Macrofaunal and isotopic estimates of the former extent of the Colorado River estuary, upper Gulf of California, México

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Faunal and isotopic evidence can be used to reconstruct the zone of fresh water influence of the Colorado River prior to its diversion for agricultural and domestic uses. The beaches and islands of the Colorado delta are predominantly composed of shells of the bivalve mollusk *Mulinia coloradoensis*. The shells date from before the construction of upstream dams, and $\delta^{18}O$ values from the shells are significantly more negative than $\delta^{18}O$ values from species living in the delta today. Both faunal and isotopic evidence indicate that *M. coloradoensis* is a brackish water species that thrived when the river flowed into the Gulf.

The proportion of empty shells of *M. coloradoensis* ranges from 80–95% near the river's mouth to only 25% 65 km to the south. Shells of the species are rare to absent 80 km south of the mouth of the river. Macrofaunal evidence indicates a mixing zone extending as far as 65 km along the western shore of the upper Gulf of California.

Average $\delta^{18}O$ values in shells of *M. coloradoensis* become more positive with increasing distance from the river's mouth, reflecting the greater dilution of river water with normal salinity Gulf water. Average $\delta^{18}O$ values in the fossil shells approach values in live bivalve mollusks at a distance 65 km south of the mouth of the river indicating that the mixing zone of the former Colorado River extended at least 65 km from its mouth. The effect of virgin Colorado River flow in the upper Gulf of California was geographically extensive.

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Introduction

In normal years, the Colorado River no longer reaches the sea. The construction of upstream dams and diversions since the 1930s has resulted in the transformation of the upper Gulf of California from an estuary, in which the river's annual discharge of

$\sim 20 \times 10^9$ m^3 yr^{-1} mixed with sea water, to an inverse estuary with salinity increasing toward the mouth of the river (Carbajal *et al.*, 1997; Lavín *et al.*, 1998). It is difficult to evaluate the ecological effects of this change because no systematic surveys were conducted in this area before the significant reduction in the flow of the river. Here, we use faunal and isotopic analysis to determine the geographic extent of the former estuary of the Colorado River. Other papers (Rodriguez *et al.*, 2001; Kowalewski *et al.*, 2000) and work in progress consider the biotic effects of the cessation of Colorado River flow. Although our immediate objective in these studies is documenting the environmental consequences of human activity specifically on the Colorado delta, we also show how paleoecological techniques can be applied to assess the environmental consequences of human activity in coastal regions in general.

Study area

We collected shells from the southernmost portion of the Colorado River delta in Baja California, Mexico (Fig. 1). This area is arid, hot, and has an exceptionally large tidal range—up to 10 m at the river's mouth (Thompson, 1968; Ezcurra and Rodriguez, 1986). Mean monthly water temperatures reach 30°C during the summer and 15°C in the winter (Thomson, 1999). The salinity of the ocean water in the delta ranges between 35% and 40% (Roden, 1964; and personal observations).
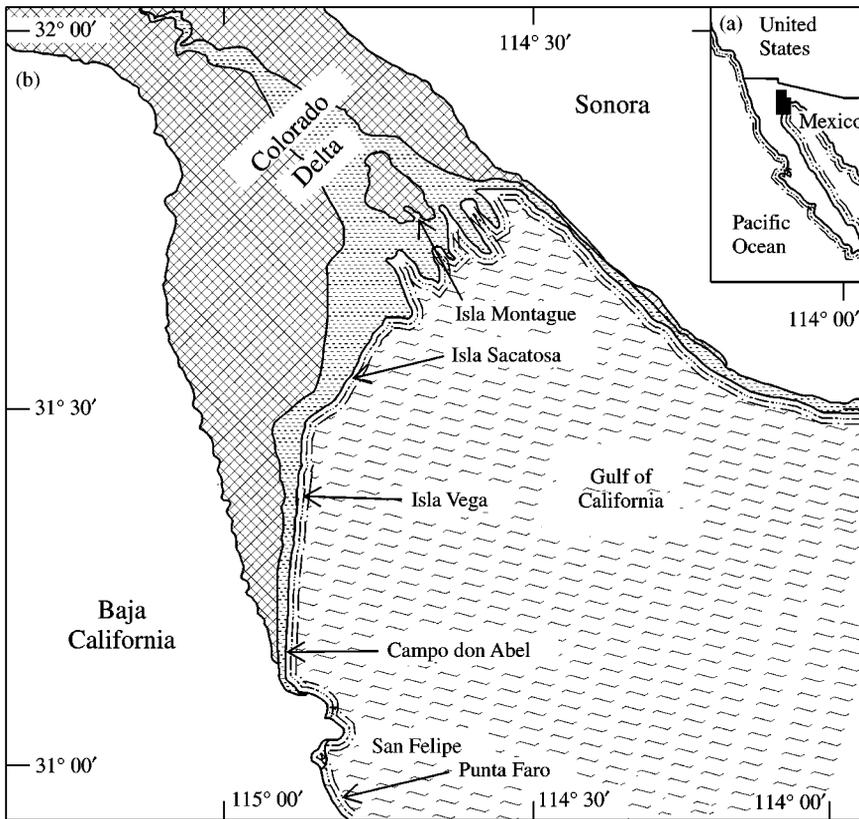
Figure 1. Study area. (a) Regional map (Baja California and Gulf of California). (b) Upper Gulf of California and Colorado River delta showing sample localities. Sampling sites, ←; Supratidal, ▨; Intertidal, ▥; Subtidal, ▱.

