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Human-Induced Desalinization of Manzala Lagoon, Nile Delta, Egypt: Evidence from Isotopic Analysis of Benthic Invertebrates

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ABSTRACT

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This study combines isotopic ($^{87}Sr/^{86}Sr$, $\delta^{18}O$ and $\delta^{13}C$) with paleontological data to derive a paleosalinity proxy in order to determine the impact of the Aswan High Dam on Manzala lagoon in Egypt's Nile delta. Analyses were made on 17 invertebrate taxa (molluscs, crustaceans, foraminifera, serpulid worms). These were collected in 17 surficial samples and 18 samples from two cores collected at the two salinity extremes of the lagoon. Of the three isotopic systems, Sr isotopes ($^{87}Sr/^{86}Sr$) best record salinity changes within the lagoon. The main control on C isotopes within shell material is the mixing of fresh and marine waters entering the lagoon; thus it is also a useful paleosalinity indicator. The oxygen isotopic composition of shells increased with decreasing salinity: this is consistent with the observation that fresh waters feeding the lagoon are enriched in ^{18}O with respect to Mediterranean seawater. However, the gradient in $\delta^{18}O$ between these end-members is not sufficient to allow us to use O isotopes as a recorder of paleosalinity. Sr isotopes from a core on the landward margin of the lagoon documents a decreased salinity shift from approximately 4–13 ppt to 1–2 ppt since about 1950. The major reduction of salinity in Manzala is due to a dramatic increase in freshwater discharge from drains into the lagoon and effects of Aswan High Dam closure in 1964. This salinity change has been the most significant in the past 100 years. This method, combining paleontological and isotopic analyses of sediment cores, provides documentation of environmental deterioration and thus holds promise for the study of anthropogenically-induced salinity changes in other deltaic systems from around the world.

ADDITIONAL INDEX WORDS: *Aswan High Dam, fisheries, invertebrate fauna, strontium, oxygen and carbon isotopes, Manzala lagoon, molluscs, Nile delta, salinity, Nile River.*

INTRODUCTION

The present study applies a multi-isotopic methodology ($^{87}Sr/^{86}Sr$, $\delta^{18}O$ and $\delta^{13}C$) to detect temporal salinity changes in cores taken from Manzala lagoon, the largest wetland in the Nile delta of Egypt. This wetland, located in the northeastern delta (Figure 1), was selected because it has been subject to accelerated human-induced alteration during the latter half of the 20th century. The purpose of this study is to determine the impact of salinity changes on the invertebrate fauna living in the lagoon as a result of increased fresh water discharge from irrigation projects since World War II and closure of the Aswan High Dam in 1964.

In a previous study of surficial samples in Manzala lagoon, we examined strontium isotopes ($^{87}Sr/^{86}Sr$) in shell material of invertebrate taxa, a method that proved effective as a salinity indicator for the modern deltaic wetland (REINHARDT *et al.*, 1998b). We found that surface samples collected along transects between the landward fresh to marine water sources accurately record modern salinity gradients within Manzala. Strontium isotopes provided much higher resolution of salinity gradients within the lagoon than paleontological analysis alone (REINHARDT *et al.*, 1998b).

The focus of the present study is to test isotopic parameters ($^{87}Sr/^{86}Sr$, $\delta^{18}O$ and $\delta^{13}C$) to determine whether they can register a human-induced salinity change within the lagoon. If the isotopic method as developed and applied herein is effective in detecting salinity changes through time in the benthic invertebrate fauna of the cores, it may then be possible to determine when and how quickly salinity changes occurred in the wetland. This information is vital for Egyptian fishery management because Manzala is the most important fishery source in the Nile delta but has experienced decreased annual catches (SHAHEEN and YOUSEF, 1979). Moreover, if the isotopic method can detect and measure recent anthropogenic salinity change, it then offers potential as a proxy for detecting climate-induced changes in River Nile flow in the Holocene and earlier geological record.

MANZALA LAGOON

Lagoon environments, typically quasi-closed coastal settings that receive water from fluvial, ground water and ma-

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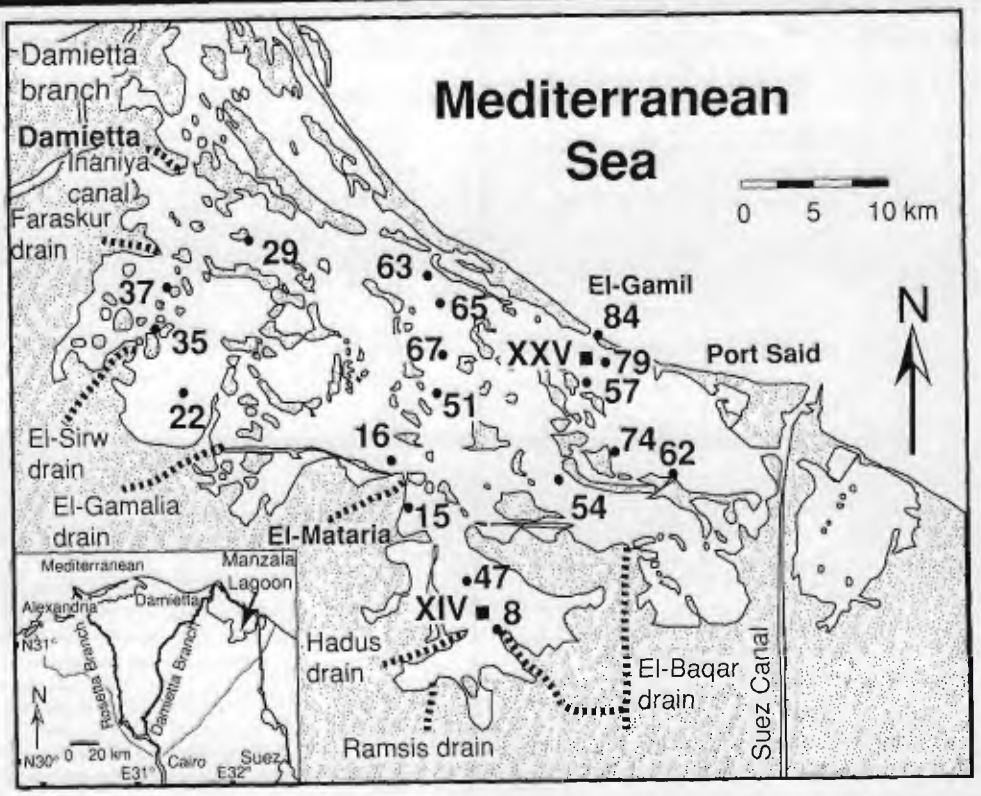

Figure 1. Map of Manzala lagoon study area in the northeastern Nile delta, Egypt, showing locations of 18 surficial and 2 core sites in the wetland. Core XIV is positioned near mouths of El-Baqar and other drains, a major freshwater source, and Core XXV near El-Gamil outlet at the Mediterranean coast.

rine sources, have highly variable salinities that may range from hypo- to hypersaline (1 to >35 ppt). Manzala lagoon, a shallow (for the most part <1 m depth) elongate wetland, is positioned in the northeastern Nile delta where it parallels the Mediterranean coast (Figure 1). The lagoon is ~50 km long, and its maximum width from NE to SW is ~30 km; the wetland is separated from the Mediterranean by a series of low (1–2 m) sand ridges and is bounded by marshes along its 3 other margins.

The main source of seawater to the lagoon is through the El-Gamil outlet, canal waters fed by the Suez Canal, and storm overwash across low-lying sand ridges. Fresh water today is derived largely from a series of large canals and drains (Figure 1) that discharge on the lagoon's S, W and E margins (EL-WAKEEL and WAHBY, 1970; STANLEY, 1996). The input of freshwater into the lagoon through drains would have been less significant in the past. The main freshwater source to the lagoon before the building of the Aswan High Dam in 1964 was groundwater and the annual flood of the Nile River (SHAHEEN and YOUSEF, 1978). The loss of the Nile flood water has been compensated by an increase in drainage water into the lagoon (SHAHEEN and YOUSEF, 1978). Water circulation within Manzala varies seasonally, and water fed from canals is presently discharged primarily through El-Gamil outlet (SHAHEEN and YOUSEF, 1978).

