. A composite seasonal $\delta^{18}O$ profile derived from five shells that grew in the absence of river-water flow is used as a baseline against which profiles of river-influenced shells are compared. Because this comparison is between matched fortnights within a year, the temperature of shell growth is likely to be very similar. The difference in $\delta^{18}O$ between the river-influenced shell and the "no-flow" composite shell therefore represents the change in the $\delta^{18}O$ of the water due to the presence of river water in the mixing zone. The river water end-member is also determined within a fortnightly context so that the change in the $\delta^{18}O$ of mixing-zone water can be used to calculate the relative proportions of seawater and fresh-water. The fresh-water end-member is calculated from the $\delta^{18}O$ of bivalves alive prior to the emplacement of dams and water diversions on the Colorado River. The marine end-member is based on direct measurements of the $\delta^{18}O$ of northern Gulf of California water during times of no Colorado River flow. The system has been calibrated to absolute flow amounts using recent releases of known volume and rate. *Copyright © 2004 Elsevier Ltd*

1. INTRODUCTION

Quantitative estimates of prehistoric river flow can provide valuable information on the natural range of variability in river discharge and the response of the hydrologic cycle to climate change. In most parts of the world, direct measurements of river discharge have been made for less than 200 yr, so proxy indicators need to be employed to provide a long-term record of drought or floods. Quantitative estimates of river discharge based on tree-rings have been successfully used to provide ~500 yr records of river flow (e.g., Stockton and Jacoby, 1978; Meko et al., 1995). Stable isotopes of strontium, oxygen, and carbon from estuarine mollusk shells have been employed to extend the record back several millennia (see the pioneering work of Ingram and Sloan, 1992; Gagan et al., 1994; Ingram et al., 1996), but calibration of isotopic variation with discharge variation has been very difficult. Other proxy indicators (typically based on proportions of particular estuarine species) have provided only semiquantitative estimates of salinity, and thus, indirectly, river discharge.

In this paper, we describe a method based on comparing seasonal isotopic variation in shells grown in the absence of any river water influence with shells grown in the presence of a known amount of river water. When coupled with information on the $\delta^{18}O$ mixing relationship of seawater and river water, the offset between river-influenced and "no-flow" shell $\delta^{18}O$ profiles can be used to calculate Colorado River discharge at its delta before upstream dam and diversions, and before the oldest direct measurements.

2. CONTEXT OF THIS STUDY

The Colorado River is one of the major sources of water for six states in the southwestern United States and two in northwestern Mexico. Its annual discharge has been completely allocated within the U.S. and Mexico and for the last 40 yr Colorado River water has discharged into the Gulf of California only during unusually wet years. The Colorado River compact of 1922 allocated the water supplied by the Colorado River among California, Arizona, Colorado, Utah, Nevada, and New Mexico. The amount of water distributed by this pact (16.2 million acre-feet or 2.0×10^{10} m^3) was based on approximately 15 yr of historical flow records covering an interval that turned out to be a time of unusually high flow in the century-long historical record of discharge (USGS, 1954; Hely 1969; Stockton and Jacoby, 1978). Thus, there is great interest in developing longer records of river flow to see if the twentieth century was typical or anomalous relative to the last one or two millennia. Tree ring studies have been used to reconstruct the last 450 yr of precipitation and river flow in the upper Colorado River basin (Stockton and Jacoby, 1978; Meko et al., 1995). These studies have suggested that the allocated flow is probably 20% greater than the average flow of the last four centuries.

Our study takes a different approach to the question of estimating long-term flow by looking at the geochemical record of flow reaching the mouth of the Colorado River (summing both the upper and lower Colorado River basins). Using shell

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