The tidal flats of the lower Colorado delta contain several parallel series of shell beaches (cheniers) separated by mud flats. The mud flats prograde seaward when the influx of sediment from the Colorado River is high. Low influx of sediment to the Gulf causes erosion of the fine-grained material and reworking of coarser sediment, mostly mollusc shells, into chenier ridges (Thompson, 1968). On the Colorado delta, the cheniers are dominated by shells of the mactrid bivalve *Mulinia coloradoensis* Dall (Kowalewski *et al.*, 1994).

The cheniers in the Colorado delta are ordered chronologically, with the most recently formed cheniers at the modern shoreline, and progressively older cheniers toward land (Kowalewski *et al.*, 1994). Specimens for this study were collected from the modern cheniers, formed within the last 70 years, when construction of dams and other diversions greatly reduced the input of sediment from the river (Thompson, 1968). Radiocarbon and amino-acid dated shells from the modern cheniers range in age from 215 to 650 radiocarbon years old (Kowalewski *et al.*, 1998).

Methods

Macrofaunal analysis

We determined how the relative abundance of *M. coloradoensis* shells changes with distance from the mouth of the Colorado River. We collected bulk shell samples from cheniers at five localities in the upper Gulf of California at varying distances from the mouth of the Colorado River: Isla Montague (at the mouth of the Colorado River), Isla Sacatosa, Isla Vega, Campo don Abel, and Punta Faro (Fig. 1). We counted all shells in each sample and calculated the percentage of *M. coloradoensis* shells. The samples consisted of 930 individuals from Isla Montague, 2000 from Isla Sacatosa, 300 from Campo don Abel, and 300 from Punta Faro. Percent values of *M. coloradoensis* for Isla Vega and south of Isla Vega are from Localities 7 and 8 of Kowalewski *et al.* (1994), where samples sizes were 1384 and 2612, respectively.

Isotopic analysis

Marine and fresh waters have different oxygen isotope compositions (Rozanski *et al.*, 1993), and this difference can be used to estimate the contribution of river water in estuarine areas (Andreasson *et al.*, 1999; Eisma *et al.*, 1981; Ingram *et al.*, 1996). The isotopic composition of water and carbonate is reported as the deviation of the $^{18}O/^{16}O$ ratio of the sample from that of a standard,

$$\delta^{18}O \text{sample} = \left(\frac{(^{18}O/^{16}O) \text{ sample} - (^{18}O/^{16}O) \text{ std}}{(^{18}O/^{16}O) \text{ std}} \right) x 1000$$

where units are per mil (%) or parts per thousand, and the standard used is standard mean ocean water (for waters) or Pee Dee Belemnite (for carbonates). In this notation, typical fresh water $\delta^{18}O$ values range from -3 to -20%, and seawater $\delta^{18}O$ is approximately 0%. In estuarine systems, more negative $\delta^{18}O$ values indicate more fresh water entering the mixing zone of the estuary; while higher values indicate less fresh water inflow. The isotopic composition of the mixed water thus reflects the relative proportions of river and seawater in estuaries.