The lagoon has been increasingly subject to human pressures, including reduction in size and altered sedimentation rate (RANDAZZO *et al.*, 1998) and hydrology (EL-WAKEEL and WAHBY, 1970; SHAHEEN and YOUSEF, 1978, 1980). These pressures include: rapid municipal growth at Port Said, Damietta and El-Mataria; higher discharge of agricultural, municipal and industrial wastes; and population densities that now locally reach >1000 persons/km^2 (STANLEY and WARNE, 1993). Reclamation of wetlands for agriculture has resulted in a reduction of annual lagoon surface area exceeding 15 km^2 per year (RANDAZZO *et al.*, 1998). The increased freshwater discharge into this smaller wetland has resulted in markedly higher sediment and pollutant accumulation rates (BENNINGER *et al.*, 1998; STANLEY and WARNE, 1998) and overall decreased salinity (SHAHEEN and YOUSEF, 1978; Figure 2).

PALEOSALINITY PROXIES

The paleontological record in lagoon deposits may be ambiguous with regards to salinity since many invertebrate taxa have wide tolerances to environmental factors (DODD and STANTON, 1990, and references contained therein). An accurate paleosalinity proxy is required in order to derive important sea-level and paleoclimatic information from lagoon deposits in the geological record. To develop such a proxy, the present study of Manzala lagoon evaluates a combined strontium, oxygen and carbon isotopic methodology for the mea-

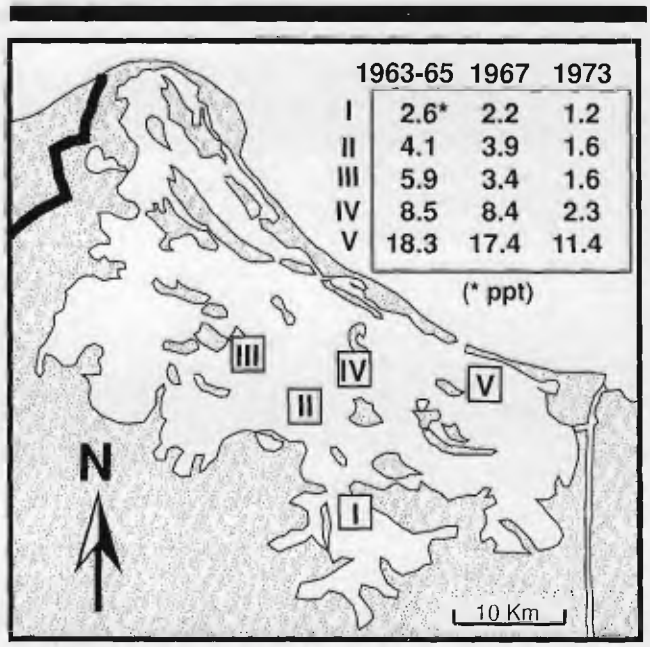

Figure 2. Map of Manzala lagoon showing changes in salinity (ppt) within the lagoon over the 1963–1973 period (from SHAHEEN and YOUSEF, 1978).

surement of high-resolution salinity changes in lagoon environments.

Recently, strontium isotopes ($^{87}Sr/^{86}Sr$) have been used as a paleosalinity proxy in other types of coastal margin environments, such as estuaries (SCHMITZ *et al.*, 1991, 1997; INGRAM and SLOAN, 1992; KOCH *et al.*, 1992; INGRAM and DEPAOLO, 1993; BRYANT *et al.*, 1995). Sr isotopes are an ideal paleosalinity proxy in these settings for several reasons: 1) biogenic carbonates record the $^{87}Sr/^{86}Sr$ value of the waters in which they precipitated, unlike other geochemical proxies (*e.g.* REINHARDT *et al.*, 1999); 2) there is a simple salinity mixing relationship between Sr in fresh and marine waters (INGRAM and DEPAOLO, 1993; ANDERSSON *et al.*, 1994; BRYANT *et al.*, 1995); 3) typically, the Sr isotopic values of modern river waters are either higher or lower than the worldwide marine value of 0.709175 (PALMER and EDMOND, 1989; HODELL *et al.*, 1990); and 4) where any diagenesis can be ruled out, deviation from this marine Sr isotopic value is the result of freshwater dilution. The method, however, has limitations because concentration of Sr in marine waters (~8 ppm) is much higher than in fresh (<1 ppm) water (PALMER and EDMOND, 1992). Thus, a significant amount of dilution by fresh water is needed to alter the $^{87}Sr/^{86}Sr$ ratio of marine waters, and the method is best suited for determining lower salinities of the type that can be found in lagoonal environments. In addition, the Sr isotopic ratio found in shell material records mixing of marine and fresh waters and is a record of salinity only in an open system where evaporation is not a significant factor in determining salinity.

Salinities can also be estimated from the stable isotopic composition of biogenic precipitates, since the isotopic composition of fresh waters and ocean waters are typically quite different. River waters are derived from continental precipitation which has $\delta^{18}O$ values significantly lower than that of seawater ($\delta^{18}O = 0$ ‰ (SMOW)), although in very dry areas the $\delta^{18}O$ value maybe higher because of evaporative effects on rain drops and clouds. The $\delta^{13}C$ value of dissolved inorganic carbon (DIC) in river waters is also lower than that of seawater ($\delta^{13}C \sim 0$ ‰ (PDB)), due to the admixture of DIC derived from the oxidation of biogenic carbon with $\delta^{13}C \sim -25$ ‰. However, this value can be higher if there is an input of DIC from carbonate rocks in the drainage basin. The carbonate component of the skeleton of most shelly organisms is principally derived from DIC of water in which the organism lived (MCCONNAUGHEY *et al.*, 1997), and should therefore reflect the carbon isotopic composition of DIC and of oxygen in the water. The mixing of oxygen isotopes of fresh and marine waters has been observed to exhibit conservative behavior in a open system like an estuary. Since carbon can also behave semi-conservatively in brackish water systems, it is possible to use the $\delta^{18}O$ and $\delta^{13}C$ values of biogenic carbonates to detect gradients in paleosalinity (CLAYTON and DEGENS, 1959; KEITH *et al.*, 1964). Stable isotope ratios can be used to calculate past salinity in Holocene environments where isotopic compositions of the fresh and marine components of the system can be inferred (INGRAM *et al.*, 1996a).

There are, however, significant limitations to this method, particularly in a restricted lagoon setting, since there are factors in coastal systems that can affect the isotopic record independently of mixing between fresh and marine waters. Oxygen isotope ratios of the biogenic carbonates can be affected by changes in temperature and vital effects, while $\delta^{18}O$ of the lagoon water may change as a result of evaporation (see HOLMDEN *et al.*, 1997 a,b). In spite of these limitations several studies have shown the use of stable isotopes as paleosalinity indicators (DODD and STANTON, 1975; INGRAM *et al.* 1996 a,b,c; HOLMDEN *et al.*, 1997a,b).

METHODOLOGY

A suite of 30 short cores were collected from Manzala lagoon in 1990 (data in RANDAZZO *et al.*, 1998). In the present study, two of these cores (sampled at 18 intervals) were selected from the two salinity extremes within the lagoon (Figure 1 and 2) for isotopic analysis (Sr, O and C). Core XIV (~100 cm length) was located near the mouth of several large drains that, together, constitute a major freshwater source. Core XXV (51 cm length) was positioned near El-Gamil outlet, the major source of marine water to the lagoon. Also examined are 18 surficial samples that were collected in 1990 and analyzed in the preliminary study by REINHARDT *et al.* (1998b); herein, we present new stable isotopic data for these 18 samples. Isotopic data for the surficial samples are listed in Table 1, and the core sample data are in Tables 2 and 3.

