THE GEOLOGICAL HISTORY OF PLIOCENE-PLEISTOCENE EVAPORITES IN MOUNT SEDOM (ISRAEL) AND HOW STRONTIUM AND SULFUR ISOTOPES RELATE TO THEIR ORIGIN

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ABSTRACT: Evaporites, comprising of gypsum, anhydrite and halite are described from the Pliocene Sedom Formation, the Caprocks units and the Pleistocene 'Amora Formation in Mount Sedom, Southern Jordan Valley, Israel. Strontium and sulfur isotopic compositions of the evaporite minerals, and their Sr/Ca and Br/Cl ratios were used to interpret their environments of deposition and processes of formation and diagenesis. Some of the evaporites of the Sedom Formation were deposited from evaporated seawater. Others were deposited from a mixture of seawater and brines. The brines were composed of seawater which penetrated the carbonate rocks of the Rift margins, participated in dolomitization processes and, when hydrologic conditions allowed, seeped out into the Sedom basin and were mixed with evaporated seawater. These processes yielded non-homogeneous fluid masses of mixtures, as indicated by their wide range of ⁸⁷Sr/⁸⁶Sr ratios (0.70824 - 0.70905) as compared to the narrow Sr/Ca ratios of the derived evaporites. Their marine origin is indicated by their δ^{34} S values which are around 20 ‰. The evaporites of the 'Amora Formation times", returning to the Sedom basin after its disconnection from the sea. The high Sr content and Sr/Ca ratios indicate that the anhydrites existing today in the Sedom and 'Amora formations were originally deposited from the evaporated seawater as gypsum which was later recrystallized at depth, at high pressures and temperatures. The caprocks are residual rocks of marine origin, formed by the dissolution of the exposed rock-salt units in the Sedom Formation. They represent mainly the gypsum (or anhydrite) beds intercalated in the rock-salt units of the Sedom Formation in Mount Sedom rather than Ca-sulfates disseminated in the halites.

INTRODUCTION

Geological Background

The greatest part of the evaporites in the Southern Jordan Valley occurs in Mount Sedom. The mountain emerges from the floor of the Jordan Rift Valley along the southwestern margins of the Dead Sea level, trending SSE-NNW (Figs. 1 and 2). The length of the mountain from north to south is about 11 km, its maximum width attains about 2 km; its maximum absolute height is about 160 m below sea level, and it rises up to about 240 m above the Dead Sea in the east and about 100 m above the 'Ami'az Plain in the west; to the north it is bordered by the delta of Nahal Zohar and to the south by Bitronot Hamarmar (Fig. 2).

Mount Sedom is a diapiric body, and is built of halite layers intercalated with sand, anhydrite and gypsum, and dolomite and marl beds, all belonging to the Har Sedom Group. Its main body is made of massive vertical rock salt layers, intercalated with thin beds of anhydrite, dolomite, marl and silt, which are also scattered in them. These layers extend to a depth of more than 3 km and were included by Zak (1967) in the Sedom Formation (Figs. 3 and 4). The salt body of the Sedom Formation. The latter is made of marl, chalk, anhydrite, gypsum and halite, which were penetrated and dragged by the diapiric mountain on its way upwards (Fig. 3). The halite layers in the members of the Sedom Formation were dissolved either by ground water or when they were exposed to the atmosphere in late "Amora times", and their insoluble

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components, which included anhydrite, gypsum, carbonates, clastics as well as remnants of undissolved halite, collapsed and spread over their yet undissolved continuation, as well as on the formerly dissolved adjacent layers to form caprocks (Fig. 3). The top of the mountain, as well as its slopes are unconformably overlain by marly-chalky layers of the Lisan Marl (Figs. 3 and 4), which covered the mountain while being submerged under Lake Lisan. Those layers were torn from the layers surrounding the mountain in the course of its ascent (Fig. 3). A more detailed description of the Sedom and 'Amora formations is given below. Further information is given in the stratigraphic study by Zak (1967) and in Weinberger (1992).

In the absence of direct dating, various ages were assigned to the Sedom and 'Amora formations by different authors (e.g. Zak 1967; Horowitz 1974; Agnon 1983; Kashai 1988), based mostly on geologic considerations. Most of these authors assign a Pliocene age to the Sedom Formation and a Pleistocene age to the 'Amora Formation, excluding Agnon (op. cit.) who assigns a Miocene age to the Sedom Formation and a Pliocene age to the 'Amora Formation, and Horowitz (op. cit.) who assigns a Pliocene age to the 'Amora Formation.

Methods and Techniques

Samples and procedures.-- Samples of evaporites representing the various members of the Sedom and 'Amora formations were chosen for the present study from sections sampled by Zak (1967). Their geographic locations and stratigraphic positions are given in Appendix 1. All samples were examined by X-ray diffractometry and the results and their main



Figure 1. Location Map showing the study area and location of boreholes in the region.

mineralogy is given in Tables 1a and 1b. The chemical compositions of the samples, including the major elements, the traces of Br and Sr with their main mineralogy are also given in Tables 1a and 1b. δ^{34} S values, 87 Sr/ 86 Sr, Sr/Ca and Br/Cl ratios, accompanied by the main mineralogy are given in Table

2. Additional Br/Cl ratios in samples from the rock-salt units were calculated from the measurements of Zak (1967) and those in brines from oil wells in the region from the measurements by Starinsky (1974). These are given in Appendices 2a and 2b (respectively).

Analytical Methods .--

<u>Chemical determinations</u>: All samples were ground to ≤ 200 mesh, and dried in an oven at 50°C. The concentrations of the ions K⁺, Na⁺, Ca²⁺, Mg²⁺, CO₃²⁻, SO₄²⁻, Sr²⁺, and in halites also Cl⁻ and Br were determined. All samples were dissolved in 1N HCl except those for Cl determinations which were dissolved in water. The determinations were executed in the methods and with the equipment as follows:

Na⁺, K^+ , Sr^{2+} - were determined by an Atomic Absorption Spectrometer (AAS), Perkin-Elmer, model 460 or 603.

 Sr^{2+} - in low concentrations - was determined by an Inductively Coupled Plasm Spectrometer (ICP), Jobin-Yvon, model JY 48, with Sc as an internal standard.

 Ca^{2+} , Mg^{2+} - were determined by titration with EDTA. The Ca was determined by AAS, and the result subtracted from the titration results to obtain the Mg^{2+} concentrations. Mg^{2+} - in low concentrations was determined by AAS.

Cl⁻ - was determined in aqueous solutions by potentiometric titration with the aid of a titratometer, Metrohm, model 636. Br concentrations (see below) were subtracted from these values.

Br - was determined by an X-ray fluorescence spectroscope (XRF), Philips, model 1410.

 SO_4^{2} - was determined by the gravimetric method, HCl dissolved sulfates reprecipitated as $BaSO_4$.

 CO_3^{2-} - was determined by the gasometric method. The volume of CO_2 emanated by dissolution in HCl was measured in a manometer containing NaCl and absorbed in KOH solution, and the volume differences were calculated.

 $+H_2O$ - crystal water was determined by the difference of the weights before and after heating in an oven at 220°C.

