# Strontium isotopic-paleontological method as a high-resolution paleosalinity tool for lagoonal environments

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## ABSTRACT

**A combined strontium isotopic ($^{87}Sr/^{86}Sr$) and paleontological method is newly applied to a modern lagoon in Egypt's Nile River delta to test its applicability as a paleosalinity proxy. Analyses of 22 surficial samples collected throughout the lagoon include 81 Sr isotopic analyses of mollusks, foraminifera, ostracods, barnacles, bryozoans, serpulid worm tubes, pore water, and gypsum crystals. Two salinity groups are distinguished in each sample: a lower salinity group (~1 ppt) mixed with a higher salinity group (~3–10 ppt) that, respectively, are interpreted as the modern biocoenosis and an older relict fauna. The relict fauna denotes higher salinity conditions in the lagoon prior to closure of the Aswan High Dam (1964), and the modern fauna records freshening of the lagoon. Recent decreased salinity is a response to regulated Nile River flow and increased discharge into Manzala of fresh water via canals and drains. Quantification of this short-term salinity change holds promise for study of modern lagoons in other world settings, and may provide paleoclimatic information for older lagoon sequences in the Nile River delta and the geologic record.**

## INTRODUCTION

Lagoon environments, typically quasi-closed coastal settings that receive water from fluvial, ground-water, and marine sources, have highly variable salinities that may range from hyposaline to hypersaline (1 to >35 ppt). The paleontological record in ancient lagoon deposits may be ambiguous with regard to salinity because many invertebrate taxa have wide tolerances to environmental factors (Dodd and Stanton, 1990, and references therein). To derive sea-level and paleoclimatic information from lagoon deposits in the geologic record, an accurate paleosalinity proxy is required. To develop such a proxy, our study of Manzala lagoon, in Egypt's northeastern Nile River delta, evaluates a combined strontium isotopic and paleontological methodology for the measurement of high-resolution salinity changes in lagoon environments (Fig. 1).

Strontium isotopes ($^{87}Sr/^{86}Sr$) have been used as a paleosalinity proxy in some marginal marine environments (Schmitz et al., 1991, 1997; Ingram and Sloan, 1992; Ingram and DePaolo, 1993; Bryant et al., 1995; Reinhardt et al., 1998b). Sr isotopes are an ideal paleosalinity proxy in these settings for several reasons. (1) Biogenic carbonates incorporate Sr isotopes in their crystal lattice during precipitation with no vital effect, recording the $^{87}Sr/^{86}Sr$ ratio of the waters in which they grew (Reinhardt et al., 1998a). (2) Typically, the Sr isotopic ratios of river waters are either higher or lower than the worldwide marine value (0.70917) and there is a simple mixing relationship between the two (Palmer and Edmond, 1989; Hodell et al., 1990; Ingram and DePaolo, 1993; Andersson et al., 1994; Bryant et al., 1995). (3) Where any diagenesis can be ruled out, deviation from this marine Sr isotopic value is the result of fresh-water dilution. The method, however, has limitations because concentration of Sr in marine waters (~8 ppm) is much higher than in fresh water (<1 ppm; Palmer and Edmond, 1989). 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 salinity gradients, which can be found in lagoonal environments. Despite numerous advantages, Sr isotopes have not been used extensively as a paleosalinity proxy in paleontological studies, and to date, the method has not been tested extensively in lagoonal environments where the method has perhaps the most potential.

**Data Repository item 9893 contains additional material related to this article.**

Since 1964, date of closure of the Aswan High Dam, there has been a significant increase of fresh water discharged from canals and drains into Manzala lagoon (Shaheen and Yousef, 1978; Randazzo et al., 1998, and references therein). The purpose of this study is to determine the salinity range in surficial deposits of this lagoon so as to independently detect this freshening and, if possible, quantify the salinity shift in the paleontological and Sr isotopic records (Fig. 1). If the method can detect and measure the anthropogenic shift induced by increased waterway discharge into the lagoon during the past 33 years, it then offers potential as a proxy for detecting short-term changes in Nile River flow in the late Quaternary and earlier geological record.