Identification of various molluscan species follows the taxonomy outlined by BERNASCONI and STANLEY (1994). This and other studies (KULYK, 1987; PUGLIESE and STANLEY, 1991; BERNASCONI and STANLEY, 1994; SLACK *et al.*, 1995) provided information on relative abundances of various taxa in the lagoon. It is on that basis and identification herein of fauna in the two cores that we analyzed several of the more dominant

Table 1. *List of taxa and isotopic data from 18 surficial Manzala lagoon samples. Legend for taxonomic groups: B—bivalve, C—crustacean (barnacle), F—foraminifera, G—gastropod, O—ostracod, S—serpulid worm tube. Environmental setting (from BERNASCONI and STANLEY, 1994): FW—fresh water, MW—marine water, L—lagoonal/euryhaline. Error on the $^{87}Sr/^{86}Sr$ values is at $2\sigma \pm 2 \times 10^{-5}$. Salinities are calculated from the $^{87}Sr/^{86}Sr$ values using mixing relationship in Figure 3; the range of salinities is at 2σ. Note: The ostracode identified as Loxochoncha sp. in REINHARDT* et al. *(1998b) is in fact Cyprideis torosa.*

Surficial Sample	Taxa	Group	Environment	$^{87}Sr/^{86}Sr$	Salinity Range (ppt)	$\delta^{13}C$ (‰) PDB	$\delta^{18}O$ (‰) PCB
MZ8	*Corbicula (C.) fluminalis*	B	FW	0.70760	1.0–1.1	−9.30	1.97
MZ8	*Cerastoderma glaucum*	B	L	0.70885	6.9–7.7	−2.31	3.22
MZ15	*Cerastoderma glaucum*	B	L	0.70861	4.1–4.5	−2.04	3.38
MZ15	*Cerastoderma glaucum*	B	L	0.70850	3.4–3.7	−2.44	4.91
MZ15	*Corbicula (C.) fluminalis*	B	FW	0.70767	1.1–1.1	−8.48	3.36
MZ15	*Melanoides tuberculata*	G	FW/L	0.70802	1.7–1.8	−7.29	3.57
MZ15	*Theodoxus (N.) niloticus*	G	FW	0.70757	1.0–1.0	−5.02	3.76
MZ15	*Gabbiella c. f. senaariensis*	G	FW	0.70764	1.1–1.1	−9.54	3.37
MZ15	*Hydrobia stagnorum*	G	L	0.70826	2.4–2.5	−2.77	3.17
MZ15	*Mercierella enigmata*	S		0.70764	1.0–1.1	−10.20	0.31
MZ15	*Abra ovata*	B	L	0.70869	4.8–5.3	−0.99	4.72
MZ15	*Ammonia beccarri* "tepida"	F	L	0.70888	7.5–8.5	−2.67	2.23
MZ16	*Cerastoderma glaucum*	B	L	0.70851	3.5–3.7	−2.18	4.06
MZ16	*Corbicula (C.) fluminalis*	B	FW	0.70773	1.2–1.2	−8.64	4.23
MZ22	*Melanoides tuberculata*	G	FW/L	0.70759	1.0–1.0	−6.36	2.77
MZ22	*Cerastoderma glaucum*	B	L	0.70859	4.0–4.3	−2.31	4.74
MZ22	*Valvata nilotica nilotica*	G	FW	0.70754	0.9–1.0	−9.57	4.43
MZ22	*Planorbis planorbis*	G	FW	0.70758	1.0–1.0	−7.51	4.90
MZ29	*Melanoides tuberculata*	G	FW/L	0.70779	1.3–1.3	−2.76	4.50
MZ35	*Corbicula (C.) fluminalis*	B	FW	0.70773	1.2–1.2	−7.99	3.31
MZ35	*Cerastoderma glaucum*	B	L	0.70870	5.0–5.4	−0.36	5.23
MZ37	*Cerastoderma glaucum*	B	L	0.70871	5.1–5.4	−0.45	4.42
MZ37	*Abra ovata*	B	L	0.70894	9.1–10.5	−2.03	3.43
MZ47	*Corbicula (C.) fluminalis*	B	FW	0.70756	1.0–1.0	−8.78	2.37
MZ51	*Cerastoderma glaucum*	B	L	0.70887	7.4–8.3	−1.21	3.82
MZ51	*Corbicula (C.) fluminalis*	B	L	0.70771	1.1–1.2	−8.24	4.38
MZ54	*Cerastoderma glaucum*	B	L	0.70882	6.5–7.2	0.14	3.98
MZ54	*Corbicula (C.) fluminalis*	B	FW	0.70767	1.1–1.2	−6.25	2.96
MZ57	*Cerastoderma glaucum*	B	L	0.70903	13.1–15.8	−1.32	3.59
MZ62	*Cerastoderma glaucum*	B	L	0.70871	5.0–5.5	−1.55	3.16
MZ62	*Melanoides tuberculata*	G	FW/L	0.70766	1.1–1.1	−4.11	3.77
MZ63	*Cerastoderma glaucum*	B	L	0.70848	3.3–3.5	−1.58	5.59
MZ63	*Abra ovata*	B	L	0.70849	3.3–3.6	−3.05	5.33
MZ65	*Cerastoderma glaucum*	B	L	0.70870	4.9–5.3	−1.06	4.20
MZ65	*Corbicula (C.) fluminalis*	B	FW	0.70771	1.2–1.2	−7.63	4.58
MZ67	*Cerastoderma glaucum*	B	L	0.70850	3.4–3.6	0.75	2.88
MZ67	*Corbicula (C.) fluminalis*	B	FW	0.70776	1.2–1.3	−8.96	3.42
MZ74	*Abra ovata*	B	L	0.70841	2.9–3.1	−2.12	4.48
MZ74	*Cerastoderma glaucum*	B	L	0.70900	11.2–13.3	−1.48	1.94
MZ79	*Abra ovata*	B	L	0.70897	10.2–11.8	−1.54	3.34
MZ79	*Cerastoderma glaucum*	B	L	0.70838	2.8–3.0	−2.45	4.30
MZ79	*Balanus* sp. 1	C	L	0.70860	4.0–4.3	−2.49	3.63
MZ79	*Ostrea edulis*	B	MW	0.70909	16.9–21.6	0.58	0.63
MZ79	*Melanoides tuberculata*	G	FW/L	0.70814	2.0–2.1	−4.22	4.76
MZ79	*Bittium reticulatum*	G	MW	0.70897	10.1–11.7	−0.20	3.05
MZ79	*Mercierella enigmata*	S		0.70791	1.5–1.5	−3.86	3.81
MZ79	*Hydrobia stagnorum*	G	L	0.70837	2.8–2.9	−2.04	4.42
MZ79	*Ammonia beccarri* "tepida"	F	L	0.70908	16.1–20.3	−0.52	0.20
MZ84	*Mactra (M.) corallina*	B	MW	0.70913	21.4–29.3	0.44	1.30

molluscan species (Tables 2, 3). Also analyzed were foraminiferal and ostracode species, along with some of the less common taxa including barnacles and serpulid worm tubes.

The shell material used for isotopic analysis was based on the nature of taphonomic character and, where possible, pristine and articulated specimens were selected. Material for analysis was sampled across growth patterns of the shell. This entailed selecting a large sample (10–100 mg), after which an aliquot was drawn for isotopic analysis. Before dissolution, the shell surface was mechanically removed to avoid any possible encrustation effects, and then crushed, leached and cleaned with 0.5 N HCl solution. The remaining shell material was ultrasonically washed in distilled water and crushed with an agate mortar and pestle. Sub-samples of the homogenized material were then taken for isotopic analyses.