X-ray diffractometry: was carried out by an X-Ray Diffractometer, Philips, generator model PW-1730/10, goniometer model PW-1820/00, and a monochromator model PW-1752/00 with Cu tube and Ni filter. The wavelengths of Cu_{kal} = 1.54051 were used for the calculations of the d-values. The operating voltage was 40 KV and the current 30 mA. The samples mounted on a carrying glass or in a cell were scanned between 3° to 60°, scanning speed 1°/minute. The mineralogical identifications were based on the tables of Berry (1974) and McClune (1986).



Figure 2. Geological Map, Mt. Sedom (after Zak & Freund 1980). Note that the members Marl Sand and Conglomerate (Amc), Marl and Anhydrite (Ama) and 'Amora Salt (As) of the 'Amora Formation are combined herein into one mapping unit designated Aas. See figure 4.

Isotopic determinations.--

<u>Strontium isotopes</u>: ⁸⁷Sr/⁸⁶Sr ratios were determined in 33 samples of gypsum, anhydrite, and anhydrite disseminated in halite.

The strontium was extracted by the ion-exchange technique by a resin, Dowex 50w-8x, 200-400 mesh. The chemical blanks were smaller than 2 ng per sample.

The ratios were determined by a Mass Spectrometer, Varian,

model CH-5. Magnetic sector: radius 21.4 cm, 90°, equipped with a Cary 401 Vibrating Reed Spectrometer. The ratios were normalized to ⁸⁸Sr/⁸⁶Sr = 8.3752. A value of 0.7081 ± 0.0003 (2 σ) was received for the standard of SrCO₃ of Eimer and Amend. The measurements were carried out in the Geological Department of the Institute of Earth Sciences of the Hebrew University, Jerusalem.

<u>Sulfur isotopes</u>: δ³⁴S values were determined in 13 gypsum, anhydrite and halite samples. In most of them ⁸⁷Sr/⁸⁶Sr ratios were also determined. The pure Ca-sulfate samples (according



Figure 3. Geological cross section east-west Mt. Sedom (Zak & Freund 1980). For symbols see Figure 4.

to chemical analyses) were measured without any treatment (except for dehydration and grinding).

Others, as well as halites, were measured as BaSO, in order to avoid contamination of carbonates and excess halite. Some pure Ca-sulfates were also measured as BaSO₄ for control. The samples were dissolved in boiling HCl to which BaCl, was added (for details of the procedure see Raab 1998). SO, was prepared from either the Ca- or the Ba-sulfate following the method described by Coleman and Moore (1978). The isotopic determinations were carried out by a Gas Source Mass Spectrometer made by VG, model SIRA 10. The reference value was that of reference material measurements of BaSO, prepared by precipitation of seawater sulfate the mean value of which was 20 ‰. The results are given in d values in ‰ in reference to the international CDT standard. NBS 122 gave +0.15% and the overall analytical reproducibility was $\pm 0.15\%$. The preparations of SO₂ and the measurements were carried out in the Isotopes Laboratories of the British Natural and Environmental Research Council in London (now in Keyworth, U.K.).

STRATIGRAPHY AND FIELD RELATIONS

The stratigraphy used herein is based on Zak (1967).

Sedom Formation

The Sedom Formation (Figs. 4 and 5) builds the greater part of Mount Sedom and attains a total thickness of up to about 2000 m, including the subsurface. The base of the formation is unexposed, and the formation is overlain by the exposed residual caprocks or, in an angular unconformity, by the 'Amora Formation which overlies also the caprocks. The Sedom Formation comprises five members, described below together with their strontium and sulfur isotopic compositions and their Sr/Ca and Br/Cl ratios (Fig. 5, Table 2) as follows (from the base upward):

Karbolet Salt and Shale Member - Sk.-- The member is made mainly of thick halite units with intercalations rich in mudstone, clay, dolomite, sandstones, anhydrite and gypsum. Its exposed thickness exceeds 550 m.

⁸⁷Sr/⁸⁶Sr ratios were determined in three samples. Two samples (IZ-987, IZ-978), mainly made of halite, originate from Sedom-1 borehole, from the depths 1270 m and 1680 m respectively and have ⁸⁷Sr/⁸⁶Sr of 0.70905 and 0.70872 respectively. The third sample (IZ-79), made of anhydrite mixed with gypsum comes from one of the anhydrite-gypsum intercalations in the halite and has a ratio of 87 Sr/ 86 Sr = 0.70847. δ^{34} S values determined in two of the samples are 19.3 ‰ in sample IZ-987 and 12.6 ‰ in sample IZ-29. Sr/Ca ratios calculated in three halite samples fall within the range of 0.0029-0.0298 and in the single anhydrite and gypsum sample Sr/Ca=0.0011. Br/Cl ratios were calculated in 12 halite samples (including 10 samples from Sedom-1 borehole between the depths of 188 m and 1694 m) (Table 2 and Appendix 2a) which are in the range of 0.060-0.145X10⁻³, while ten of them do not exceed 0.076X10⁻³ showing no regularity. It should be noted that the highest values were detected in the lowest samples in Sedom-1 borehole (ca 1500 m).

Lot Salt Member - Sl.-- The Lot Salt Member is made of massive halite layers with some dolomite, clay and anhydrite between and within them. Its thickness is 700-1000 m.

Strontium and sulfur isotopic compositions were analyzed only in one sample (IZ-377) from this member, yielding a ratio of 87 Sr/ 86 Sr=0.70893 and a value of δ^{34} S=19.9 ‰. Sr/Ca ratios were calculated in two samples (IZ-375 and IZ-377) and their



Figure 4. A generalized lithostratigraphic columnar section in the Sedom and 'Amora formations and in the Caprocks Members at Mt. Sedom.

values were 0.124 and 0.182 (respectively) (Table 2). Br/Cl ratios were calculated in 12 samples (Tables 1 and 2), out of them 11 are in the range of 0.025-0.027X10⁻³. One sample (IZ-377) is exceptional, having a value of 0.081X10⁻³ and probably contains traces of a mineral precipitated later in the succession of seawater evaporation (?carnallite, ?sylvite) having a distribution coefficient of bromine higher in about an order of magnitude than that in halite (Braitsch 1971; Holser 1979).

Benot Lot Shale Member - $Sb_{1,3}$ --This member is made of sandstones, anhydrites, shales and dolomites. It includes three subunits differentiated by the different ratios of their lithologic components and the cycles of their appearance. It is worth mentioning the occurrence of dolomitic "paper" laminae containing fossil fish and plant remains. The thickness of the member is 140-175 m. Halite occurs randomly along the section, especially in the upper part of the sequence in the upper subunit Sb₃, where massive halite beds may occur (Mumila borehole).