Bivalve molluscs grow by precipitating calcium carbonate ($CaCO_3$) in accretionary bands along the outer margin of the shell thus creating a chemical record of local environmental conditions. The isotopic composition of shell is a function of the $\delta^{18}O$ of the water in which the individual is living, the ambient temperature (Grossman & Ku,

1986), and evaporation. Changes in the $\delta^{18}O$ of water are directly recorded in the shell while it is growing. Small temperature changes, however, have little effect on the shell $\delta^{18}O$ values. A temperature shift of $4 \cdot 7°C$ changes the $\delta^{18}O$ values by only 1‰ (Grossman & Ku, 1986).

We can estimate the effects of temperature and evaporation on the isotopic composition of shell material by sampling shells of bivalves living in the absence of fresh water influx. Here, we use the $\delta^{18}O$ variation in bivalves currently living in the delta as a measure of the $\delta^{18}O$ values during times of no Colorado River flow. $\delta^{18}O$ values from dead clams in the Colorado delta that are below the minimum values of the typical temperature-driven range in live bivalves reflect the influence of Colorado River water.

Chione (Chionista) fluctifraga (Sowerby), an abundant bivalve living in the Colorado River delta today, was used to document the primarily temperature-driven seasonal cycle of $\delta^{18}O$ in shell in the absence of significant amounts of Colorado River water. *Mulinia coloradoensis* was abundant when Colorado River water reached the Gulf of California (Rodriguez *et al.*, 2001). The isotopic composition of dead *M. coloradoensis* shells is here used to estimate river influx to the delta when the Colorado was flowing.

We collected live specimens of *Chione fluctifraga* from Isla Sacatosa and fossil specimens of *M. coloradoensis* from Isla Montague, Isla Sacatosa, Isla Vega, and Campo don Abel (Fig. 1). Three valves of live-collected *C. fluctifraga* and 13 valves of fossil *M. coloradoensis* were sliced into thick sections ($\sim 1 \cdot 0$ mm thick) from the umbo to the commissure. Within each section four to eight holes were drilled within discrete growth bands with a fine point ($0 \cdot 5$ mm) dental drill.

The resulting powders (< 1 mg) from each drill hole were analysed for their stable isotope composition at the University of California, Santa Cruz, U.S.A. Samples were roasted under vacuum at $200°C$ for 1 h and analysed with an Autocarb device coupled to a Fisons Prism Mass Spectrometer. Each sample was reacted in a common acid bath at $90°C$. All specimens sampled were unaltered aragonite. All values are reported in the (per mil, ‰) notation relative to the Pee Dee Belemnite (PDB) standard. A more detailed description of the study area, methods and isotopic results are in Rodriguez *et al.* (2001).

We used weighted linear regression of the mean $\delta^{18}O$ value per shell (number of samples per shell was used as weight) with distance from the river mouth to test for a relationship between $\delta^{18}O$ values and distance from the river mouth.

Results

Macrofaunal analysis

Mulinia coloradoensis shells dominate the cheniers on the Colorado River delta (Fig. 2). Near the mouth of the river (Isla Montague to Isla Vega) *M. coloradoensis* valves comprise between 75 and 95% of all of the shells. With increasing distance from the mouth of the river, the relative abundance of *M. coloradoensis* shells decreases. Proportions of *M. coloradoensis* shells drop to 27% at Campo don Abel, and no shells were found at Punta Faro, 75 km south of Isla Montague.

Isotopic analysis

$\delta^{18}O$ values in shells of live-collected *C. fluctifraga* range between $0 \cdot 79$‰ and $-2 \cdot 48$‰ with a mean of $-1 \cdot 35$‰ (Fig. 3, Appendix 1). The range measured in the live-collected *C. fluctifraga* from Isla Sacatosa is similar to the modern marine range measured in live-collected shells of *C. fluctifraga* from other locations in the upper Gulf of California.