Micropaleontological samples were hand-picked from the sediment and only pristine specimens were selected. Microfossils were cleaned in an ultrasonic bath of distilled water,

Table 2. *List of taxa and isotopic data from 11 samples in Core XIV. See Table 1 for additional information.*

Core XIV Depth (cm)	Taxa	Group	Environment	$^{87}Sr/^{86}Sr$	Salinity Range (ppt)	$\delta^{13}C$ (‰) PDB	$\delta^{18}O$ (‰) PDB
3–5	*Ammonia beccarri* "tepida"	F	L	0.70894	9.3–10.7	−2.82	2.58
3–5	*Cyprideis torosa*	O	L	0.70792	1.5–1.6	−6.08	1.99
12–14	*Ammonia beccarri* "tepida"	F	L	0.70888	7.6–8.6	−2.17	2.30
20–22	*Abra ovata*	B	L	—	—	−0.82	4.03
20–22	*Theodoxus (N.) niloticus*	G	FW	0.70755	0.9–1.0	−7.12	3.11
20–22	*Abra ovata*	B	L	0.70891	8.4–9.6	−0.84	4.46
20–22	*Corbicula (C.) fluminalis*	B	FW	0.70749	0.9–0.9	−9.13	2.65
20–22	*Cerastoderma glaucum*	B	L	0.70906	14.8–18.3	1.05	4.22
20–22	*Ammonia beccarri* "tepida"	F	L	0.70888	7.7–8.7	−3.01	2.60
20–22	*Cyprideis torosa*	O	L	—	—	−7.33	0.54
30–33	*Abra ovata*	B	L	0.70864	4.3–4.7	−1.15	4.05
30–33	*Abra ovata*	B	L	0.70864	4.4–4.7	−3.10	2.99
30–33	*Corbicula (C.) fluminalis*	B	FW	0.70762	1.0–1.1	−8.84	2.16
30–33	*Cerastoderma glaucum*	B	L	0.70876	5.6–6.1	−0.49	5.20
30–33	*Melanoides tuberculata*	G	FW/L	0.70761	1.0–1.1	−6.03	2.54
30–33	*Lanistes sp.*	G	FW	—	—	−9.14	2.29
30–33	*Ammonia beccarri* "tepida"	F	L	0.70893	8.8–10.1	−2.38	2.37
50–53	*Abra ovata*	B	L	—	—	−1.50	4.55
50–53	*Ammonia beccarri* "tepida"	F	L	0.70908	16.0–20.2	−2.35	2.74
50–53	*Cyprideis torosa*	O	L	—	—	−3.88	4.97
60–63	*Abra ovata*	B	L	0.70886	7.1–8.0	−1.78	4.06
60–63	*Ammonia beccarri* "tepida"	F	L	0.70905	14.0–17.2	−3.08	2.40
68–71	*Abra ovata*	B	L	—	—	−1.20	3.27
68–71	*Ammonia beccarri* "tepida"	F	L	0.70901	12.0–14.3	—	—
77–79	*Abra ovata*	B	L	0.70881	6.3–6.9	−1.64	3.17
77–79	*Cerastoderma glaucum*	B	L	0.70898	10.4–12.1	0.03	2.50
77–79	*Melanoides tuberculata*	G	FW/L	0.70882	6.4–7.1	—	—
77–79	*Ammonia beccarri* "tepida"	F	L	0.70905	14.1–17.3	−1.92	2.31
77–79	*Cyprideis torosa*	O	L	—	—	−2.89	3.59
83–85	*Abra ovata*	B	L	0.70900	11.5–13.6	−0.92	3.55
83–85	*Cerastoderma glaucum*	B	L	0.70899	11.0–12.9	−1.72	1.47
83–85	*Ammonia beccarri* "tepida"	F	L	—	—	−1.20	2.80
88–90	*Cerastoderma glaucum*	B	L	0.70909	17.0–21.7	0.76	3.15
88–90	*Abra ovata*	B	L	0.70899	11.0–12.9	−1.53	3.35
88–90	*Cyprideis torosa*	O	L	—	—	−3.01	3.01
88–90	*Ammonia beccarri* "tepida"	F	L	0.70904	13.2–15.9	−1.84	2.00
91–96	*Cerastoderma glaucum*	B	L	—	—	2.13	3.70

Table 3. *List of taxa and isotopic data from 7 samples in Core XXV. See Table 1 for additional information.*

Core XXV Depth (cm)	Taxa	Group	Environment	$^{87}Sr/^{86}Sr$	Salinity Range (ppt)	$\delta^{13}C$ (‰) PDB	$\delta^{18}O$ (‰) PDB
0–3	*Cerastoderma glaucum*	B	L	0.70912	20.9–40	−0.70	2.92
5–7	*Cerastoderma glaucum*	B	L	0.70918	24–40	0.96	0.52
5–7	*Mercierella enigmata*	S		0.70914	24–40	−3.59	1.53
13–16	*Bittium reticulatum*	G	MW	0.70909	16.9–21.6	1.57	2.33
13–16	*Hydrobia stagnorum*	G	L	0.70892	8.6–9.9	−1.34	2.48
21–24	*Abra ovata*	B	L	0.70876	5.7–6.2	−1.19	3.77
21–24	*Bittium reticulatam*	G	MW	0.70890	8.1–9.1	1.05	2.60
21–24	*Cerastoderma glaucum*	B	L	0.70895	9.5–10.9	0.38	2.89
21–24	*Hydrobia stagnorum*	G	L	—	—	0.53	3.58
28–30	*Cerastoderma glaucum*	B	L	0.70895	9.4–10.9	−0.56	3.14
28–30	*Abra ovata*	B	L	0.70898	10.5–12.3	−1.27	3.10
28–30	*Bittium reticulatum*	G	MW	0.70910	18.2–23.7	1.81	2.26
35–37	*Bittiam reticulatam*	G	MW	0.70910	18.4–24.0	1.09	3.54
35–37	*Cerastoderma glaucum*	B	L	0.70906	14.6–18.1	0.83	2.65
35–37	*Hydrobia stagnorum*	G	L	0.70895	9.4–10.9	−1.99	3.86
35–37	*Hydrobia stagnorum*	G	L	—	—	−0.73	2.15
43–46	*Abra ovata*	B	L	0.70911	19.8–40	−0.12	2.03
43–46	*Bittium reticulatum*	G	MW	0.70905	14.4–17.7	0.59	2.24
43–46	*Cerastoderma glaucum*	B	L	0.70917	24–40	2.01	1.02
43–46	*Hydrobia stagnorum*	G	L	0.70895	9.6–11.1	0.90	2.41
43–46	*Hydrobia stagnorum*	G	L	—	—	1.81	4.13

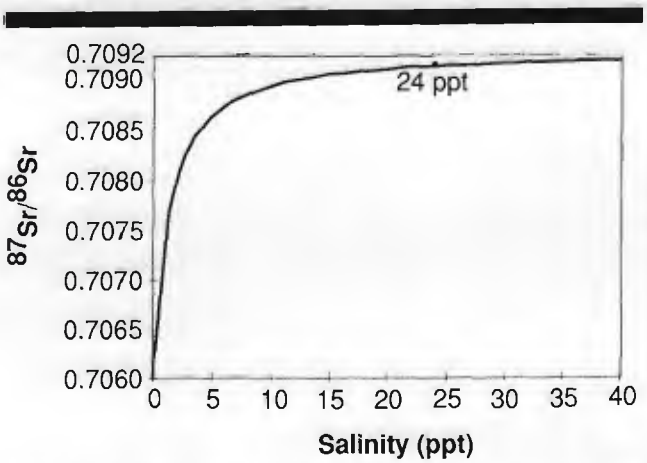

Figure 3. Salinity mixing curve ($^{87}Sr/^{86}Sr$ ratio versus salinity in ppt), after REINHARDT *et al.* (1998b) using Sr isotopic and concentration data from River Nile (BRASS, 1976) and from sea water (EMELYANOV and SHIMKUS, 1986; HODELL *et al.*, 1990). The salinity detection limit using Sr isotopes in Manzala lagoon is 24 ppt (explanation in text).

followed by cleaning with 0.5 N HCl to remove any encrusting material.