Га	ble	la	. M	inera	logi	cal	and	ch	emi	cal	com	po	siti	on	of	the	eva	pori	tes	in '	the	Se	dom	i Fo	orma	ation	. For	leg	end	see	Table	: 1b
												F F																				

		10.57	No	r	Ca	Ve	SO 4	CO3	CI	+H ² 0	AIP.	TOTAL	Sr	Br
NRK	NU.	MARN HOCK	w1%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	ppm	ppm
	<u> </u>	MUNERALION	35.74	0.05	1.30	0.43	2.0	1.44	37.00	0.32	1.77	100.1	51	108
~	030 030	100 100	3817	0.02	0.60	0.07	1.4	0.11	58.90	0.09	0.30	99.7	110	80
20	020	ija j	37 59	0.01	1.20	0.02	3.1	0.09	58.00	0.05	BDL	100.1	61	108
	04JA 0250		1.20	012	24.00	5.71	31.0	31.12	1.90	BDL	2.83	97.88	923	
	603		0.38	0.09	27.70	0.62	65.6	0.97	0.80	1.30	1.37	98.8	1612	
	094 407		0.50	0.09	28.60	0.47	65.9	0.69	1.50	1.32	0.81	100.1	1272	
5	006	an he cir	4.28	0.16	20.30	1.95	48.7	2.84	7,30	2.98	9.19	97.7	506	
SIDC	030	an: na; yuz	1.01	0.06	22.50	0.53	53.6	1.44	7.50	10.07	1.00	100.7	743	
	130	ant ye, na	197	0.13	23.70	1.48	56.5	3.72	2.10	7.47	1.79	98.3	815	
	133	an he of	5.78	0.09	23.40	0.42	55.9	0.53	11.50	2.79	0.53	100.9	759	
	 	ba ha	81.8°	0.04	1.00	0.30	2.1	0.80	58.00	0.19	0.55	99.4	117	90
	78	ha	36.56	0.04	1.60	0.06	4.1	0.01	56.40	0.14	0.09	99.0	471	82
	61 61	he	36 71	2.36	1.10	0.04	3.1	0.01	56.60	0.93	0.02	100.9	99	171
c	40	ha	38.21	0.42	0.70	0.03	1.8	BDL	58.90	0.16	BDL	100.2	148	188
5111	18	ha	37.59	1.29	0.60	0.13	1.3	0.22	58.00	9.27	0.01	99.4	92	222
	617	ha	38.10	0.88	0.70	0.27	3.5	0.05	57.40	0.08	BDL	99.3	240	132
	611	ha	36.80	0.02	1.00	0.24	2.4	0.63	58.60	0.09	0.03	99.8	190	100
	RAQ	an: some do	2.85	0.45	18.80	3.48	36.0	i 3.66	4.80	8.08	10.47	96.6	640	
	998	an some ha	3.80	0.14	22.80	124	53.4	3.75	6.10	2.75	4.22	98.2	305	
3.1	701	90	4.21	0.33	16.50	3.98	38.7	6.90	7.20	2.55	15.35	95.7	297	
340	7021	632 BOTTIE \$1	0.03	0.11	20.10	2.97	43.7	9.73	0.20	13.97	6.62	97.4	514	
	7028	an: some ev	0.03	0.06	24.30	0.39	58.1	0.95	0.30	9.15	3.95	97.2	509	
	179F	aD	1.16	0.30	25.00	1.98	4.2				16.50	76.5	1100	
	1795	do do	0.40	0.31	11.30	7.53	0.7	37.54	0.75		40.73	99.6	130	
52	715	dor an: gv	0.02	3.08	21.70	2.64	40.4	14.57		11.13	7.73	98.3	396	
	716A	an	0.28	0.03	28.10	0.22	67.4	1.05	0.40	0.37	1.19	99.3	833	
	716B	an	0.10	\$0.0	28.40	0.05	68.5	0.27	0.20	0.20	2.50	100.2	973	
	727		0.18	0.01	23.10	0.07	55.3	0.34	0.30	19.91	1.36	100.6	313	
	742	an: some gy	0.13	0.08	25.90	1.02	57.1	5.30	0.40	4.33	3.78	98.0	833	
Shi	781	an: some gy	0.50	0.04	27.30	0.25	63.7	1.78	1.10	4.20	0.54	99.6	331	
	791	80	1.09	0.21	27.50	0.26	65.8	0.30	3.70	1.66	0.32	100.8	416	
Śłc	364	an: some gy	1.44	0.11	25.10	0.54	59.9	0.90	-2.90	5.34	1.82	98.1	971	
3	377	ha	38.05	0.37	0.40	0.12	1.9	0.02	58.70	0.03	0.02	99.6	159	107
	375	ha	37.71	0.02	0.80	0.12	2.1	0.23	58.10	0.27	0.13	99.5	217	33
	838	an	0.12	0.07	28.00	1.47	59.5	7.18	0.20	0.84	1.13	98.5	504	
Ske	640	an	0.17	0.04	27.80	0.58	65. 8	1.16	0.30	0.76	1.93	98.5	542	
	998	an	0.50	0.10	27.80	0.58	65.7	0.74	1.30	1.45	0.65	98.8	1100	
	999	80.	0.22	0.04	28.10	0.23	66.7	0.42	0.30	1.98	0.84	98.7	1064	
	29	an: gy	0.52	0.02	22.80	2.50	44.6	12.95	0.80	14.41	1.12	99.7	551	
Sk	1005	ha: qtz	7.10	0.20	17.50	3.64	0.2	32.31	13.00	2.50	19.73	95.2	1589	
•••	978	ha	37.52	0.02	1.20	0.03	2.9	0.18	57.90	0.05	1.05	100.9	76	100
	987	ha	38.39	0.01	0.50	BDL	1.2	BDL	59.20	21.0	0.02	88.1	325	100

Two samples of powdery anhydrite (IZ-742, IZ-791) containing about 20% gypsum and 10% dolomite from the lower subunit of the member (Sb,) have ⁸⁷Sr/⁸⁶Sr ratios of 0.70851 and 0.70824 (respectively) (Table 2). ⁸⁷Sr/⁸⁶Sr ratios were determined in four samples from the middle subunit (Sb₂). Sample IZ-727, composed of idiotopic crystallized gypsum has a ⁸⁷Sr/⁸⁶Sr ratio of 0.70843; sample IZ-716, composed of powdery anhydrite yielded a ratio of ⁸⁷Sr/⁸⁶Sr = 0.70842. Sample IZ-179M, made of laminar dolomite ("paper shales"), included fish bones (IZ-179F) between the laminae; the fish bones are composed of apatite with about 20% dolomite. They yielded 87 Sr/86 Sr ratios of 0.70860 and 0.70820 (respectively). An additional sample of fish bones (IZ-198), has the same mineralogical composition and yielded the same ratio - 0.70820. The considerably different values of the ratio ⁸⁷Sr/⁸⁶Sr in the dolomite and in the bones may probably indicate an active biological fractionation of strontium. A

sample made of gypsum with about 30% anhydrite from the upper subunit (Sb₃) yielded a ratio of ⁸⁷Sr/⁸⁶Sr=0.70859 and a value of δ^{34} S=20.9 ‰.

Sr/Ca ratios calculated in 14 samples of different mineralogies (anhydrite, gypsum, dolomite and apatite) fall within the range of 0.0006-0.0016. Br/Cl ratios, calculated only for the halite samples of the upper unit (Sb₃), fall in the range of 0.07- $0.11X10^{-3}$.

Me'arat Sedom Salt Member - Sm.--is made mainly of halite with some anhydrite and in places some dolomite. Its thickness is 200-250 m. Determinations of ${}^{87}Sr/{}^{86}Sr$ ratios were performed in two adjacent samples (IZ-48, IZ-49) composed of massive crystalline halite and in one of them (IZ-49) the value of $\delta^{34}S$ was also determined. These were 0.70889, 0.70897 and 20.2 ‰, respectively (Table 2).

