Revised version of Ms. Ref. No.: EPSL-D-07-00458 Strontium stable isotopes fractionate in the soil environments?

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Abstract

This study shows that the stable isotopic composition of strontium (the ⁸⁸Sr/⁸⁶Sr ratio expressed as $\delta^{88/86}$ Sr value relative to the NBS987 standard) varies significantly in sedimentary terrestrial environments. The abundances of ⁸⁶Sr, ⁸⁸Sr isotopes were analyzed by MC-ICP-MS "Nu Plasma". All studied rocks and waters show $\delta^{88/86}$ Sr values that are distinctly different from the measured NBS987 standard (yielding 0.01±0.05 ‰, all errors are reported as 2σ). Modern corals from the northern Gulf of Aqaba, Red Sea yielded significantly different value then seawater ($\delta^{88/86}$ Sr=0.22±0.07 ‰, compared to 0.35±0.06 %, respectively), in an excellent correlation with the $\delta^{88/86}$ Sr analyses reported by Fietzke and Eisenhauer (2006) on other coral samples. All carbonate samples that originated in the marine environment: corals (*porites* and *acropora* from the northern Gulf of Aqaba); Cretaceous limestone and runoff from the Judea Mountains as well as lacustrine evaporitic aragonite (Dead Sea); and Red Sea and Atlantic seawater yield an average $\delta^{88/86}$ Sr value of 0.26±0.1‰. On the other hand, secondary materials (products of chemical weathering) from the terrestrial environment of the Judea Mountain such as terra rossa soil and speleothem calcite (that derives its Sr from the above-lying soil) yielded significantly lower $\delta^{88/86}$ Sr value of -0.17±0.06‰. This indicates that strontium isotopes fractionate in the soil environment calling for a possible development of strontium isotopes as a tracer for processes of chemical weathering and pedogenesis.

1. Introduction

Strontium isotopes (⁸⁸Sr, ⁸⁷Sr, ⁸⁶Sr and ⁸⁴Sr) have been widely applied in geosciences both as chronological and petrogenetic tools (e.g. Faure, 1986), where the radiogenic isotope ⁸⁷Sr (decay of ⁸⁷Rb) was normalized to ⁸⁶Sr. The ⁸⁸Sr, ⁸⁶Sr and ⁸⁴Sr isotopes were used to correct for instrumental fractionation in TIMS analyses. However, the new developments in MC-ICP-MS analyses demonstrated the potential of analyzing very small differences among the "non traditional stable isotopes" of elements such as calcium, magnesium and iron (cf. Halicz et al. 1999, Galy et al. 2001 and 2002, Albarede and Beard, 2004, Fietzke et al., 2004). Recently, Fietzke and Eisenhauer (2006) reported on temperature dependent fractionation in the stable isotopes of strontium (⁸⁸Sr versus ⁸⁶Sr) in biogenic aragonite of the coral *pavona clavus* and to a lesser extent in chemical aragonite, precipitated in a temperature controlled experiment. Fractionation of the stable strontium isotopes between

seawater and marine carbonates (coral and giant clam) was also reported by Ohno and Hirata (2006). These discoveries stimulated the idea that the ⁸⁸Sr/⁸⁶Sr ratio can vary among different geological environments where strontium concentration (e.g. Sr/Ca ratio) and strontium isotopes have been widely used in the petrological-geochemical interpretation. Here, we examine the possibility that rocks from several representative marine and terrestrial environments in the vicinity of Israel underwent strontium isotope fractionation producing different ⁸⁸Sr/⁸⁶Sr ratios. These environments include: the coral reefs at the northern Gulf of Aqaba, Red Sea; the lacustrine hypersaline environment of the Dead Sea basin; the Cretaceous shallow marine environment where limestones and dolomites deposited; and the terrestrial environment of Judea Mountains where caves speleothem precipitate and terra rossa soil accumulate. We also analyze desert dust loess material, which derived some of its mineralogical components from crustal rocks (e.g. the late Proterozoic Pan African granites in North Africa). Thus, we cover a wide range of terrestrial and marine environments, which represent a wide range of depositional conditions differing in temperature, salinity, ionic composition, pH, etc.