## METHODOLOGY

We analyzed 81 specimens in 22 samples, including 21 invertebrate species (Fig. 1; Table DR1[1]). Identification of various invertebrate taxa follows previously established taxonomy (Bernasconi and Stanley, 1994, and references therein). Particular attention was paid to different taxa and sedimentary components (pore waters and gypsum crystals) analyzed in two specific samples to determine the potential salinity variation and overall faunal diversity at two salinity extremes along sample transects: MZ15, near fresh-water canal discharge; and MZ79, near the coast and proximal to salt water sources (Fig. 1). On the basis of this information from these two samples (MZ15 and 79) and the ecological constraints of the taxa (i.e. marine, euryhaline, freshwater; Bernasconi and Stanley, 1994) indicator species were selected for the areal analysis of Manzala lagoon. Shell material for Sr isotopic analysis was selected based on taphonomic character and,

[1]Data Repository item 9893, Table DR1, $^{87}Sr/^{86}Sr$ results, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

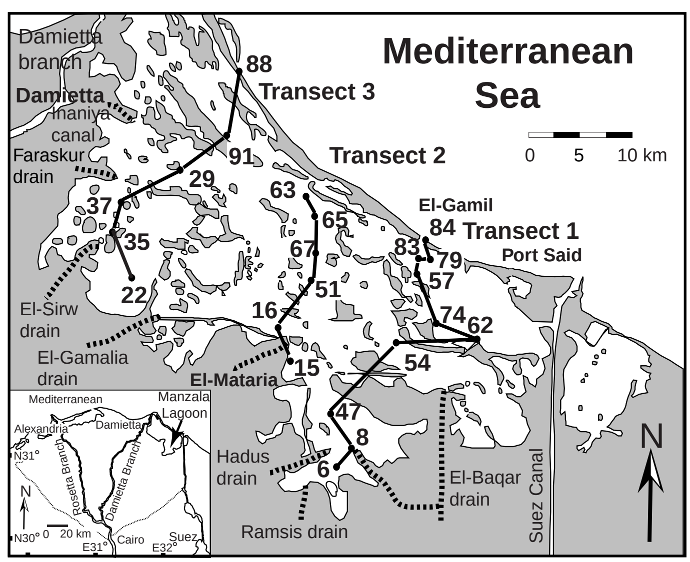


**Figure 1. Map of Manzala lagoon study area in the northeastern Nile River delta, Egypt, showing 22 sample sites positioned along three transects.**

where possible, pristine and articulated specimens were used. Material for analysis was selected across growth patterns of the shell. This entailed selecting a large sample (10–100 mg) for dissolution, 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 leached and cleaned with 0.5 *N* HCl solution. The remaining shell material was ultrasonically washed in distilled water and then dissolved in 2.5 *N* HCl solution. Pore-water values were obtained by washing sediment with distilled water and analyzing an aliquot of this solution. Clear gypsum crystals were also selected, and leached in hot HCl (125 °C) for 12 hrs. Sr separatory techniques followed standard procedures as reported in Patterson et al. (1995). Sr isotopic analysis was performed on a Finnegan MAT 261 multicollector mass spectrometer. Replicate analyses of the NBS 987 Sr standard yielded a $^{87}Sr/^{86}Sr$ ratio of $0.71025 \pm 2 \times 10^{-5}$ and a ratio of $0.70802 \pm 2 \times 10^{-5}$ for the Eimer and Amend standard. Internal precision (standard [std] deviation of the mean) for all analyses was less than $1 \times 10^{-5}$.

Salinity measurements for the analyzed taxa were determined using the mixing curve shown in Figure 2. This curve was derived via a two-component mixing equation (Andersson et al., 1994; Bryant et al., 1995) using Nile River 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 Shinkus, 1986; Hodell et al., 1990) as the two end members. The salinity detection limit at 24 ppt is based on the widely reported error on the Sr isotopic method of $\pm 2 \times 10^{-5}$ and is the point at which the deviation of the $^{87}Sr/^{86}Sr$ measurement from the seawater value can be detected (Bryant et al., 1995).