Sr separatory techniques followed standard procedures as reported in PATTERSON *et al.* (1995). Sr isotopic analysis was performed on a VG 354 multicollector mass spectrometer at McMaster University. Replicate analyses of the NBS 987 Sr standard yielded a $^{87}Sr/^{86}Sr$ ratio of $0.71028 \pm 2 \times 10^{-5}$ and all $^{87}Sr/^{86}Sr$ values reported here have been normalized to 0.71025. Internal precision (standard deviation of the mean) for all analyses was less than 1.5×10^{-5}. Stable isotope analyses were performed on a SIRA gas-source mass spectrometer at McMaster University using a common 100% phosphoric-acid bath at 90° C. Precision was ± 0.07 ‰ $\delta^{18}O$ and ± 0.10 ‰ for $\delta^{13}C$, and all values are reported relative to PDB.

Salinity measurements for the analyzed taxa were determined using the $^{87}Sr/^{86}Sr$ values within the shell and applying the mixing curve shown in Figure 3. This curve was derived via a two-component mixing equation (ANDERSSON *et al.*, 1994; BRYANT *et al.*, 1995) using River Nile water ($^{87}Sr/^{86}Sr$ = 0.7060; [Sr] = 0.235 ppm; BRASS, 1976) and hypersaline eastern Mediterranean seawater ($^{87}Sr/^{86}Sr$ = 0.709172; [Sr] = 9 ppm; EMELYANOV and SHIMKUS, 1986; HODELL *et al.*, 1990) as the two end-members. We cannot distinguish salinities greater than 24 ppt, at which point the $^{87}Sr/^{86}Sr$ ratio is indistinguishable from that of modern seawater. Some of the samples may, however, have been formed at significantly higher salinities than 24 ppt (BRYANT *et al.*, 1995). Measured salinity values in the present study are an average for the life span of the organism and incorporate seasonal and year-to-year variations (RHOADS and LUTZ, 1980).

In order to use $\delta^{18}O$ and $\delta^{13}C$ to estimate paleosalinity, it is necessary to know the isotopic compositions of the corresponding mixing components. The marine component is assumed to be normal Mediterranean water whose $\delta^{18}O$ is about 1.5 ‰ (PIERRE, 1999). The fresh water component of the lagoon is assumed to be water flowing into the lagoon from agricultural fields through a series of drains (Figure 1). The oxygen isotopic composition of water in these drains has been studied by SIMPSON *et al.* (1987). Water entering into the easternmost part of the lagoon had $\delta^{18}O$ values of 3.10 ± 0.38 ‰ while water draining into the remainder of the lagoon had $\delta^{18}O$ values of 4.34 ± 0.28 ‰. These values are equal to or slightly enriched with respect to water in the Nile which gave values of 3.8 ± 0.5 ‰ over the period from November, 1984 to March, 1985. STURCHIO *et al.* (1999) report a somewhat lower value of 2.9 ‰ for water from the Nile in March, 1997. In either case, these values record a significantly enrichment in ^{18}O with respect to Mediterranean seawater. Typically, the use of O isotopes as a tracer of paleosalinity is based on the assumption that $\delta^{18}O$ of river water is much lower than that of the sea-water component in the mixture. The data for the waters of Manzala lagoon suggest that we would expect a small salinity-controlled isotopic gradient, but with higher $\delta^{18}O$ values corresponding to *lower* salinity.

We do not have any direct measurements of $\delta^{13}C$ of DIC in the water emptying into the lagoon from the drains. However, we can estimate the $\delta^{13}C$ value of the DIC by analyzing a known freshwater invertebrate shell, which was done on several different taxa ($\delta^{13}C \approx 8$–9 ‰; Table 1–3). This value is considerably higher than would be expected if DIC in the lagoon was derived entirely from decay of C3 organic matter ($\delta^{13}C \approx -25$ ‰; *i.e.* wheat, barley). The higher value may be due to the presence of some C4 vegetation ($\delta^{13}C \approx -12$ ‰; *i.e.* millet and sorghum) in areas of the delta draining into the lagoon; as well, the higher value may be a result of partial re-equilibration of the fresh water with atmospheric CO_2 (leading to $\delta^{13}C$ of DIC approaching 0 ‰). In the absence of any analyses of the lagoon waters themselves the causes of these higher $\delta^{13}C$ values can only be matter of speculation at this time. We also do not know the concentration of total inorganic carbon in the fresh water, a parameter which is relevant to the interpretation of the covariation $\delta^{13}C$ and salinity. However, we can examine the relationship between $\delta^{13}C$ and salinity by using Sr isotopes which respond with salinity with more certainty.

OBSERVATIONS

Ninety-four Sr isotopic analyses and 105 O and C isotopic analyses were performed on 17 invertebrate taxa from both surficial samples (n = 18; Table 1) and from the two cores (n = 18; Tables 2 and 3). Graphs of surface and core samples determined relationships between the three isotopic systems in Manzala lagoon and salinity (Figures 4 and 5). The salinity values were derived using the mixing relationship shown in Figure 3. The lithology of the sampled core intervals is shown in Figure 6.

There is a strong direct relationship between Sr and C isotopic values for both the surficial and core samples. A linear regression gives a high correlation coefficient of $R^2 = 0.78$. However, from the distribution of points on the cross-plot of these variables (Figure 4A) it is clear that the data tend to be distributed in a non-linear array, as will be discussed below. In contrast, there is no significant relationship between $\delta^{18}O$ of carbonate and $^{87}Sr/^{86}Sr$ ($R^2 = 0.07$) in the 35 samples,