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MBR	NO.	MAIN	Na	K	Ca	Mg	SO ₄	CO ₃	Cl	+H ² 0	AIR	TOTAL	Sr	Br
	12-	MINERALOGY	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	ppm	ppm
	620	gу	0.33	0.14	25.70	1.84	7.0	36.00	7.20	10.30	7.31	95.8	3435	
	601	an	0.20	0.05	28.90	0.81	54.9	6.08	3.20	4.68	0.34	99.2	1500	
Am	600	an	0.84	0.17	26.60	0.72	59.7	0.98	3.80	4.55	2.84	100.2	1080	
	597	an; some ha	3.50	0.13	23.80	0.68	53.3	2.83	7.50	3.35	3.08	98.2	496	
	592	an; gy; ha	5.34	0.09	19.10	0.50	41.1	3.02	10.30	14.61	5.25	99.3	1023	
	567	an; some ha	<u>3.31</u>	0.05	25.70	0.33	58.2	2.52	6.40	2.33	2.84	101.7	1434	
	547A	ha	38.74	BDL	0.20	0.02	0.1	0.23	59.70	0.08	0.11	99.2	13	101
As	547B	ha	31.61	0.06	3.90	0.33	2.6	5.15	48.70	1.25	4.22	97.8	180	71
	544	ha	38.97	0.03	BDL	0.01	0.1	0.03	60.10	0.06	0.03	99.3	5	89
	538	ha	38.28	0.01	0.50	0.06	0.2	0.65	<u>59.00</u>	0.10	0.46	99.2	26	102
٨ma	532	an	0.22	0.09	27.20	0.36	61.9	3.64	0.30	4.16	0.32	98.2	1444	
	504	an	0.08	0.05	27.90	0.43	63.3	2.07	1.80	1.67	1.40	98:7	1288	
	489	an; some ha	4.34	0.08	25.30	0.12	59.1	0.69	8.30	1.36	0.32	99.6	495	
	486	an; ha	4.90	0.20	23.10	0.65	48.9	4.94	9.40	2.59	4.38	99.1	830	
	485	an; some gy	1.09	0.09	27.10	0.38	59.9	3.10	1.70	2.89	3.59	99.8	667	
Amc	478	an; some gy	0.13	0.14	25.10	0.54	53.6	5.65	1.00	3.80	5.55	95.5	23481	
	465	gy	0.03	0.01	23.30	0.04	55.1	0.70	BDL	20.16	0.48	99.8	300	
	451	an; ha	4.90	0.11	23.60	0.36	53.5	2.44	8.30	3.16	2.52	98.9	675	
	442	an	0.67	0.07	28.00	0.11	65.8	0.26	1.50	1.31	0.36	98.1	485	

Table 1b. Mineralogical and chemical composition of the evaporites in the 'Amora Formation.

Sr/Ca ratios were calculated in 7 halite samples and they are in the range of 0.0041-0.0157. Br/Cl ratios, calculated in 17 samples (Table 2 and Appendix 2a) are in the range of $0.045-0.17X10^{-3}$.

Hof Shale and Salt Member - Sh.-- is made of sandstones, clay, halite and anhydrite and is up to about 90 m thick.

A ratio of 87 Sr/ 86 Sr=0.70864 and a value of 54 S=18.7 ‰ were determined in one massive, coarse crystalline, almost pure halite sample with ca 2% anhydrite (IZ-826) from the lower part of the member.

Sr/Ca ratios were calculated in four halite samples and in one anhydrite with some dolomite (Table 2). These fall in the range of 0.0018-0.0084. Br/Cl ratios, calculated in 6 samples (Table 2, Appendix 2a) fall within the range of 0.060- 0.096×10^{-3} .

Caprocks Members

The Sedom Formation includes also three caprocks members (Figs. 4 and 6) which, based on field relations (Zak 1967), were formed due to the dissolution of the halite in the members Karbolet Salt and Shale (Sk), Lot Salt (Sl) and Me'arat Sedom Salt (Sm) members. The composition of the caprock units, which are mainly made of residual rocks - clastics, gypsum, anhydrite and in places halite remnants - is a consequence of the composition of their mother rocks. The caprocks units attain a thickness of 40 m, and they are either exposed or covered by young terraces, formed at the coasts of Lake Lisan. Their lithologies, strontium and sulfur isotopic compositions

and Sr/Ca and Br/Cl ratios are as follows (Fig. 6 and Table 2).

Karbolet Salt and Marl Caprock Member - Skc.--Two samples were examined from this member. One sample (IZ-998) is mainly made of massive anhydrite and the other of massive anhydrite with ca 10% dolomite. ⁸⁷Sr/⁸⁶Sr ratios were 0.70858 and 0.70838 respectively. Sample IZ-998 yielded a value of δ^{34} S = 19.0 ‰. The layers of the member are overturned and thus sample IZ-638, taken very near to the top of the member (ca 1 m), is at lower altitude than sample IZ-998. Sr/Ca ratios calculated in 4 anhydrite samples fall within the range of 0.0008-0.0019.

Lot Salt Caprock Member - Slc.-- One sample (IZ-364) made of powdery anhydrite with ca 20% gypsum, and collected near the top of the member was analyzed. The sample yielded a ratio of ⁸⁷Sr/⁸⁶Sr = 0.70836, and a value of δ^{34} S = 19.1 ‰. The Sr/Ca ratio in this sample was 0.0018.

Sedom Salt Caprock Member - Smc.-- Three samples were analyzed, two of them (IZ-896, IZ-135) collected from the base of the sequence (in two different sections: the southern and the northern parts of the Mt. Sedom), and the third one 2(IZ-692) near its top. Sample IZ-896 is mainly composed of anhydrite with ca 30% halite, yielding a ratio of 87 Sr/ 86 Sr = 0.70896 and a value of δ^{34} S = 20.5 ‰. Sample IZ-135 is mainly composed of anhydrite with ca 10% of gypsum and about 5% of halite and yielded a ratio of 87 Sr/ 86 Sr = 0.70859. Sample IZ-69 is composed almost entirely of anhydrite with a ratio of 87 Sr/ 86 Sr = 0.70864. Sr/Ca ratios were calculated in 6 samples (including the one mentioned above) and they fall within the range of 0.011-0.027. Table 2. Main mineralogy, δ^{34} S values and 87 Sr/ 86 Sr, Sr/Ca and Br/Cl ratios in the samples of the Sedom (including caprocks) and 'Amora formations. For symbols see legend in Table 1b.