Possible errors with salinity values derived from the mixing curve could be due to variation of the isotopic content and concentration of Sr in Nile River water flowing into the lagoon, as Sr composition of river water has been known to vary by >50% (Palmer and Edmond, 1989, 1992). However, we have measured the yearly to decadal average of $^{87}Sr/^{86}Sr$ values which appear to be constant, as shown by the analyses of 17 freshwater specimens close to the sources of freshwater to the lagoon (MZ6, 8, 22, 37, 47; mean 0.707596; std $5 \times 10^{-5}$; salinity 0.9–1.2; Table DR1 [see footnote 1]; Fig. 3; Fig. 4A). The computed salinity range of these specimens fits the salinity measured in this portion of the lagoon in 1973 by Shaheen and Yousef (1978) of approximately 1.2 ppt. The analysis of biogenic carbonate from known freshwater taxa is probably a better reflection of the average riverine $^{87}Sr/^{86}Sr$ value as opposed to direct water measurements which can vary amongst tributaries in the drainage basin and over yearly seasonal changes (Bryant et al., 1995; Palmer and Edmond, 1989, 1992).

Another possible error may be introduced from the mixing relationship because it does not account for fluctuations due to evaporation or precipitation. Such losses or gains will tend to under or overestimate the salinity from Sr isotopic analyses. However, the study by Shaheen and Yousef (1978) indicates that salinity gradients in the lagoon are primarily due to mixing of fresh and marine waters, rather than to evaporation or rainfall.

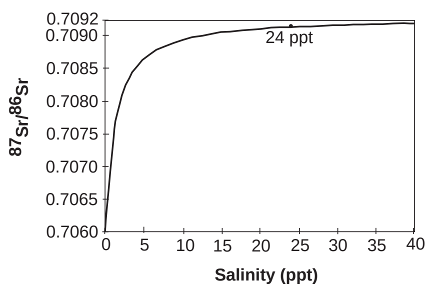


**Figure 2. Salinity mixing curve ($^{87}Sr/^{86}Sr$ ratio vs. salinity in ppt) using Sr isotopic and concentration data from Nile River (Brass, 1976) and from seawater (Emelyanov and Shinkus, 1986; Hodell et al., 1990). Salinity detection limit using Sr isotopes in Manzala lagoon is 24 ppt (see text).**

## DISCUSSION

### Within-Sample Salinity Variation

The 21 analyses in landward sample (MZ15), positioned near the southern marshes and fresh-water outlets, showed a wide range of salinity values, ranging from ~1.0 to 8.5 ppt (Fig. 3). Although specific individuals could not be dated, two groups are recognized (T-test: t = 4.6, d.f. = 6, significant at the 0.3% level): A, which comprises low-salinity taxa (~1–1.8 ppt) having low variability and B, characterized by higher and more highly variable salinity taxa, ranging from 2.4 ppt to 8.5 ppt. Most of the fauna in less-saline group A are known freshwater taxa and are commonly articulated with their periostracum intact and are generally better preserved than those of group B suggesting that these specimens were either alive during collection or not long dead.

Various taxa living in the same salinity regime would be expected to record nearly similar to identical $^{87}Sr/^{86}Sr$ values. However, analysis of shells of different species in a single sample shows that they do not record the same values. Because there is no reason to believe that the data record a seasonal event, as most molluscan taxa (fresh, brackish, and marine) have a similar growing season (Rhoads and Lutz, 1980), we interpret less-saline group A as the modern living biocoenosis and B as the relict fauna. This interpretation is in accord with previous studies that have indicated recent freshening of the lagoon. Our salinity values for the two groups (A, 1.0 to 1.8 ppt; B, mostly 2.5 to 5 ppt) derived by Sr isotopes match salinities measured in this section of the lagoon in pre- and post-Aswan High Dam closure periods (4.1 to 1.6 ppt; Shaheen and Yousef, 1978, and references therein). The sediment that has accumulated in the lagoon since 1964 is approx. 26–30 cm, measured by $^{210}Pb$ and fission product radionuclides (Benninger et al., 1998). Based on this relatively shallow depth and the fact that intense bioturbation was observed in X-ray radiographs of short cores taken from the lagoon, the two groups were homogenized through bioturbation mixing the pre- and post-1964 shell material (Flessa et al., 1993; Bernasconi and Stanley, 1994).

The pore-water value of 1.8–1.9 ppt is intermediate between values of groups A and B, and suggests mixing between uppermost modern less saline and underlying older more saline pore waters, perhaps through bioturbation.