Shells of fossil *M. coloradoensis* frequently have $\delta^{18}O$ values that are much lower than those of live *C. fluctifraga* shells (Fig. 3, Appendix 2). The $\delta^{18}O$ values range from $1 \cdot 0$‰
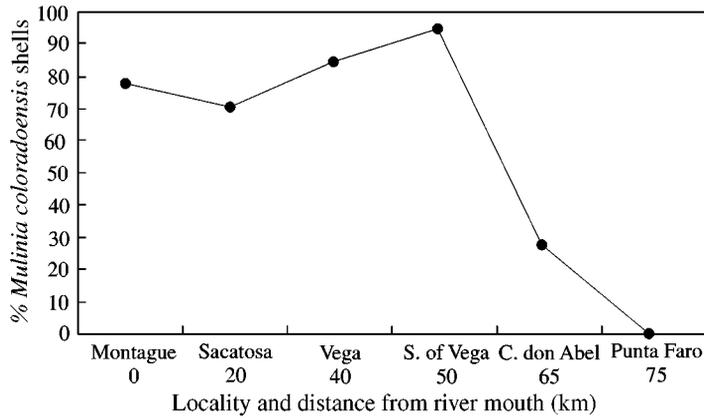
Figure 2. Relative abundance of *Mulinia coloradoensis* shells in chenier and beach deposits of the Colorado Delta.

to about -6.0% with a mean of -2.0%. This indicates isotopic variation in *M. coloradoensis* shells was influenced by periods of major fresh water influx.

The average $\delta^{18}O$ value of shells of *M. coloradoensis* increases with increasing distance from the mouth of the river (Fig. 4). Shells collected from Isla Montague, the locality
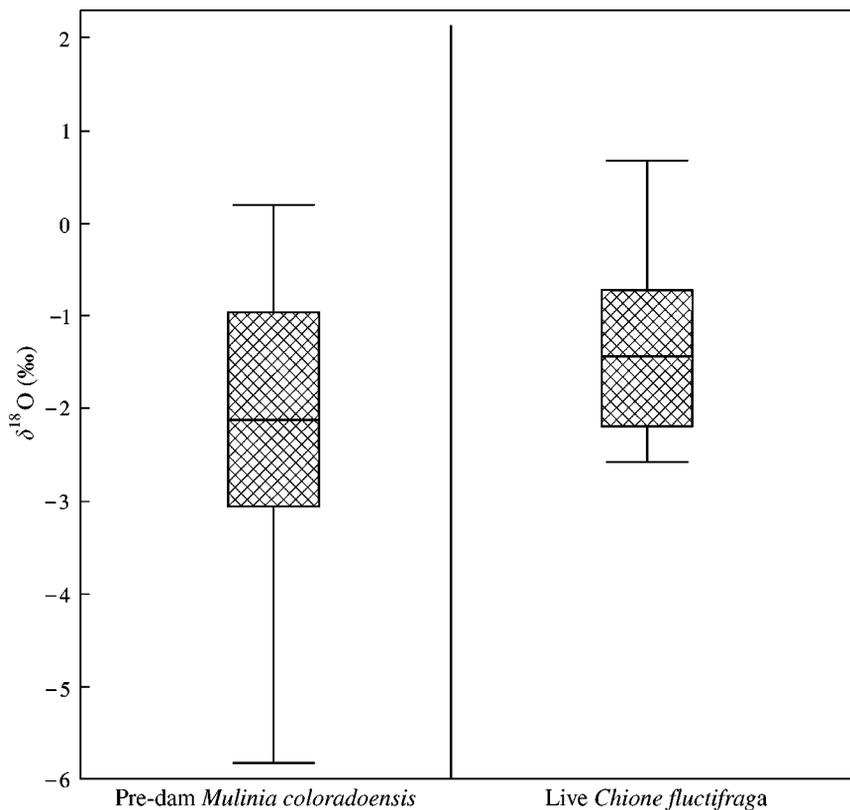
Figure 3. Oxygen isotope values and ranges for fossil *Mulinia coloradoensis* and live-collected *Chione fluctifraga*. Box area encloses 25 and 75‰ quantiles, center line is the mean; upper and lower lines define the 5 and 95‰ values.
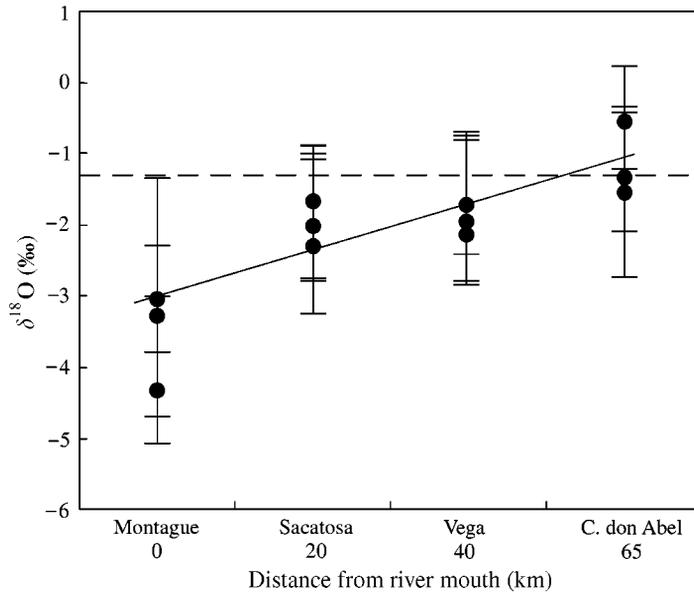
Figure 4. Average oxygen isotope values from empty shells of *Mulinia coloradoensis* within the Colorado River Delta. Bars are 95% confidence intervals. Dashed horizontal line represents average $\delta^{18}O$ value for today from live-collected *Chione fluctifraga*. See Fig. 1 for localities. Solid sloping line is linear regression based on 12 shells, with number of samples per shell used as weights ($r = 0.865$, $F = 29.6$, $p = 0.0003$).