MBR	NO. 1Z	MAIN MINERALOGY	⁸⁷ Sr/ ⁸⁶ Sr	δ ³⁴ 5%0	<u>Sr/Ca</u> molar	Br/Cl motarX1000
	620	gy			0.0061	
	601	an	0.70817		0.0024	
Am	600	an	0.70831	23.0	0.0019	
	597	an; some ha			0.0010	
	592	an; gy; ha			0.0024	
	567	an; some ha	0.70838		0.0025	
	547A	ha	0.70809	3.8	0.0030	0.0750
As	547B	ha; some gy	0.70808		0.0021	0.0549
	544	ha	0.70830			0.0658
	538	ha	0.70806	18.4	0.0024	0 0771
Ama	532	80	0.70805		0.0024	
	504	an	0.70835		0.0021	
	489	an: some ha	0.70818		0.0009	·······
	486	an: ha	0.70826		0.0016	
	485	an: some gv			0.0011	
Ame	478	an: some gy: cel-tr			0.0428	
	465	av	0 20802	22 R	0.0400	
	451	an ha	0.10001	0	0.0000	
	442	an	0 70822		0.0013	
	690		0.10000		0.0000	0.0920
-Th	826	ha	0 70864	187	0.0010	0.0000
	8251	ha	0.10004	10.1	0.0004	0.0003
	825B	na anu da			0.0023	0.0000
	607		0 709 / 6		0.0010	
	807		0.10040	20.5	0.0027	
3	0.01	au an ha ata	0.10090	20.5	0.0020	
SILIC	126	an; na; quz			0.0011	
	100	an; gy, na	0 50050		0.0015	
	130	an thu the	0.70859		0.0016	
	137	an; na; gy			0.0015	
	527	ha t			0.0053	0.0687
	76	ha			0.0135	0.0647
	53	na N			0.0041	0.1341
SID.	49	<u>ha</u>	0.70889	20.2	0.0097	0.1416
	48	ha	0.70897		0.0070	0.1702
	632	ha; cel-tr			0.0157	0.1021
	631	ha			0.0087	0.0754
	889	an; some do			0.0016	
	888	an; some ha			0.0006	
363	701	9U)			0.0008	
	702A	gy; some an	0.70859	20.9	0.0012	
	702B	an; some gy			0.0010	
	179F	ар	0.70820		0.0020	
	179M	do	0.70860		0.0005	
362	715	do, an; gy			0.0008	
	716A	an	0.70842		0.0014	
	716B	an			0.0016	
	727	gy	0.70843		0.0006	
	742	an; some gy	0.70851		0.0015	
ж1	781	an; some gy			0.0006	
	791	80.	0.70824		0.0007	
lc.	364	an; some gy	0.70836	19.2	0.0018	
1	377	ha; ?syl-tr	0.70893	19.9	0.0182	0.0809
	375	ha			0.0124	0.0254
	638	80.	0.70838		0.0008	
kc	640	an			0.0009	
	998	9 0	0.70858	19.0	0.0010	
	900	90	0.10000	10.0	0.0013	
	20	on' av	0 708 47	126	0.0011	
ъ	1805	he at a	V.I VO11	14.0	0.0011	
/ ** .	079	ner der	0 70005	10.2	0.0041	01010
	0.877	ha	0.10803	19.0	0.0069	0.1010
	901 	201	0.10014		0.0298	0.0730

an-anhydrite; ap-apatite; cel-celestite; do-dolomite; gy-gypsum; ha-halite; syl-sylvite; tr-traces;

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Figure 5. Stratigraphic section, δ^{34} S values and 87 Sr/ 86 Sr, Sr/Ca and Br/Cl ratios in the Sedom Formation.



Figure 6. Stratigraphic section, δ^{34} S values and 87 Sr/ 86 Sr ratios in the caprocks members

'Amora Formation

The 'Amora Formation (Figs. 4 and 7) is overlying unconformably the Sedom Formation, and in places the caprocks as well. It is overlain with an angular unconformity by the Lisan Marl. The formation partly surrounds the mountain with strong dips, and occurs in places on its top (Fig. 3). The exposed thickness of the formation is more than 400 m, and in Melech Sedom-1 borehole it attains a thickness of more than 2,000 m. The formation comprises 5 members. Their lithologies, strontium and sulfur isotopic compositions and Sr/ Ca and Br/Cl ratios are as follows (Fig. 7 and Table 2).

Marl, Sand and Conglomerates Member - Amc.-- is composed of marls and chalks alternating with sandstones, anhydrite, conglomerates and salt. Its thickness is more than 130 m.



Figure 7. Stratigraphic section, δ^{34} S values and 87 Sr/ 86 Sr, Sr/Ca and Br/Cl ratios in the 'Amora Formation.

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Sr isotopic ratios were determined in 4 samples, and δ^{34} S in one of them. Sample IZ-442, from the base of the section, is composed almost entirely of fibrous anhydrite and yielded a ratio of ⁸⁷Sr/⁸⁶Sr = 0.70822. Sample IZ-465 from the middle of the section is composed of almost pure selenite and yielded a ratio of ⁸⁷Sr/⁸⁶Sr = 0.70807 and a value of δ^{34} S = 22.8 ‰. Two additional samples (IZ-486; IZ-489) from near the top of the section, are composed of anhydrite with more than 10% halite and have ⁸⁷Sr/⁸⁶Sr ratios of 0.70826 and 0.70818 respectively.

Sr/Ca ratios were calculated in 7 samples and fall within the range of 0.0006-0.0016, except for one (IZ-478) which yielded the exceptional ratio of 0.0428.

Marl and Anhydrite Member - Ama.-- The member is made of marl and chalk alternating with anhydrites, sandstones, conglomerates and rock salt, and attains a thickness of 70 m. Two samples were examined, one (IZ-504) collected near the base of the member and the other (IZ-532) very near to its top. The lower sample is mainly composed of anhydrite, whereas the upper one includes also about 10% gypsum. The ⁸⁷Sr/⁸⁶Sr Three samples, collected near the base (IZ-538), in the middle (IZ-544) and at the top (IZ-547) of the member were examined. All of the samples are composed of coarsecrystalline halite. However, the upper sample includes in addition to the salt (IZ-547A) some calcite and gypsum (IZ-547B). The ⁸⁷Sr/⁸⁶Sr ratios obtained were 0.70806 for sample IZ-538, 0.70830 for IZ-544, and 0.70835 and 0.70805 for sample IZ-547 A and B, respectively. Obviously, there is no influence of the calcite and gypsum content on the Sr isotopic composition. δ^{34} S values determined in samples IZ-538 and IZ-538 and IZ-547A were 18.4 ‰ and 3.8 ‰ respectively.

a relatively large brine reservoir was evaporated.

Sr/Ca ratios in three samples fall within the range of 0.0021-0.0030. The Ca in a fourth sample was below the limit of detection. Br/Cl ratios were calculated in 14 halite samples (including 10 calculations from the data of Zak 1967) (Appendix 2a). Twelve of the Br/Cl ratios fall within the range of 0.065-0.080X10⁻³. The other two samples, showing a ratio around 0.134X10⁻³, are halites from a marly unit.

Marl Member - Am.-- This member is composed of marl, chalk, anhydrite, sand and some halite and it contains sulfur concretions. Its lithology is changing laterally and its thickness is 130-150 m. ⁸⁷Sr/⁸⁶Sr ratios were determined in three samples. One (IZ-567) from the base of the member is composed of anhydrite with about 10% halite and some gypsum. Two samples (IZ-600 and IZ-601), adjacent to each other, from the upper part of the section are composed of anhydrite with some gypsum, the latter containing also about 10% aragonite. The ⁸⁷Sr/⁸⁶Sr ratios obtained were 0.70838, 0.70831 and 0.70817 respectively. Another sample (IZ-597) originating also from the upper part of the member and composed of anhydrite, some halite and apparently some gypsum, yielded a value of $\delta^{34}S = 23.0$ ‰.