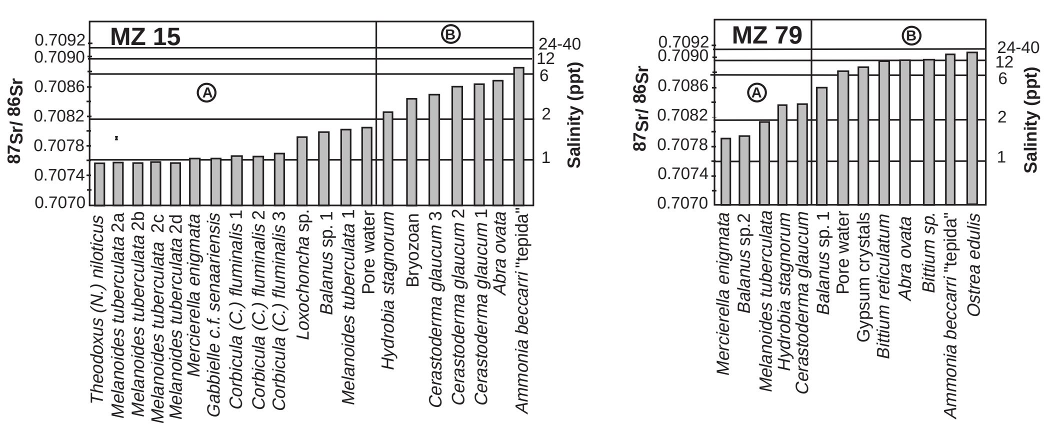


**Figure 3. Distribution of $^{87}Sr/^{86}Sr$ values and corresponding salinities of taxa and other components in two Manzala lagoon samples (see Fig. 1). Low-salinity taxa (group A) and higher salinity taxa (group B) are distinguished (see text). Error bar at 2σ ($\pm 2 \times 10^{-5}$) shown in MZ15 group A is applicable to all Sr ratios.**

Of note in MZ15 is a byrozoan attached to a barnacle (*Balanus* sp.1) that, in turn, is attached to a *Cerastoderma glaucum* shell (Fig. 4B); separate analyses of each indicate that the three organisms grew in different salinity regimes.

The 13 analyses in sample MZ79, positioned close to coastal barriers and El-Gamil outlet, also show a wide range of salinity values (1.5 to 22.0 ppt; Fig. 3). Two salinity groups are identified (T-test: $t = 4.9$, d.f. $= 7$, significant at the 0.3% level): A comprises lower salinity taxa (1.5 to 3.0 ppt); and B includes more saline values (4.0 to 22.0 ppt). The distribution and variation of salinity values in this sample differ from those in sample MZ15: Group A is more variable, and group B is more constant. Because this sample was proximal to the sea, the site location may occupy a transitional area where the assemblage may have been influenced by a lower salinity front that fluctuated on a yearly basis, and/or some of the lower salinity specimens may have undergone some lateral displacement. The low-salinity taxa may also be due to a temporary closure of El-Gamil outlet in the late 1960s to early 1970s, which lowered salinities in the lagoon (Shaheen and Yousef, 1978). The pore-water value in this sample is 6.7 to 7.4 ppt, or considerably higher than that in MZ15, as would be expected at a site influenced by more marine conditions; moreover, the value is transitional between the two extreme salinity values recorded by groups A and B.

**Spatial Salinity Variation in the Lagoon**

Several species that record salinity extremes in samples MZ15 and MZ79 were selected for spatial analysis of Manzala lagoon and the same two salinity trends were observed in the three transects (Fig. 5). Lower salinity taxa, typical of group A (*C. fluminalis* and *M. tuberculata*), occur in all southern sections of transects, and all samples contain taxa that indicate elevated salinities, typical of group B (primarily *C. glaucum* and *Abra ovata)*. The coexistence and widespread distribution of taxa groups A and B are interpreted as a time-averaged assemblage that records the lower salinity shift in the lagoon due to the increased fresh-water discharge after the closure of the Nile River by the Aswan High Dam in 1964.