2. Materials and Methods

2.1. Sample selection

Several geological samples from the above mentioned geological environments were selected for MC-ICP-MS strontium isotope analyses. Our sampling strategy was to select waters and rocks (e.g., runoff water, desert dust) constituting "large geological samplers" that average large volumes of various marine and terrestrial geological environments.

(1) Nine biogenic aragonite samples recovered by drilling from a *porites lutea* coral head located in the nature reserve off the shore of the Interuniversity Institute for Marine Sciences (IUI), Elat, northern Gulf of Aqaba, Red Sea. This coral was previously analyzed for its oxygen isotope and elemental ratios (Sr/Ca, Mg/Ca and U/Ca) that showed annual fluctuations (Enmar et al., 2000; Lazar et al., 2004). For the present study we selected coral sites that display large variation in Sr/Ca ratios, without going into the interpretation of these changes (e.g., temperature or subtle diagenetic effects, see Enmar et al., 2000). We mainly aimed at examining possible fractionation of the "non traditional" Sr isotopes with varying Sr/Ca ratios.

- (2) Primary evaporitic aragonite was sampled from the lacustrine Lisan Formation. The aragonite was deposited from the saline Lake Lisan - the last glacial (70-14 ka) precursor of the Dead Sea (cf. Haase-Schramm et al., 2004) and was sampled at the PZ1 section at Perazim valley, SW of the current Dead Sea. The Lisan aragonites yielded ⁸⁷Sr/⁸⁶Sr ratios reflecting the mixing between groundwater from the carbonate aquifers and runoff water from the Judea desert draining mainly Cretaceous carbonates (Stein et al., 1997).
- (3) Calcitic limestone material from the Cretaceous Judea Group (the Netzer Formation) that was apparently deposited in the shallow marine environment and epigenetic dolomite formed by interaction of evaporated seawater. The limestone yielded ⁸⁷Sr/⁸⁶Sr ratio of 0.7074 consistent with the Cretaceous seawater (Stein et al., 2000).
- (4) Groundwater and runoff draining Cretaceous limestones and dolomites and Senonian chalks and surface cover (e.g. dust) of the Judea Mountain. The runoff and groundwater provide a "regional sampler" of the Mesozoic carbonate terrains.
- (5) Calcitic speleothem material from two Pleistocene caves (Sorek and Qesem) in the Judea Mountains (Bar-Matthews et al., 2003) and the terra rossa representing the soil covering the caves. The terra rossa soil is composed of quartz grains of eolian origin and clays (Yaalon and Dan, 1967). The grains are coated by iron oxides, reflecting the pedogenesis process. Frumkin and Stein (2004) suggested that terra rossa soil accumulated above the cave cap rock is the source of strontium to the speleothem. The soil is characterized by ⁸⁷Sr/⁸⁶Sr isotope ratio of ~0.7087 on the high side of the speleothem range (0.7078-0.7084).
- (6) Loess sample from the northern Negev desert. The loess represents desert dust material composed mainly of quartz and calcite grains (Yaalon and Dan, 1967). The loess can be considered as a "large sampler of continental crust". It was blown to the region during the last glacial period, probably from dried accumulation basins in Africa and Arabia (e.g., Prospero et al., 2000).
- (7) Seawater samples from the Atlantic (the international standards NASS-4 and IAPSO) and the Indian Oceans (GOA-1).