Sr/Ca ratios calculated in 5 anhydrite samples, some of them with a little halite, fall within the range of 0.0010-0.0025. One

gypsum sample shows a somewhat higher ratio of Sr/Ca = 0.0061.

Marl, Chalk and Sand Member - Ams.-- The member is composed of marl, chalk, sand and sandstones, anhydrite and conglomerates and shows lateral changes. Its thickness attains 45 m. Chemical and isotopic determinations were not performed in this member due to the lack of appropriate evaporites.



Figure 8. Correlation between K and ⁸⁷Sr/⁸⁶Sr ratios in the evaporitic rocks of the Sedom Formation.



Figure 9. ⁸⁷Sr/⁸⁶Sr ratios in the evaporites of the Sedom and 'Amora formations, in groundwater and in Messinian to modern Seawater.

THE ENVIRONMENTS OF DEPOSITION OF THE EVAPORITIC SEQUENCE IN MOUNT SEDOM

Introduction

As described above the evaporitic sequence in Mt. Sedom is divided into three formations: Sedom, 'Amora and Lisan Marl (Fig. 4). The latter is composed mainly of carbonates, and was not included within the present study.

The Sedom Formation is composed of 85% evaporites and the remainder is detrital material; its thickness (including subsurface) reaches about 2 km. The evaporites comprise halites and Ca-sulfates (gypsum and anhydrite) in the ratio 1:11 (halites 77%, Ca-sulfates 7%; Zak 1967).

The 'Amora Formation consists of a 450 m sequence of which 2/3 are evaporites (comprising 40% carbonates, 19% Ca-

sulfates and 18% halite) and 1/3 are clastic rocks (Zak 1967).

According to Zak (1967) the evaporites originated from seawater which penetrated inland from the north, and were evaporated to precipitate Ca-sulfates and halite.

The geochemical indicators used to analyze and interpret the environments of deposition were strontium and sulfur isotopes, and Sr/Ca and Br/Cl ratios (Table 2).

Sedom Formation

The Sedom Formation (Fig. 5) is composed mainly (ca 3/4) of halite units with some anhydrite, dolomite and some clastics alternating with thinner shale units composed of dolomite, clays, anhydrite and gypsum (Zak 1967). The Sedom Formation includes also the caprock units which will be dealt with below.



Figure 10. ⁸⁷Sr⁸⁶Sr ratios in the members of the Sedom Formation and comparison of parent members and caprocks. ANH&GYP-anhydrite and gypsum.



Figure 11. Sr/Ca ratios in the evaporites, in the Dead Sea Rift brines, in evaporated seawater and in gypsum precipitated from them. CEL. TR. - celestite traces.

Sr Isotopes.-- As Rb is present in K-minerals in the rocks, the relation K - 87 Sr/ 86 Sr was examined in order to verify that radiogenic 87 Sr, formed by the decay of 87 Rb was not added to the system since the evaporites were formed. Figure 8 shows that no correlation exists between the two, and therefore all of the 87 Sr originates from the solution depositing the evaporites and not from a radioactive decay of Rb.

If the evaporites would have been a direct product of Plio-Pleistocene evaporated seawater, the ⁸⁷Sr/⁸⁶Sr ratio in them should have to be around 0.709 (Burke et al. 1982; DePaolo and Ingram 1985; Farrell et al. 1995). In the present study ⁸⁷Sr/ ⁸⁶Sr values were found to range from 0.7082 to 0.7091 throughout the Sedom Formation (Figs. 5, 9, and 10). There is no regularity in the change of these ratios with the geological section (Figs. 5 and 10) and therefore such a wide range by itself, instead of one uniform value, indicates that the rocks were not formed from a homogeneous mass of evaporating seawater and that they were influenced to different degrees by 'foreign' contributions.

Sr/Ca ratio in the evaporites.-- The Sr/Ca ratios in the halite, gypsum and anhydrite samples fall in the wide range of 0.0005-0.03 (Figs. 11 and 12). A meaningful difference within this range exists between the halite samples, which show a considerable scatter and the anhydrite and gypsum samples, in which the ratios are much less scattered and show low values (<0.003). The wide range in the halites is explained by the



Figure 12. Comparison of the ⁸⁷Sr/⁸⁶Sr and Sr/Ca ratios in the different lithologies of the Sedom and 'Amora formations. The insert shows the different fields of the Sedom and 'Amora formations.

existence of various concentrations of celestite, in accordance with the conditions of the formation of this mineral during seawater evaporation. Celestite starts to precipitate early in the halite field, at about 13x degree of evaporation in the process of evaporation of seawater (Herrmann 1961; Braitsch 1971; Raab 1998). Therefore, the Sr/Ca ratio can not serve as an indicator for the concentrations of Sr in its precipitating brines.

There is also some uncertainty in the interpretation of Sr/Ca ratios in anhydrites. It is likely that the anhydrites of the Sedom Formation were originally precipitated as gypsum from the evaporating water body, since anhydrite is rarely precipitated as a primary mineral even in its own stability field (see e.g. Holser and Kaplan 1966; Kinsman 1974; Raab 1998; Usdowsky 1973). Today the majority of the sulfates in the section of the Sedom Formation are anhydrites. These rocks were probably transformed at depth, under relatively high pressure and temperature conditions (Berner 1971). The change from gypsum to anhydrite depends on the geothermal gradient as well as on the composition of subsurface brines. Anhydrite will generally replace gypsum at depths of 300-700 m. Depending on the availability of water, gypsum from anhydrite will appear at varying depths, normally between 100 and 300 m (Friedman et al. 1992, p. 138). In the Persian Gulf (Abu Dahbi) (Shearman 1963; Friedman 1995) and in the Sinai Peninsula (Ras Muhammad) anhydrite has formed in modern Sabkha settings (Friedman et al. 1985). Only later, due to the rise of Mt. Sedom, the anhydrites were exposed to atmospheric conditions. The transformation anhydrite ---> gypsum is sluggish, and therefore the anhydrite is still existing in spite of the fact that the pressure and temperature conditions in the area are suitable for gypsum formation. Using the homogeneous partition coefficient of Sr in gypsum which is 0.11 (Raab 1998), the concentrations of Sr in the Ca-sulfates agree with those which should have existed in gypsum precipitating from evaporated seawater (Fig. 11). However,

the conditions which dictated the Sr/Ca ratios in anhydrite rocks in the transformation gypsum ---> anhydrite at depth (composition of solutions, pressure and temperature), are unknown.

The ratios ⁸⁷*Sr*/⁸⁶*Sr vs. Sr/Ca.--* This relation (Fig. 12) shows that the Sedom and 'Amora formations fall within different fields. The samples of the Sedom Formation have both, ⁸⁷*Sr*/ ⁸⁶*Sr* and *Sr*/*Ca* ratios higher than those of the 'Amora Formation.