The Sr isotopic method provides high-resolution salinity measurements for this lagoon that cannot be derived from paleontological data alone (Bernasconi and Stanley, 1994). Numerical data provide a means to infer salinity conditions in the wetland prior to the Aswan High Dam closure, quantify conditions at present, and enable some salinity predictions to be made for the future (Fig. 6). From the majority of the sample stations, it appears that there has been a 2 to 6 ppt shift to less-saline conditions (now to ~1.0 ppt) from before and after 1964; this finding matches salinity changes reported by Shaheen and Yousef (1978) of 1.4 to 6.9 ppt within Manzala (Fig. 6).

Taking into account the marked annual decrease in lagoon area, associated with a large and fairly constant input of fresh water from canals and drains, we expect that (1) the low-salinity front will move farther northward to near the southern margin of the barrier ridges, and (2) the volume of less-saline water discharged seaward through El-Gamil outlet will increase substantially (Fig. 6; Randazzo et al., 1998).

The range of salinity values for two of the most abundant fresh-water species (*M. tuberculata, C. fluminalis*) and two euryhaline species (*A. ovata, C. glaucum*), listed in Table 1, will be of use in future studies. Results herein confirm previously established low-salinity tolerances of the two fresh-water species, as shown by low mean salinity measurements and standard deviations. In contrast, the more euryhaline species have correspondingly higher mean salinities and deviations.

**CONCLUSIONS**

Study of surficial Manzala deposits shows the potential of a combined Sr isotopic-paleontological method for determination of paleosalinity in a modern lagoon. The method is useful from an ecological perspective because it facilitates determination of salinity constraints for a wide variety of taxa. Sr isotopes allow the impact of salinity to be isolated from other ecological parameters such as temperature, oxygen content, and substrate type. In addition, the method may be of use in taphonomic studies, because it can serve to distinguish mixed relict and modern faunas. Species examined in this study

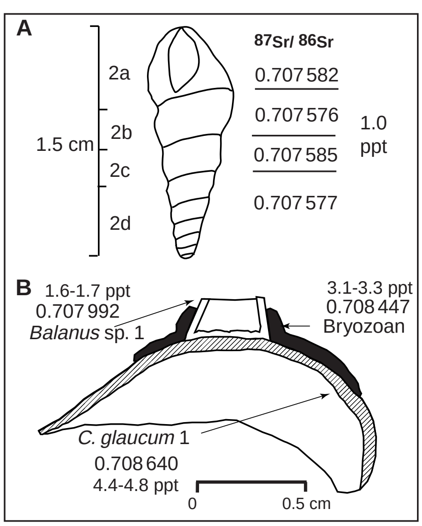


**Figure 4. A: Homogeneous distribution of four $^{87}Sr/^{86}Sr$ values in one shell of *M. tuberculata*. B: Variable distribution of $^{87}Sr/^{86}Sr$ values, and corresponding salinities, for two organisms encrusted on *C. glaucum* shell.**

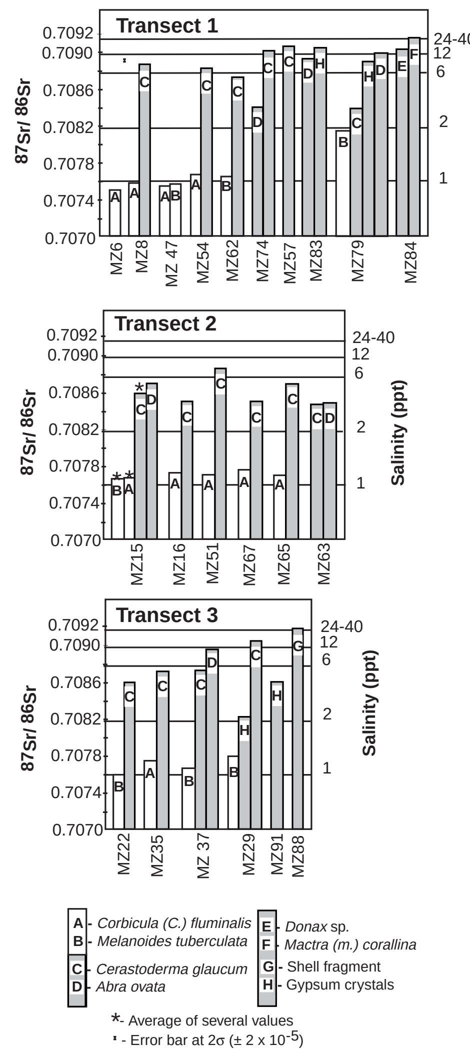


**Figure 5. Distribution of $^{87}Sr/^{86}Sr$ values and corresponding salinities in 22 samples along three transects (see Fig. 1) showing the clear separation between low (white bars) and higher (gray bars) salinity measurements made at each lagoon sample site. Error bar, shown for transect 1, is applicable to all Sr ratios.**