2.2. Chemical and isotope analytical methods

All abovementioned samples were crushed to fine powder, carbonate sample were dissolved in 1 N nitric acid (Spectra grade, Baker) and silicate samples were dissolved in mixture of concentrated acids (HF, HNO₃ and HCl – Spectra grade Baker). The recovery of Sr in acids dissolution procedure was >98% compared to total decomposition by lithium metaborate melt. The samples from decomposition methods were analyzed for Sr by ICP-AES with Sc as internal standard. Separation of Sr from matrix was done using a column containing the Eichrom-Sr-spec (50-100 mesh) resin. The matrix was rinsed with 3.5N HNO₃ and strontium was eluted with 0.05 N HNO₃. The recovery of Sr in this procedure was >98% (Sr analysis before and after separation was conducted by ICP-AES).

Precise analysis of isotope ratios by MC-ICP-MS requires addressing the problem of matrix effect. This topic was investigated for precise isotope ratio measurement of light and heavy elements such as Mg (Galy et al. 2001), Cu (Ehrlich et al. 2004), Pb (Ehrlich et al. 2001b) and Sr (Ehrlich et al. 2001a). To avoid the matrix effect problem rigorous matrix separation must be done. Thus, we analyzed all our samples (solids as well as solutions like seawater) after column separation. The calcium concentration in the eluted solutions was very low (generally <20 ppb) and the maximum concentration of all other elements like Mg, Na, Al, Fe, Ba and Rb was ~ 1 ppb (analyses were done using ICP-MS – Sciex Perkin Elmer DRC II). This ensured that the matrix of the standard (NBS987) was the same as that of the samples. Equal matrix effect for standards and samples is a mandatory condition when using bracketing method for the isotopic analysis (Ehrlich et al., 2001a and 2004). The need of an exact concentration matching between standards is somewhat ambiguous, it is either considered to be critical for obtaining a reliable analysis (Zhu et al., 2002) or not (Fietzke and Eisenhauer, 2006). Our experience with the problem showed that exact concentration matching is important, therefore we took special care to adjust the concentrations of the acid and matrix in standards and samples.

2.2.1. Mass Spectrometry

The work was carried out using MC-ICP-MS instrument "Nu Plasma" (Nu Instruments, Wrexham, UK fitted with Aridus sample introduction system). Five Faraday collectors were used for measurement of following isotopes: ⁸³Kr, ⁸⁵Rb ⁸⁶Sr, ⁸⁷Sr and ⁸⁸Sr. ⁸³Kr was measured in order to correct interference of ⁸⁶Kr

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(⁸⁶Kr=1.52·⁸³Kr, IUPAC table value) with the ⁸⁶Sr peak, due to the Kr contamination of the argon gas. The ⁸⁷Sr was measured for estimating the effect of fractionation on the determination of the traditional ⁸⁷Sr/⁸⁶Sr ratio of in the samples when using the table ratio of ⁸⁶Sr/⁸⁸Sr (0.1194 Steiger and Jäger 1977) and exponential law for instrumental mass bias correction.

⁸⁵Rb was measured in order to correct ⁸⁷Rb interference. ⁸⁷Rb was calculated from the ratio ⁸⁷Rb=0.3860^{.85}Rb, after mass discrimination correction using the exponential law (Ehrlich et al., 2001).

Each measurement comprised three blocks; each block consisted of 28 measurements of 10 seconds integration time. The zero reference points were reset simultaneously for all measured masses by deflecting the potential of the electrostatic analyzer before each block measurement. The background of 0.1 N HNO₃ for masses 85, 87 and 88 was lower than 0.1-0.2 mV and on-peak zero correction was not necessary. The optimum ⁸⁸Sr concentration was 0.1-0.2 mg·L⁻¹, giving sensitivity of ~50-70 V·ppm⁻¹.

Mass discrimination for Sr isotopes in the MC-ICP-MS is $\sim 2.5 \ \% \ u^{-1}$ and was monitored with reference to an external Sr isotope standard using the standard-sample-standard bracketing technique.