Figure 12 shows also the wide range of the ⁸⁷Sr/⁸⁶Sr ratios in the evaporites of the Sedom Formation (see also Figs. 9 and 10). The higher ratios of the Sedom halite, which are scattered around 0.7090, evidently indicate that they were precipitated from seawater. There remains therefore to explain the wide range of the 87Sr/86Sr ratios in the sulfates, and to find a mechanism which will explain how the precipitating brines acquired such a wide range. Without dealing at this stage of the discussion with the question of the origin of the salts - marine or nonmarine - the question of how the water acquired such a wide range of ⁸⁷Sr/⁸⁶Sr ratios should be explained. These ranges of ratios in the brines are interpreted as a result of dolomitization processes which took place through the reactions between the country rocks, viz. the carbonate rocks of the Rift walls west of the Dead Sea, and the magnesium and sulfate-rich evaporating brines as follows:

(1)
$$2Ca(Sr)CO_3 + Mg^{2+} \leftarrow CaMg(CO_3)_2 + Ca(Sr)^{2+}$$

(2) $Ca(Sr)^{2+} + SO_4^{2-} - - > Ca(Sr)SO_4 - 2H_2O$ (gypsum)

Facies changes in the Judea Group in the rift walls were described by Bentor and Vroman (1960), and epigenetic dolomitization phenomena were discussed by Raz (1983). Lowengart (1962), Starinsky (1974), Zak (1974, 1980) and



Figure 13. δ^{34} S values in the Sedom Formation and in the caprocks members. The caprocks have δ^{34} S lower or equal to the halite members indicating different or similar sulfur sources (see text for explanation).

Starinsky and Bielsky (1981) explain the chemical composition of the brines in the subsurface in the rift area (like those found in the boreholes 'Arava-1, Heimar-1, Lot-2, Sedom-1 and Sedom-2) by the reaction of ancient evaporated seawater with the carbonate country rocks of the Judea Group. These rocks, which are Upper Cretaceous marine limestones, have a ⁸⁷Sr/⁸⁶Sr ratio around 0.7075, following the secular changes curve in the ocean (Burke et al. 1982; DePaolo and Ingram 1985). A rock having such a ratio, reacting with brines which have a higher ratio (around 0.709), will result in the water in an intermediate value between these two end values.

Based on this process it is suggested that the wide range of ⁸⁷Sr/ ⁸⁶Sr ratios in the Sedom Formation is an intermediate value, which depends on the degree of the reaction progress in which the brines took part in the process of dolomitization. This scenario describes evaporated water, which arrived to the sedimentation basin of the Sedom Formation and precipitated gypsum and halite. Some of the waters penetrated into the marine Cretaceous country rocks (0.7075, Burke et al. 1982; DePaolo and Ingram 1985) and reacted with them in dolomitization processes, resulting in the decrease of the ⁸⁷Sr/ ⁸⁶Sr ratio and in the change in the Sr/Ca ratio. A quantitative description of such a process for saline waters in the Coastal Plain of Israel was given by Starinsky et al. (1983). At various times during the deposition of the Sedom Formation, these waters seeped out from the walls of the basin margins, where they were mixed with water existing in the basin, evaporating later and precipitating the evaporites.

Sulfur isotopes (δ^{34} S).-- Sulfur isotopes in anhydrite rocks can answer the question whether the origin of Sedom Formation is marine or nonmarine. δ^{34} S can change or remain unchanged in waters precipitating gypsum following the processes: (1) in an aquatic environment, where sulfur reduction occurs, the $\delta^{34}S$ of the residual solution increases, as the H₂S formed in this process is enriched in light sulfur isotope. (2) In dolomitization processes $\delta^{34}S$ values are not changing since dolomitization processes are not accompanied by sulfur isotopic fractionation (eq. 2).

 δ^{34} S values were determined in 6 anhydrite samples from the Sedom Formation (Table 2 and Fig. 13). The mean of 5 of them is 19.8 \pm 0.8 ‰. This value represents young seawater (Upper Tertiary; Nielsen 1979; Claypool et al. 1980) and points to the marine origin of the SO₄²⁻ in the water which precipitated the original gypsum. One anhydrite sample from the Karbolet Salt and Shale Member shows an extremely low δ^{34} S value (Fig. 13) although no product of a reducing environment (like pyrite) has been detected.

Br/Cl ratio in the halite rocks.-- This ratio falls within the range of 0.03-0.18X10⁻³ (Fig. 14). It is possible to assume that Br and Cl values represent those of the original evaporated seawater, even though it was stated above that part of the water which deposited the evaporites of the Sedom Formation interacted with the country rocks and therefore their original composition had been changed (as the ratios Ca/Mg, Sr/Ca and ⁸⁷Sr/⁸⁶Sr). On the basis of this assumption it is possible to reconstruct the Br/Cl ratios in the depositing brines, using the Br/Cl ratios in the halite rocks. Figure 15, which shows the Br/Cl ratios in the salts vs. those in evaporated seawater in the range of halite precipitation (degrees of evaporation of seawater 10x-50x). shows that the halites of the Karbolet Salt and Shale, Lot Salt, Benot Lot Shales and Hof Shales and Salt Members agree with degrees of evaporation in the early part of the halite field, from 10x to 20x only. Only the Me'arat Sedom Salt Member shows a wider range, up to ~28x.



Figure 14. Br/Cl ratios in the halite members of the Sedom and 'Amora formations.

Figure 15. Mean Br/Cl ratios $(\pm 1\sigma)$ in the halite units of the Sedom and 'Amora formations and in brines that could have deposited them. Br/Cl ratios in seawater at different degrees of evaporation, in subsurface brines in boreholes in the region and in halites that could precipitate from them are given for comparison.

Figure 15 displays also the Br/Cl ratios in brines from the deep boreholes in the area ('Arava-1 Heimar-1, Lot-2, Sedom-1 and Sedom-2). The Br/Cl ratio in halites precipitated from such brines should have been much higher. It is possible that these brines represent much later evaporation stages, in which carnallite and sylvite were precipitated. Carnallite and sylvite were found in some of the halite members of the Sedom Formation in Mt. Sedom and in the Lisan Peninsula (Zak 1974).

Caprocks Units

The caprocks members (Fig. 6) are composed of residual rocks which remained after the dissolution of the halite layers of the Sedom Formation. Consequently they are composed of the undissolved gypsum, anhydrite and detrital material, either in their original form or after diagenetic alterations. Halite remains are rarely found.

Sr/Ca ratio.--This ratio is not exceeding 0.0027 and its range agrees with that in the gypsum and anhydrite of the Sedom Formation, especially to that of Benot Lot Shale Member (Figs. 10 and 11), which due to the lack of halite rocks, remain rather intact, and thus do not have an equivalent caprock. This ratio is low relative to that in the halite samples, due to the lack

of celestite which occurs in the halite rocks. Though hardly soluble, it seems that the lack of celestite in the caprocks, is due to dissolution in the course of their formation.

The ratio ⁸⁷Sr/⁸⁶Sr.-- This ratio was determined in 6 samples from the three caprock members (Fig. 6). The values fall within the range of 0.70836-0.70896 (Fig. 9). The range of the values of ⁸⁷Sr/⁸⁶Sr ratios in the caprocks agrees with that in the gypsum and anhydrites in the halite members of the Sedom Formation, and especially with those of the Benot Lot Shale Member. Although the number of samples used for comparison between the samples of the Sedom Formation members and their equivalent caprock units is small, it can be seen that the ⁸⁷Sr/⁸⁶Sr values in all caprock members are lower than those in their mother member (Fig. 10). A single sample from the Me'arat Sedom Salt Caprock Member, which contains about 30% of undissolved halite, has a value of 0.7090, which agrees with its mother halite, and preserves its marine value.