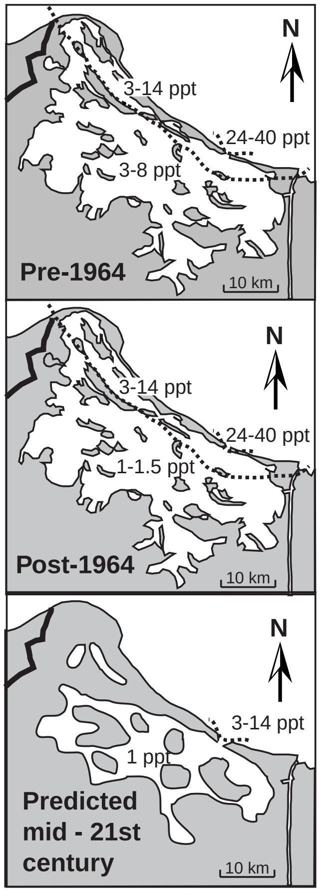


**Figure 6. Salinity gradients within Manzala lagoon, based on Sr isotopic data from this study, shown for pre- and post-1964 Aswan High Dam closure and predicted for mid-21st century.**

TABLE 1. SUMMARY DATA

| Taxa | Mean $^{87}Sr/^{86}Sr$ | Std dev | Salinity (ppt) | Max (ppt) | Min (ppt) | Variability (ppt) |
|---|---|---|---|---|---|---|
| *Corbicula (C.) fluminalis* | 0.707667 | 0.000076 | 1.2 | 1.2 | 1.0 | 0.2 |
| *Melanoides tuberculata* | 0.707702 | 0.000199 | 1.2 | 1.5 | 0.9 | 0.6 |
| *Abra ovata* | 0.708753 | 0.000264 | 5.8 | 13.3 | 3.4 | 9.9 |
| *Cerastoderma glaucum* | 0.708702 | 0.000198 | 5.2 | 8.6 | 3.5 | 5.1 |

Note: Std dev - standard deviation, Max - maximum, Min - minimum.

are generally abundant in lagoon environments and are cosmopolitan, and thus it is likely that the strontium isotopic-paleontological method could be applied effectively to other lagoons with different salinity regimes.

With regard to Manzala, findings in this study confirm the shift in salinity during a period of less than three decades following the construction of the Aswan High Dam. This temporal resolution holds promise for the study of older lagoonal sequences recovered in Nile River delta long cores (Coutellier and Stanley, 1987), where it may provide a paleoclimatic proxy indicating changes in Nile River discharge in the late Quaternary. The method also shows potential as a salinity proxy for modern lagoon settings in other regions, and for ancient analogs in the geologic record.

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## REFERENCES CITED

Andersson, P. S., Wasserburg, G. J., Ingri, J., and Stordal, M. C., 1994, Strontium, dissolved and particulate loads in fresh and brackish waters: The Baltic Sea and Mississippi Delta: Earth and Planetary Science Letters, v. 124, p. 195–210.

Benninger, L. K., Suayah, I. B., and Stanley, D. J., 1998, Manzala lagoon, Nile delta, Egypt: Modern sediment accumulation based on radioactive tracers: Environmental Geology, v. 31, p. 112–134.

Bernasconi, M. P., and Stanley, D. J., 1994, Molluscan biofacies and their environmental implications, Nile delta lagoons, Egypt: Journal of Coastal Research v. 10, p. 440–465.

Brass, G. W., 1976, The variation of the marine $^{87}Sr/^{86}Sr$ ratio during Phanerozoic time: Interpretation using a flux model: Geochimica et Cosmochimica Acta, v. 40, p. 721–730.