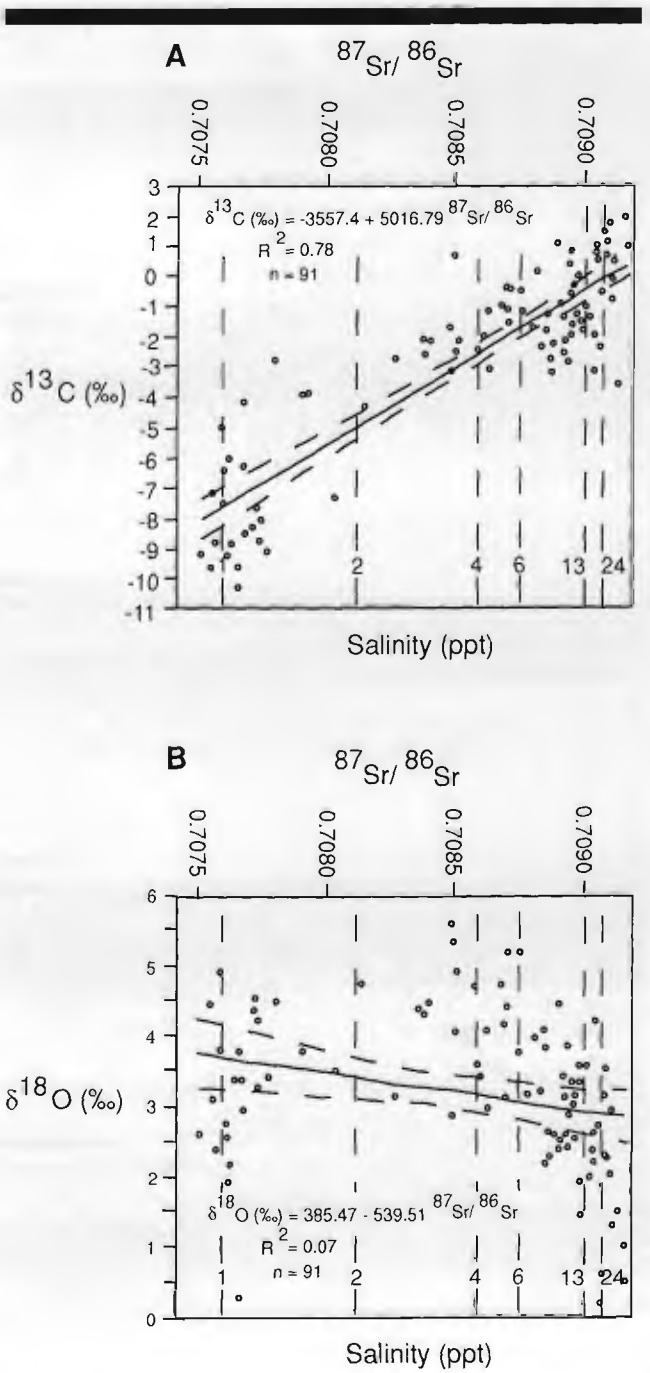

Figure 4. The relationship among three isotopic systems using 18 surficial and 18 core samples from Manzala lagoon. A, Graph shows the direct relationship between Sr and C isotopes within the lagoon and corresponding salinities derived from the mixing relationship in Figure 3. B, Graph shows lack of a relationship between Sr and O isotopes within the lagoon and corresponding salinities derived from the mixing relationship in Figure 3. Explanation in text.

although there is a large degree of variation in $\delta^{18}O$ for any given range of $^{87}Sr/^{86}Sr$ (Figure 4B).

In the deeper part of Core XIV (below 50 cm) we observe fauna whose isotopic ratios suggest salinities in the range of 6–20 ppt (Figure 6A, B). Starting at a depth of between 50 and 30 cm below core top, we observe fauna with isotopic ratios corresponding to salinities in the range from 1–2 ppt, much lower than that represented by the lower part of the core (Figure 6A, B). These low-salinity shells are admixed with an approximately equal proportion of shells indicative of higher salinities like those seen in the deeper part of the core. The upcore shift in salinity is not documented by an upcore change in lithology at that depth.

In Core XXV, the isotopic data for the seven intervals are also shown: the Sr and C isotopic data (Figure 6D, E) do not record the same vertical shift in values as Core XIV. The majority of Sr isotopic values record salinities that are in the 8 to >24 ppt range, with only one interval that decreases to ~ 6 ppt at 21–24 cm from the core top.

DISCUSSION

Relationships Between Isotopic Systems

Analysis of the data from both surficial and core samples shows that while there is a strong positive correlation between Sr and C isotopes, there is no correlation between $^{87}Sr/^{86}Sr$ and $\delta^{18}O$. As previously established for Manzala (REINHARDT *et al.*, 1998b) the Sr isotopes record salinity changes associated with the mixing of River Nile and marine water. While Figure 4A shows a strong relationship between Sr and C isotopes, the relationship with salinity is clearly non-linear. This is to be expected since there are differences in the relationships between salinity and the isotopic ratios of Sr and carbon respectively. These differences would exist even if carbon had behaved semi-conservatively in the mixing system. In fact, it is possible that the carbon isotope ratio was also varying as a result of changes in the isotopic chemistry of DIC induced by changes in pH, alkalinity, pore water effects or biological activity (MOOK and KOENE, 1975; STRAIN and TAN, 1979). As was the case for strontium isotope ratios, plots of $\delta^{13}C$ *vs* S generate a series of parabolas whose curvature depends on both the difference in isotopic composition and concentration of inorganic carbon in the fresh water and seawater. The isotopic composition and DIC concentration of the seawater component may also vary somewhat because these parameters vary steeply in the upper few tens of meters depth in the sea (KROOPNICK 1980; PIERRE, 1999). As a result of the uncertainty in the values of the relevant parameters it would be difficult to use $\delta^{13}C$ directly as a measure of salinity as was done using $^{87}Sr/^{86}Sr$. Nevertheless, it is worthwhile to study the variation in $\delta^{13}C$ of the biogenic carbonate to compare with the paleosalinity as inferred from Sr isotope ratios.

To make this comparison, we can plot the $\delta^{13}C$ of each of the samples against the salinity as inferred from the corresponding $^{87}Sr/^{86}Sr$ ratio (Figure 5A and B). As expected, a strongly non-linear, parabolic relationship between these variables is recorded. The parabolic curve for this relationship is

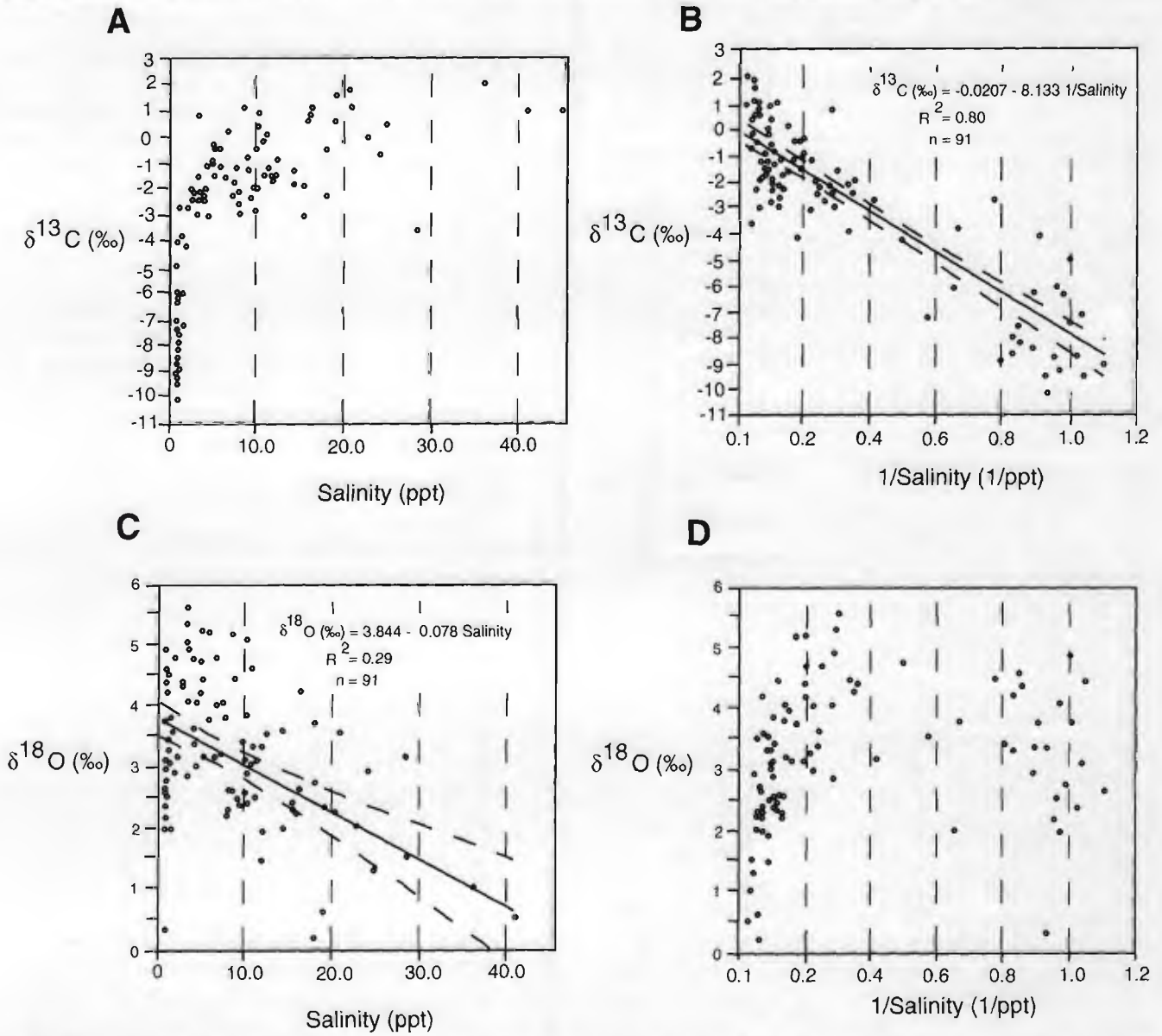

Figure 5. The relationships between O and C isotopes and salinity as derived from the $^{87}Sr/^{86}Sr$ ratios and the mixing relationship in Figure 3. Dashed lines represent 95.5% confidence limits.