closest to the river mouth, had the lowest average isotopic values, while those from Campo don Abel, the farthest from the river, had the highest ($r^2 = 0.7474$; $n = 86$; mean $\delta^{18}O = -3.045 + 0.033$ distance; $p = 0.0003$).

Discussion

Macrofaunal analysis

The overwhelming dominance of *M. coloradoensis* shells at the mouth of the Colorado River and their decline with increasing distance suggests that populations of *M. coloradoensis* are linked to the influence of fresh water inflow. Indeed, live individuals of *M. coloradoensis* are very rare today, and the decline in the population is likely due to the decreased influx of river water (Rodriguez *et al.*, 2001). Kowalewski *et al.* (2000) estimate that population densities of bivalves reached $\sim 50/m^2$ before upstream diversions. *Mulinia coloradoensis* appears to have required the lower salinity conditions formerly present in the upper Gulf of California. It is also possible that spawning of *M. coloradoensis* is linked to episodes of high influx of fresh water from the Colorado River or that nutrients linked to fresh water influx created a favorable habitat for this species.

The sharp decrease in abundance of *M. coloradoensis* south of the Campo don Abel locality, 65 km from the river's mouth, suggests that under normal conditions, the mixing zone of river water and sea water extended to this area.

Isotopic analysis

The $\delta^{18}O$ variation within shells of live-collected *C. fluctifraga* appears to be driven by the seasonal temperature cycle. Goodwin *et al.* (2001) show that growth in this bivalve

begins in late March or early April when water temperatures reach $\sim 17°C$ and growth slows or halts when water temperatures reach their summer maximum at $\sim 31°C$. Because a temperature change of $4·7°C$ results in a $1‰$ change in isotopic composition of molluscan aragonite (Grossman & Ku, 1986), the annual range in growth temperature of $\sim 14°C$ could account for most of the $3·27‰$ variation in live *C. fluctifraga* ($3·27 \times 4·7°C/‰ = 15·4°C$). Evaporation may have driven the $\delta^{18}O$ of seawater (and thus of shell material) to some of the more positive values. Because Colorado River water did not flow into the Gulf of California when these specimens were alive, the isotopic variation in these shells is due solely to the seasonal variation in water temperature and evaporation.