The data are expressed by the $\delta^{88/86}$ Sr notation relatively to pure strontium carbonate standard NBS987 (Fietzke and Eisenhauer, 2006):

$$\left(\delta^{88/86} \mathrm{Sr} = \left(\frac{\left(\frac{88}{86} \frac{\mathrm{Sr}}{\mathrm{Sr}}\right)_{\mathrm{samp}}}{\left(\frac{88}{6} \frac{\mathrm{Sr}}{\mathrm{Sr}}\right)_{\mathrm{NBS987}}} - 1\right) \cdot 1000\right)$$

 $\delta^{88/86}$ Sr_{NBS987} is the average of two NBS987 measurements conducted before and after each particular sample (bracketing). Precision (2 σ) for $\delta^{88/86}$ Sr_{std} is ±0.05‰, where the standard value ($\delta^{88/86}$ Sr_{std} = 0.01, see Table 1) was calculated as "unknown sample" bracketed by two measurements of the same standard. The $\delta^{88/86}$ Sr value of the IAPSO seawater standard was determined to be 0.35±0.10 ‰ (N=15) where the error represents the external reproducibility (2 σ) over a period of five months.

3. Results

All results are listed as $\delta^{88/86}$ Sr in Table 1 and precision is expressed as 2σ . The averages of our results for $\delta^{88/86}$ Sr of seawater and modern corals (relative to NBS987) correlate well with the values reported by Fietzke and Eisenhauer (2006) for the similar samples (Figure 1) with an apparent slope of 1.1. Given the rather large variance on the results (part of the variance stems from a natural variability among samples, e.g. temperature dependence of the $\delta^{88/86}$ Sr value in corals) the 1.1 slope represents a good analytical match between two independent laboratories. This result supports the validity of the analyses and the $\delta^{88/86}$ Sr values reported by both laboratories and hence corroborate our findings that stable Sr isotopes do fractionate in the soil environment as outlined below.

3.1. Modern corals

 $δ^{88/86}$ Sr values of the *Porites* coral samples from the Gulf of Aqaba (average of 0.22±0.07) show no relation with Sr/Ca (9.62-9.96 mmol·mol⁻¹, see Table 1). Seawater from the Gulf of Aqaba yielded a $δ^{88/86}$ Sr value of 0.31± 0.14, within the 2σ range of the coral value but plots slightly higher. It appears however that our average $δ^{88/86}$ Sr value for seawater (0.35±0.06 average for Gulf of Aqaba and Atlantic, see Table 1) is higher than the value of the corals and beyond the 2σ range. This result could indicate an enrichment of the lighter isotope in the coral relative to seawater, which is in accordance with the general expectation from the Ca-isotope system where in general the precipitate is enriched in the light isotope relative to the bulk solution (Halicz et al. 1999; Skulan et al., 1997, Skulan and DePaolo, 1999 ; Zhu and Macdougal, 1998). Nevertheless, the variations we find are small and many more seawater analyses (from different oceanic locations) are needed to verify this statement.

3.2. Mesozoic and Cenozoic marine carbonates

The Cretaceous Judea limestone, and the Pleistocene Lisan evaporitic (primary) aragonite yielded $\delta^{88/86}$ Sr values that are similar but somewhat higher than those of the recent aragonitic corals 0.27 ± 0.16 to 0.37 ± 0.08 ‰ compared to 0.22 ± 0.08 ‰, respectively, Table 1 and Figures, 2 and 3). Strontium in the Lisan aragonite was deposited from the lake water, which is a terminal trap for a large drainage area (e.g. the lake derived its water from the paleo-Jordan river originating in the Jurassic carbonatic aquifers of Mount Hermon and runoff draining the carbonatic Judea Mountains (Stein et al. 1997)). Thus, all marine or lacustrine samples that

derive their strontium from Mesozoic and Cenozoic marine carbonate rocks in the vicinity of Israel yielded $\delta^{88/86}$ Sr values similar to that of seawater. We note, however, that if $\delta^{88/86}$ Sr of Modern carbonates is lower than that of Modern seawater (see above) this could be also the case for Mesozoic carbonates as compared to Mesozoic seawater (Figure 3).