Bryant, J. D., Jones, D. S., and Mueller, P. A., 1995, Influence of freshwater flux on $^{87}Sr/^{86}Sr$ chronostratigraphy in marginal marine environments and dating of vertebrate and invertebrate faunas: Journal of Paleontology, v. 69, p. 1–6.

Coutellier, V., and Stanley, D. J., 1987, Late Quaternary stratigraphy and paleogeography of the eastern Nile delta, Egypt: Marine Geology, v. 77, p. 257–275.

Dodd, J. R., and Stanton, R. J., 1990, Paleoecology concepts and applications: New York, John Wiley and Sons, 502 p.

Emelyanov E. M., and Shinkus K. M., 1986, Geochemistry and sedimentology of the Mediterranean Sea: Reidel, 553 p.

Flessa, K. W., Cutler, A. H., and Meldahl, K. H., 1993, Time and taphonomy: Quantitative estimates of time-averaging and stratigraphic disorder in a shallow marine habitat: Paleobiology, v. 19, p. 266–286.

Hodell, D. A., Mead, G. A., and Mueller, P. A., 1990, Variation in the strontium isotopic composition of seawater (8 Ma to present): Implication for chemical weathering rates and dissolved fluxes to the oceans: Chemical Geology, v. 80, p. 291–307.

Ingram, B. L., and Sloan, D., 1992, Strontium isotopic composition of estuarine sediments as paleosalinity-paleoclimate indicator: Science, v. 255, p. 68–72.

Ingram, B. L., and DePaolo, D. J., 1993, A 4300 year strontium isotope record of estuarine paleosalinity in San Francisco Bay, California: Earth and Planetary Science Letters, v. 119, p. 103–119.

Palmer, M. R., and Edmond, J. M., 1989, The strontium isotopic budget of the modern ocean: Earth and Planetary Science Letters, v. 92, p. 11–26.

Palmer, M. R., and Edmond, J. M., 1992, Controls over the strontium isotope composition of river water: Geochimica et Cosmochimica Acta, v. 56, p. 2099–2111.

Patterson, R. T., Blenkinsop, J., and Cavazza, W., 1995, Planktic foraminiferal biostratigraphy and $^{87}Sr/^{86}Sr$ isotopic stratigraphy of the Oligocene-to-Pleistocene sedimentary sequence in the southeastern Calabrian microplate, southern Italy: Journal of Paleontology, v. 69, p. 7–20.

Randazzo, G., Stanley, D. J., Di Geronimo, S. I., and Amore, C., 1998, Human-induced sedimentological changes in Manzala lagoon, Nile delta, Egypt: Environmental Geology, v. 31 (in press).

Reinhardt, E. G., Blenkinsop, J., and Patterson, R. T., 1998a, Assessment of a Sr isotope ($^{87}Sr/^{86}Sr$) vital effect in marine taxa from Lee Stocking Island, Bahamas: Geo-Marine Letters, v. 18 (in press).

Reinhardt, E. G., Patterson R. T., Blenkinsop, J., and Raban, A., 1998b, Paleoenvironmental evolution of the Inner Basin of the Ancient Harbor at Caesarea Maritima, Israel; Foraminiferal and Sr isotopic evidence: Revue de Paléobiologie, v. 17(1) (in press).

Rhoads, D. C., and Lutz, R. A., eds., 1980, Skeletal growth of aquatic organisms: Biological records of environmental change: New York, Plenum Press, 750 p.

Schmitz, B., Åberg G., Werdelin, L., Forey, P., and Bendix-Almgreen, S. E., 1991, $^{87}Sr/^{86}Sr$, Na, F, Sr, and La in skeletal fish debris as a measure of the paleosalinity of fossil-fish habitats: Geological Society of America Bulletin, v. 103, p. 786–794.

Schmitz, B., Ingram, S. L., Dockery, D. T., III, and Åberg, G., 1997, Testing $^{87}Sr/^{86}Sr$ as a paleosalinity indicator on mixed marine, brackish-water and terrestrial vertebrate skeletal apatite in late Paleocene-early Eocene near-coastal sediments, Mississippi: Chemical Geology, v. 140, p. 275–287.

Shaheen, A. H., and Yousef, S. F., 1978, The effect of the cessation of Nile flood on the hydrographic features of Lake Manzala, Egypt: Archiv für Hydrobiologie, v. 84, p. 339–367.

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