The $\delta^{18}O$ values below the upper Gulf marine range of variation (estimated from live-collected *C. fluctifraga*) that are found in fossil shells of *M. coloradoensis* reflect the inflow of fresh water from the Colorado River. Though both evaporation and temperature can also cause variation in $\delta^{18}O$ values, these cannot explain the low values found in fossil specimens of *M. coloradoensis*. Increasing evaporation would drive the $\delta^{18}O$ values in water and shell material toward higher values, not lower ones, and decreased evaporation would drive the values closer to the average ocean value of approximately $0‰$, but not below.

Increased temperature when the fossil *M. coloradoensis* were alive would indeed drive the $\delta^{18}O$ values lower than those found today. However, the shells date from 215 to 650 radiocarbon years ago (Kowalewski *et al.*, 1998), a time when global temperatures are estimated to have been $\sim 1·0°C$ cooler (Porter, 1986). Furthermore, temperature change is unlikely to have caused the low $\delta^{18}O$ values in the shells of *M. coloradoensis*. Minimum $\delta^{18}O$ values in *M. coloradoensis* are about $4‰$ lower than the low values found today in *C. fluctifraga* (Appendix 1). This $4‰$ difference would require a $\sim 20°C$ increase in temperature (Rodriguez *et al.*, 2001). Because an increase in temperature of this magnitude is unlikely, we conclude that higher water temperatures do not explain the lowest values recorded in *M. coloradoensis* shells.

The increase in $\delta^{18}O$ values in fossil *M. coloradoensis* shells with increasing distance from the river's mouth (Fig. 4) is expected because the influence of river water should decrease with distance. Andreasson *et al.* (1999) also found that documented $\delta^{18}O$ minima within isotopic profiles of mollusc shells became less pronounced with distance from the discharge area, indicating the increased mixing with normal seawater.

At Campo don Abel, 65 km away from the mouth of the River, the average isotopic signature of the shell reflects normal marine salinity. This indicates that, on average, Colorado River water had completely mixed with Gulf seawater at that distance and that isotopic variation in this area is due to temperature and evaporation.

Our estimate of the extent of the estuarine mixing zone of the upper Gulf of California probably under-estimates its maximum size. This is due to the strongly seasonal flow in the pre-diversion Colorado River. Before the construction of upstream dams, the Colorado River delivered 70% of its annual flow in months of May, June, and July (Harding *et al.*, 1995). This maximum flow was the result of the spring snow-melt on the western slope of the Rocky Mountains. Because the regression equation that describes the relationship between $\delta^{18}O$ and distance is based on average, rather than minimum values, it underestimates the maximum extent of the estuarine zone. In addition, our limited sample size per shell (eight samples) may not have been adequate to ensure the sampling of the lowest $\delta^{18}O$ values—those diagnostic of maximum river flow. The estuarine zone may have often extended past the 65 km distance to Campo don Abel that is estimated by our regression equation.

Our results agree with two other estimates of the extent of the former estuary. Carbajal *et al.* (1997) used estimates of river discharge during historic time to model the size of the mixing zone of Colorado River water and Gulf marine water. Their model predicts that normal marine salinity was reached at a distance of approximately 70 km from the mouth of the river along the west side (Baja California) of the Gulf. Lavín and Sanchez

(1999) sampled upper Gulf of California water during a controlled release of Colorado River in March and April, 1993. The controlled discharge approximated normal April flows of the virgin Colorado River ($\sim$25% of the maximum virgin June flows). They found that salinities approximated those of normal Gulf water at a distance of approximately 70 km from the mouth of the river along the west side of the Gulf.

   Estuaries are often productive environments and supply important nutrients for marine life (Campbell *et al.*, 1991; Flores-Verdugo *et al.*, 1990; Herrgesell *et al.*, 1981—although under some circumstances, river flow to estuarine zones can actually suppress productivity (Ortner & Dagg, 1995). The decreased fish catches off the Nile delta following the completion of the Aswan High Dam (Aleem, 1972) suggests that the upper Gulf of California may have experienced a similar decrease in productivity following completion of Hoover and Glen Canyon Dams. Indeed, Galindo-Bect *et al.* (2000) report that the size of shrimp catches in the upper Gulf of California correlate positively with the size of controlled releases of Colorado River water. Rodriguez *et al.* (2001) and Kowalewski *et al.* (2000) suggest that Colorado River inflow to its estuary supported large populations of the bivalve *M. coloradoensis*. Here, we show that the effect of virgin Colorado River flow in the upper Gulf of California may have been geographically very extensive.