3.3. Terrestrial samples

The terrestrial samples of the calcitic speleothem and the terra rossa soil (Table 1 and Figure 2) yielded $\delta^{88/86}$ Sr values of -0.17±0.06 ‰, which are distinctly lower than those of the marine carbonates. In contrast, the loess sample yielded $\delta^{88/86}$ Sr similar to the marine carbonate values (Table 1).

3.4 Implications for ⁸⁷Sr/⁸⁶Sr analyses

The significant difference between the ⁸⁶Sr/⁸⁸Sr ratio of the NBS987 standard (the IUGS value = 0.1194, Steiger and Jäger 1977) and the ⁸⁶Sr/⁸⁸Sr ratio shown by all analyzed samples could have an effect on the calculated fractionation factor and thus on the corrected value of the ⁸⁷Sr/⁸⁶Sr ratio. For example, in the standard seawater IAPSO (OSIL Hampshire UK) the ⁸⁷Sr/⁸⁶Sr isotope ratio is 0.709238±0.000006 (GSI laboratory) as determined by using the IUGS value of ⁸⁶Sr/⁸⁸Sr = 0.1194. Using the $\delta^{88/86}$ Sr value determined here for NBS987 (0.35‰) yields a modern seawater ⁸⁷Sr/⁸⁶Sr ratio of 0.709364±0.000012, which is similar to the value reported by Eisenhauer et al., 2007). In the speleothems the ⁸⁷Sr/⁸⁶Sr ratio would change by 0.7x10⁻⁴ from 0.708440±0.000012 to 0.708368±0.000012. However, the similarity in the $\delta^{88/86}$ Sr values of most marine Mesozoic and Cenozoic samples as well as the loess implies that among carbonates such corrections should be considered so far only when comparing high-precision strontium records from the marine and terrestrial-diagenetic environments, such as that of the terra rossa soil.

4. Fractionation of Sr isotopes in the marine and terrestrial environment

Our analyses indicate very small or no variations in $\delta^{88/86}$ Sr values of waters and solids that were either directly formed in the marine environment, relicts of marine rocks or their dissolved products. The *porites* and *acropora* corals from the Gulf of Aqaba yielded $\delta^{88/86}$ Sr values that lie at the low side of the range of modern seawater (Figure 3), which is consistent with earlier study of Fietzke and Eisenhauer, (2006 and Figure 3). However, while Fietzke and Eisenhauer (2006) found an apparent correlation between $\delta^{88/86}$ Sr and Sr/Ca ratios (applied as temperature proxy), the Gulf of Aqaba corals show no clear relation to the large variations in the Sr/Ca ratio (Table 1).

Considering the possible small shift between the Modern seawater and Modern corals as mentioned above (Figure 3), one could envisage that also during the Mesozoic $\delta^{88/86}$ Sr values of seawater were slightly higher than those of their contemporaneous carbonates. This would imply that $\delta^{88/86}$ Sr in the Mesozoic oceans was slightly higher than the Cenozoic values. On the other hand, if the $\delta^{88/86}$ Sr isotopic shift in primary carbonates is temperature dependent (see in Figure 3 the direction of the trend observed by Fietzke and Eisenhauer, 2006), than the $\delta^{88/86}$ Sr of Mesozoic carbonates may reflect their deposition in a warm ocean (e.g. Veizer et al. 1999). However, in view of our $\delta^{88/86}$ Sr analyses of Red Sea coral (Table 1), the possible relation between $\delta^{88/86}$ Sr and seawater temperature requires additional study.