much more sharply curved than that for $^{87}Sr/^{86}Sr$ (Figure 5A), showing that $\delta^{13}C$ would not be a very useful indicator of paleosalinity in this system (Manzala Lagoon), except perhaps over a range of very low salinities. The low $\delta^{13}C$ values seen at the low salinity end of the distribution suggest that $\delta^{13}C$ of DIC in the fresh water component of this system is ~ −10 ‰. Figure 5B shows the relation between $\delta^{13}C$ and 1/S; the strong linear correlation seen here indicates that parameters controlling this relationship ($\delta^{13}C$ and C, the isotopic composition and concentration of DIC in the fresh water component) remained relatively uniform during the history of deposition of these sediments.

Although there is no significant relationship between $\delta^{18}O$ of the shells and their $^{87}Sr/^{86}Sr$ ratios, we can observe some suggestion of a relationship between $\delta^{18}O$ and salinity as calculated from the $^{87}Sr/^{86}Sr$ ratios, as seen in Figure 5C and D. This weak negative correlation (R^2 = 0.29) is as predicted from the observed gradient in $\delta^{18}O$ between the slightly evaporated waters of the drainage channels and the lower-$\delta^{18}O$ water of the Mediterranean. The gradient is clearly not well-enough defined to be useful to reconstruct paleosalinity. Note especially the series of low $\delta^{18}O$ samples with the lowest $^{87}Sr/^{86}Sr$ values (lowest salinity). These samples plot well below the main trend and suggest that they were formed at some

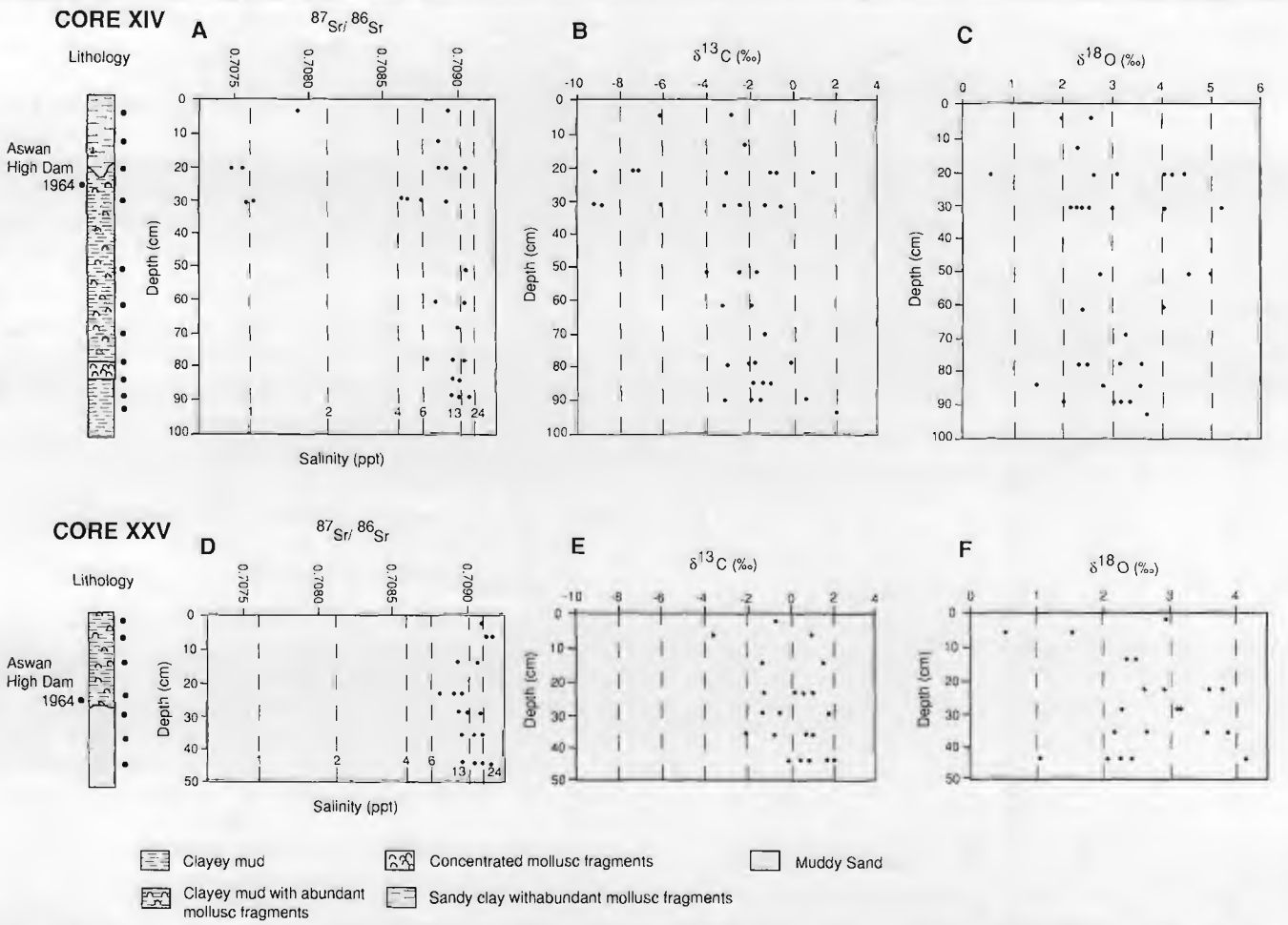

Figure 6. Lithological logs of the two cores taken in Manzala lagoon show the 18 sample intervals analyzed. Also depicted are the temporal distributions of Sr, O and C isotopic data and corresponding salinities derived from the Sr isotopes and the mixing curve shown in Figure 3. The estimated depth of sediment accumulation since the building of the Aswan High Dam in 1964 is marked on the cores. Uncertainty on the $^{87}Sr/^{86}Sr$ measurements is $\pm 2 \times 10^{-5}$ at the 2σ confidence limit.

time when drainage waters were much less evaporative: this cluster includes both modern and ancient samples. The values of $\delta^{18}O$ of these shells would also depend on the temperature at which the shells grew, increasing by 1 ‰ for each 4 °C decrease in temperature. At a temperature near 25 °C, $\delta^{18}O$ of shells with respect to PDB is numerically close to the $\delta^{18}O$ of the ambient water on the SMOW scale. The lowest $\delta^{18}O$ values for shells from this site are about 1 ± 1 ‰, which probably corresponds to shells precipitated from normal Mediterranean sea-waters with $\delta^{18}O \approx 1.5$ ‰. Some of the observed variation could also be due to differences in mineralogy; although, the difference in fractionation between aragonite and calcite is negligible at elevated temperatures (< 1 ‰ at 20–25 °C).