Conclusions

Macrofaunal analysis and analysis of stable isotopes in fossil bivalve shells can be used to determine the geographic extent of fresh water influence in estuarine areas no longer receiving river water. Faunal and isotopic variation both indicate that the influence of the inflow of fresh water from the Colorado River extended about 65 km into the upper Gulf of California. These results agree with previously published numerical models of the former mixing zone and direct measurements during controlled releases. Before upstream dams, Colorado River inflow to the Gulf of California created a very large estuarine zone.

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Appendix I. *Oxygen isotope values for live-collected* Chione fluctifraga *from Isla Sacatosa. Sample number increases with distance from commissure (growing edge)*

Sample position	$\delta^{18}O$
Specimen ST1-A2L	
1—at commissure	− 2·22
2	0·10
3	− 2·22
4	− 0·86
5	− 1·66
6	0·79
7	− 1·76
8	0·34
Specimen ST1-A4R	
1— at commissure	− 1·57
2	− 2·05
3	− 2·48
4	− 1·70
5	− 2·11
6	− 1·67
7	− 0·04
8	− 1·96
Specimen ST1-A3R	
1—at commissure	− 1·58
2	− 1·75
3	− 2·12
4	− 0·55

Appendix II. *Oxygen isotope values for fossil* Mulinia coloradoensis. *Sample number increases with distance from commissure (growing edge)*

Isla Montague Sample position	$\delta^{18}O$	Isla Sacatosa Sample position	$\delta^{18}O$
Specimen IM6-D3L		*Specimen ST8-D3L*	
1—at commissure	− 2·53	1—at commissure	− 2·27
2	− 5·77	2	− 0·63
3	− 4·80	3	− 4·14
4	− 1·99	4	− 1·58
5	− 3·88	5	− 0·53
6	− 1·15	6	− 1·27
7	− 0·85	7	− 2·89
		8	− 3·71
Specimen IM6-D1R		*Specimen ST8-D2R*	
1—at commissure	− 2·13	1—at commissure	− 1·69
2	− 2·31	2	− 2·04
3	− 3·09	3	− 0·63
4	− 4·13	4	− 1·39
5	− 2·98	5	− 4·52
6	− 1·75	6	− 1·42
7	− 3·99	7	− 0·99
8	− 3·69	8	− 2·11

Appendix II— *Continued*

Isla Vega Sample position	$\delta^{18}O$	Campo don Abel Sample position	$\delta^{18}O$
Specimen IM4-D44L		*Specimen ST8-D1R*	
1—at commissure	− 2·63	1—at commisure	− 1·56
2	− 3·60	3	− 3·35
3	− 6·37	4	− 1·70
4	− 3·83	5	− 0·72
5	− 2·70	6	− 1·43
6	− 3·68	7	− 3·22
7	− 5·82	8	− 0·95
8	− 3·74		
Specimen IV1-D6R		*Specimen CD1-D4L*	
1—at commissure	− 0·14	2—at commissure	− 0·30
3	− 2·86	3	− 0·20
5	− 0·73	4	0·05
6	− 2·25	5	0·23
7	− 2·28	6	− 0·37
8	− 2·12	7	− 1·90
Specimen IV3-D1R		*Specimen CD1-D6L*	
1—at commissure	− 1·16	1—at commissure	− 2·69
2	− 0·56	2	− 1·79
3	− 1·94	3	− 0·91
4	− 1·93	4	− 0·74
5	0·18	5	0·60
6	− 1·62	6	− 0·84
7	− 2·63	7	− 2·22
8	− 2·91	8	− 3·51
Specimen IV3-D2L		*Specimen CD1-D5L*	
1—at commissure	− 3·32	1—at commisure	− 1·58
2	− 3·11	2	− 1·69
3	− 1·62	3	− 0·69
4	− 0·38	4	− 0·92
5	0·27		
6	− 0·66		
7	− 2·49		
8	− 2·23		