The $\delta^{88/86}$ Sr values of most geological materials we analyzed for the study (Table 1 Figures 2, 3) were remarkably uniform with minute fluctuations. The materials included: 1. Carbonates deposited in extremely variable depositional environment such as the shallow marine environments of the Cretaceous seas and the hypersaline conditions in lacustrine environment of the Dead Sea basin; 2. carbonates processed by the hydrological cycle and water-rock interaction such as the rain-groundwater-marine carbonate rock interaction that produced the Mount Hermon groundwater, draining Jurassic limestones and the Judea Mountains runoff draining Cretaceous limestones (both eventually feeding the Dead Sea-Lake Lisan lacustrine system, see Figure 2); and 3. Loess that was possibly transported from accumulation basins in the Sahara Desert during the last glacial period (Frumkin and Stein, 2004 and references there). The loess contains both silicate (mainly quartz grains representing crustal material) and carbonate minerals, and is a product of a long evolutionary path. Yet, no substantial fractionation in its stable strontium isotope composition is observed.

The only materials that do show significant fractionation of $\delta^{88/86}$ Sr relative to seawater and marine carbonate ($\delta^{88/86}$ Sr~0.32‰) were the cave-speleothem and the terra-rossa soil ($\delta^{88/86}$ Sr=-0.17‰, Figure 3). The terra rossa composed mainly of clays

and quartz grains (originated from desert dust) and contains iron oxides provided the strontium to the speleothem-carbonate (Frumkin and Stein, 2004). We speculate that these soil formation processes were responsible for the strontium isotope fractionation.

While, a thorough study of the strontium behavior in the terra rossa and other soils, is certainly requires, this result clearly indicates that stable strontium isotopes can be used as a new tracer of geochemical (e.g. soil production?) processes within the terrestrial environment. Moreover, since the speleothem can provide long datable records of the late Pleistocene time and contributions of dust material (e.g. Ayalon et al. 1999; Bar-Matthews et al. 2003; Frumkin and Stein, 2004), stable strontium isotopes in the speleothem can be used to trace soil production processes in high–chronological resolution throughout the late Pleistocene period.

5. Summary

- The δ^{88/86}Sr value of Modern seawater (0.35±0.06‰) is slightly higher than that of Modern corals (0.22±0.07‰).
- 2. The average $\delta^{88/86}$ Sr values of carbonates formed in various Jurassic, Cretaceous and Pleistocene marine and lacustrine environments lie in a narrow range (0.28±0.13‰) that is slightly but insignificantly below the value of Modern seawater. It appears that the strontium isotopes in the carbonates are almost not affected by the geochemical conditions in these environments or by the hydrological cycle (e.g. rain-runoff-evaporation).
- 3. It is possible that $\delta^{88/86}$ Sr Mesozoic seawater was higher than that of Modern seawater. These relations should be verified in future analyses of additional samples.
- 4. Terra rossa soil yielded $\delta^{88/86}$ Sr value of -0.17±0.06 ‰, which is distinctly different from all marine–carbonate derived samples. This may indicate that secondary sedimentary processes (e.g. soil pedogenesis) induce significant strontium fractionation. Thus, $\delta^{88/86}$ Sr can be developed as a new geochemical tracer to secondary sedimentary processes in the terrestrial environment.

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Figure captions

Figure 1. Correlation between $\delta^{88/86}$ Sr analyses conducted in this study (samples analyzed NBS987 standard, modern corals and standard seawater) and the analyses conducted by Fietzke and Eisenhauer (2006) on similar samples. The correlation between the two laboratories is very good yielding a slope of 1.1 (see text). The 1:1 relation between the two measurements is shown by the dashed line.

Figure 2. A W-E schematic traverse crossing the Mediterranean-Judea Mountain– Dead Sea rift showing the locations of various carbonate samples used in this study. The samples include: *Limestone* from the Cretaceous Judea Group (representing deposition in the shallow marine environment of the Cretaceous Sea); *Runoff* draining the Judea limestones and chalks; *Aragonite* deposited in the late Pleistocene-Dead Sea Lake Lisan that received waters from the Jurassic and Cretaceous limestone-aquifers; Terra-rossa soil covering the Judea limestones and dolomites and cave-speleothems. Also marked in the figure are the ⁸⁷Sr/⁸⁶Sr ratios of the various lithologies and waters and the $\delta^{88/86}$ Sr values of the marine carbonates (0.29±0.12‰) soil and the speleothem (-0.17±0.06 ‰).