Shells with higher $\delta^{18}O$ grew in water with lower salinity containing a larger fraction of River Nile water. In addition, some of the variation in $\delta^{18}O$ values may be due to: 1) spatial precipitation and evaporation effects that have affected the isotopic composition of lagoon waters; and 2) temperature and "vital effects" that control the partitioning of oxygen isotopes between the shell and ambient water. There is also no clear spatial or temporal relationship between the isotopic values within one taxa (*i.e. Corbicula* or *Cerastoderma*). Thus, any deviation between species is not entirely due to vital effects, but also includes significant localized temperature, precipitation and evaporation effects. Previous studies using O isotopes as a salinity proxy were conducted in open systems such as estuarine environments with highly contrasting isotopic values between the marine and freshwater sources (*e.g.* INGRAM *et al.*, 1996a,b,c). However, Manzala lagoon is a semi-closed system, since the water has a residence time within the wetland, and it is thus affected by local factors other than the mixing between marine and fresh water. In addition, the freshwater is coming from several drains drawing water from agricultural fields where variable degrees of evaporation or addition of precipitation may have occurred. The Sr isotopes are not affected to the same degree and are accurately recording salinities in the lagoon (SHAHEEN and YOUSEF, 1978;

REINHARDT *et al.*, 1998b). In this case, the O isotope system has not proven to be useful as a paleosalinity indicator.

Historic Salinity Changes in the Cores

The Sr isotopic data in Core XIV detects an ~ 3–5 ppt drop in salinity below 30 cm downcore from the surface. Between the closure of the Aswan High Dam in 1964 and the recovery of the core in 1990, ~26 cm of sediment is inferred to have accumulated, based on ^{137}Cs and ^{210}Pb data (~1 cm/yr accumulation rate) in cores from the lagoon (BENNINGER *et al.*, 1998). This accumulation of sediment matches closely our observed onset of less saline conditions within the lagoon (Figure 6A). Thus, the combined effects of dam closure and increased irrigation waterway discharge have caused a significant shift in salinity in the lagoon. The small difference may be due to time averaging as a result of bioturbation or wave action during winter storms which has been recognized in X-radiographs of the short cores (BENNINGER *et al.*, 1998). The range of salinities measured in the upper 30 cm (1–2 ppt to 4–13 ppt) of the core can also be attributed to bioturbation and taphonomic mixing of freshwater and more brackish taxa (FÜRISCH and ABERHAN, 1990; FLESSA *et al.*, 1993; BERNASCONI and STANLEY, 1994; FLESSA and KOWALEWSKI, 1994). In a previous study of deposits from an ancient harbor on the Israeli coast we also had widely varying salinities in a single sample horizon (REINHARDT *et al.*, 1998a; REINHARDT and RABAN, 1999). If all the taxa were living at the same time and in the same location, they should have identical $^{87}Sr/^{86}Sr$ values, which is not the case in the upper 30 cm of the Manzala core. The more brackish water taxa (mostly 4–13 ppt) are identified as the relict fauna that existed before the building of the Aswan High Dam closure and the increased freshwater discharge from the drains into the lagoon; the freshwater taxa (1–2 ppt) are part of the modern biocoenosis (Tables 1, 2 and 3). This shift of salinity measured from the cores matches the shift in water salinities in Manzala lagoon which were measured before and after High Dam closure (SHAHEEN and YOUSEF, 1978; Figure 2). These salinity measurements also match the salinity shift recorded in surface samples from the lagoon reported in REINHARDT *et al.* (1998b). This change has been the most significant salinity shift over the ~100 year record documented by the cores. The C isotopic values also record the same shift in salinity in the cores, with the lower values representative of lower salinities within the lagoon. As discussed previously, some of the variation in the C isotopes could be due to other factors such as changes in organic matter decay and productivity within the lagoon.

Core XXV, positioned close to coastal barriers and El-Gamil outlet, records salinity values that were higher (8 to >24 ppt; Figure 6D). Previously analyzed surficial sample MZ79, which was close to where Core XXV was taken, had a range of salinities of 1.5 to 22 ppt (REINHARDT *et al.*, 1998b). This salinity range is not recorded in the top interval of Core XXV as the core was located in proximity to the marine source of water entering the lagoon. The lower salinities measured in MZ79 may be due to transport of lower salinity specimens from the inner portion of the lagoon due to storm activity, or the MZ79 sample site could represent an area where seasonal salinities fluctuated more than at the Core XXV location. Alternatively, the differences between the two sites could be a sampling artifact since the area of sediment recovered by the core barrel is 3–4 times smaller than the grab sampler and thus we may have missed the lower salinity taxa in the core. There is one interval, at 21–24 cm, where salinity was lower, at ~6 ppt. This lower salinity probably represents temporary closure of the El-Gamil outlet in the late 1960's to early 1970's which reduced salinities in the lagoon (SHAHEEN and YOUSEF, 1978; reproduced in Figure 2). The C isotopes also showed no temporal pattern in the core, and did not record the slight freshening of the lagoon at the 21–24 cm interval. Since the shift in salinity was small, as recorded by Sr isotopes, the corresponding shift in C isotopes is masked by localized changes in organic matter decay and productivity as previously discussed.

Environmental Significance

Since World War II, industrialization and agriculture have increased in the Nile delta, augmenting discharge of wastewater and associated pollutants into Manzala lagoon. Nevertheless, this wetland is of vital economic importance since the fishery constitutes only 2.4% of the fishing grounds in Egypt and yet contributes ~35% of the country's fish catch (SHAHEEN and YOUSEF, 1980; WORLD BANK, 1984). Declines in fish catches since the early 1980's have been attributed to overfishing in Manzala and also possibly to increased accumulation of pollutants and eutrophication of the lagoon from increased discharge of fertilizers and organic nutrients (Ichthyopathology Center, El-Gamil, Egypt, 1990, general communication; SIEGEL, 1995; RANDAZZO *et al.*, 1998).

Since the decline of the marine fishery seaward of the delta immediately after the building of the High Dam in 1964 (SHAHEEN and YOUSEF, 1979), Manzala's annual fish catch grew to ~20–27 thousand tons due to increased fishing activity in the wetland. Marked changes in the fish populations have been documented with changes in salinity in the lagoon associated with closure of the High Dam and increased freshwater discharge into the lagoons from drains and canals (SHAHEEN and YOUSEF, 1980). Changes in invertebrate fauna in Manzala associated with increased fresh water discharge from the drains have been more difficult to quantify due to a lack of systematically collected information on living and extinct taxa, although, some studies are now being conducted (*e.g.* SAMIR, 2000). By studying the isotopic and paleontological record in cores, the data from the pre- and post-impact environment can be recovered (Tables 1–3) allowing us to gauge the effect of altered salinity on wetlands and allow us to place other pollution sources in context. The recent salinity change (1964 through sampling in 1990) within the lagoon clearly has been the most significant over the past 100 years.

SUMMARY

1. Of the three isotopic systems (Sr, C, O), Sr isotopes ($^{87}Sr/^{86}Sr$) best record salinity changes within the lagoon. The Sr isotopes in invertebrate shell material from one of the cores document a salinity drop (~3–5 ppt) within the lagoon from the pre- to post-Aswan High Dam (1964) period.

2. The main control on the C isotopes within shell material found in the lagoon is mixing of fresh and marine waters entering the lagoon; thus it is a useful paleosalinity indicator.
3. The O isotopic gradient in Manzala is the reverse of that usually encountered in an estuary, with lower salinities corresponding to higher $\delta^{18}O$ values. Waters of Manzala lagoon are 2 to 3 times enriched in $\delta^{18}O$ with respect to seawater and the $\delta^{18}O$ values from the invertebrate shells varied as a result of other effects besides salinity. Therefore, there was no distinct oxygen isotope gradient with salinity within the lagoon.
4. The major reduction of salinity in Manzala, which began about 1950, is due to a marked increase in freshwater discharge from drains and waterways into the lagoon which has caused a major change in salinity. This salinity shift has been the most significant in the lagoon over the past ~100 years, the approximate time-span recorded by the cores.
5. Combining paleontological and isotopic analyses of sediment cores holds promise for the study of anthropogenically-induced salinity changes in other deltaic systems from around the world. These core data serve to reconstruct and measure human pressure on an environment, particularly when the character of the pre-humanly impacted environment is not known.

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