Figure 3. $\delta^{88/86}$ Sr data for sample groups in which the Sr was derived from: Modern seawater, Modern corals from the Gulf of Aqaba, Mesozoic carbonates and terra rossa soil. The bar entitled "F&E, 2006" denotes the whole range of coral Sr isotope data measured by Fietzke and Eisenhauer (2006); the arrow above the bar shows the direction of decreasing water temperature. The width of each rectangle represents the $\pm 2\sigma$ range of the results. The NBS987 standard is given for comparison. Note the possible lower $\delta^{88/86}$ Sr value of the Modern carbonate relative to the Mesozoic carbonates that may reflect warmer Mesozoic seas (see text).

Table 1: $\delta^{88/86}$ Sr values in waters and rock materials. Averages and standard deviations refer to the number of individual samples analyzed for each lithological or water sample group (e.g. *Porites* corals). The last column lists the Sr/Ca ratios of the modern corals.

Sample	Location	type/mineralogy	δ ^{88/86} Sr (‰)	error (±2σ) (‰)	N^1	Sr/Ca (mmol/mol)
NBS987	Standard	SrCO ₃	0.01	0.05	9	-
	Madama Caral			- 1 4		
wodern Corais and seawater (Sr derived from modern seawater)						
Porites corals						
T 008		1 011100 00111	0.21	0.12	6	8.72
T 021-4A			0.26	0.14	6	8.75
T-028-3A			0.19	0.35	6	8.73
Т 034			0.24	0.35	6	8.75
T 042	Gulf of Agaba		0.31	0.32	6	8.72
T 047	Red Sea	Aragonite	0.20	0.32	6	8.91
T 054-2A			0.23	0.30	6	8.80
T 061			0.23	0.31	6	8.84
T 083			0.19	0.23	6	8.76
T 112-1A			0.16	0.12	6	9.03
Average, Porit	es		0.22	0.07	10	8.80
g .,		Acropora				
MBL-1	- 10 0 · 1		0.22	0.20	8	8.95
MBL-2	Gulf of Aqaba	Aragonite	0.20	0.24	8	9.03
Average, Acro	pora		0.21	0.22	2	8.99
Average, mode	ern corals		0.22	0.07	12	8.83
Seawater						
GOA-1	Gulf of Aqaba	salinity 41	0.31	0.14	8	-
IAPSO	Atlantic	salinity 35	0.35	0.10	15	-
NASS-4	Atlantic	salinity 35	0.38	0.11	8	-
Average, seawa	ater	-	0.35	0.06	3	-
Carbonate rocks, aeolinites and waters draining carbonate rocks (Sr derived from Mesozoic marine carbonates)						
T NT 1	N	T	0.20	0.14	ſ	
LN-I	Negev	Loess	0.29	0.14	6	-
AAAS-6	Judea Mt.	Mesozoic calcite	0.27	0.12	5	-
URIA-9A	Judea Mt.	groundwater	0.25	0.15	6	-
ESHTAOL-6	Judea Mt.	Runoff	0.31	0.16	6	-
M-2483	Lake Lisan	Quaternary aragonite	0.37	0.08	3	-
Average Mesoz	zoic marine carbona	ites	0.30	0.10	5	-
			• • •		•1\	
l errestrial carbonate, speleothems (Sr derived from terra rossa soil)						
10-44-R1	Iudea Mt	speleothem/calcite	-0 14	0.17	3	-
03-06-G	Judea Mt	speleothem/calcite	-0.20	0.08	3	-
TR-1	Judea Mt	terra rossa soil	-0.18	0.15	6	-
Average, terre	strial	1011a 1055a 5011	-0.17	0.06	3	-

¹Number of individual runs of the same sample.



Figure 1



Figure 2



Figure 3