By analyzing the Sr/Ca ratios it can be deduced that the Sr isotopic composition in the mother units is representing in fact the mineral celestite, which was probably deposited with the halite, rather than the gypsum or the anhydrite within the halite. The explanation for the higher ⁸⁷Sr/⁸⁶Sr ratio in celestite will be

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Figure 16. δ^{34} S values in the different lithologies of the Sedom and 'Amora formations.

discussed below in the chapter on the conditions of deposition of gypsum and halite in the Sedom basin.

The ratios ⁸⁷*Sr*/⁸⁶*Sr vs Sr/Ca.--* This system of coordinates shows that all of the values of the caprocks fall within the field of the Sedom Formation (Fig. 12).

Sulfur isotopes (δ^{34} S).-- Sulfur isotopes were measured in 3 samples of the Sedom caprocks and they and fall within the range of 19.0-20.5 ‰ (mean value 19.6 ±0.7 ‰) (Fig. 16). This range overlaps that of their mother members (Fig. 13). As already noted by Holser and Kaplan (1966, p. 15), diagenesis and transformation of one sulfur-bearing mineral to another, does not change the sulfur isotopic composition, and the substituting mineral preserves the fingerprints of the original δ^{34} S. Therefore, these δ^{34} S values attest to the marine origin of the caprock layers and supply additional evidence that they are derivatives of the respective Sedom Formation members, as interpreted by Zak (1967).

The conditions of deposition of gypsum and halite in the Sedom basin.-- The range of ⁸⁷Sr/⁸⁶Sr values in gypsum and anhydrite occurring as layers, in the Benot Lot Shales as well as in the insoluble residue of the halites of the caprocks is 0.7083-0.7086, whereas in the halite layers the range is 0.7086-0.7091 (Figs. 9 and 10). The fact that celestite, as a trace mineral in the halite, had been completely dissolved in the caprock layers, suggests that gypsum or anhydrite, which are more soluble than celestite and which are only minor constituents in the halite, would also be dissolved in the process of the formation of the caprocks. Therefore, the anhydrite and the gypsum which compose the caprocks represent individual layers of gypsum or anhydrite, which were intercalated between the halite layers in the members. Hence, the caprocks are remnants of a sequence and not just remnants of the sulfates disseminated in the halite layers. This conclusion is supported by the similarity of the values of ⁸⁷Sr/⁸⁶Sr in the Benot Lot Shale Member with those in the caprocks.

When building layers, the gypsum rocks are connected to the phase of the dolomitization. They were formed as a result of the reaction of the carbonate rocks of the rift margins with brines rich in Mg²⁺ and in SO₄²⁻ (eqs. 1 and 2).

As the origin of part of the Ca and Sr is the Judea Group rocks of the rift margins, which have a relatively low 87Sr/86Sr value (around 0.7075), those values in the gypsum should also be relatively low. This is not true for the Sr in the halite sections, which partly appears as celestite. The occurrence of this mineral points to a deposition from normal seawater, evaporated to degrees of evaporation between 13x to 23x (Raab 1998). This fact agrees with the Br/Cl ratios in the Sedom Formation halites, and therefore, the celestite represents values of ⁸⁷Sr/⁸⁶Sr closer to those of the original seawater (which most probably was near to 0.709). The obvious marine origin is demonstrated also by the δ^{34} S values, which were not affected by the dolomitization process. Therefore, a marine environment of deposition with varying contributions from the land is suggested for the Sedom Formation.

'Amora Formation

The 'Amora Formation (Fig. 7) includes a 450 m sequence of which about 2/3 are evaporites (composed of 40% carbonates, 19% Ca-sulfates and 18% halite) and 1/3 clastic rocks (Zak 1967).

Sr isotopes.-- The 87 Sr/ 86 Sr ratios in the anhydrites and in the halite of the 'Amora Formation fall both within the same range of 0.7080 - 0.7084 (Figs. 7 and 9). As in the Sedom Formation, no regularity in the variations of the 87 Sr/ 86 Sr ratios along the section was found.

Sr/Ca ratios.-- These ratios fall in the range of 0.0008-0.0061 with one exception - a sample which contains celestite (Figs. 7 and 11). Unlike the Sedom halites, however, celestite was not

detected in the 'Amora halites (only in one example), and the Sr/Ca ratios both in the halites and in the anhydrites are of the same range. Again, the presence of anhydrite points either that the sequence was at some stage deeply buried and under high pressure and temperature conditions, or deposited in favorable Sabkha conditions (see p. XX=106 herein).

The ratios ⁸⁷Sr/⁸⁶Sr vs. Sr/Ca.-- Figure 12 illustrates the difference between the Sedom and the 'Amora formations, where the 'Amora Formation shows a lower range of ⁸⁷Sr/⁸⁶Sr ratios relative to that of the Sedom Formation. This phenomenon points to the fact that the 'Amora Formation was mainly deposited from waters with a dominant and variable terrestrial contribution, most probably Ca-chloride waters, which returned from the walls of the Rift margins after the disconnection of the Sedom basin from the sea. These lower values in the 'Amora Formation suggest to the continuation of the dolomitization, but this time without the marine constituent (viz. a ⁸⁷Sr/⁸⁶Sr ratio around 0.709) as a partner in the mixing. Contrary to the process which occurred in the Sedom Formation, where ⁸⁷Sr/⁸⁶Sr ratios were explained by mixing of seawater with brines returning from the Rift walls, the evaporites of the 'Amora Formation were deposited only from returning brines, which were originally seawater. This is true also for the halite ('Amora Salt Member-As) which shows the same ⁸⁷Sr/⁸⁶Sr ratios as the anhydrites of the other 'Amora Formation members.

Sulfur isotopes (δ^{34} S).--Sulfur isotopes were determined in 4 samples from the 'Amora Formation. Three of them have δ^{34} S values around 21 ‰ (18-23 ‰) and one, very low -3.8 ‰ (Figs. 7 and 16). The higher values, which are similar to those in the Sedom Formation, express the same mother solutions which precipitated the rocks of the Sedom Formation. No reasonable explanation (like a record of the existence of sulfides) for the exceptionally low δ^{34} S value was found.

Br/Cl ratio.-- The Br/Cl ratio in the halite of the 'Amora Formation is in the range of $0.065 - 0.13 \times 10^{-3}$; most of the samples have a narrower ratio around 0.075×10^{-3} (Fig. 15). The mean value of the ratio is about 0.08×10^{-3} (Fig. 15, As), and is similar to those in most of the members of the Sedom Formation. As mentioned above, Br is not participating quantitatively in the processes which occurred in the rocks of the rift margins formations. Therefore, these data support the conclusion that the 'Amora salt was deposited from the same type of brines which deposited the Sedom Formation evaporites (without the seawater end member though).

CONCLUSIONS

1. The evaporites of the Sedom Formation were formed from evaporated seawater which penetrated the region most probably from the north, forming a narrow bay, intermittently disconnected from the sea.

2. Direct precipitation of Ca-sulfates and halite took place

within the lake and water also penetrated the carbonate formations of the Rift margins and participated in dolomitization processes.

3. At different times, within the course of the deposition of the Sedom Formation, hydrological conditions enabled the Cachloride brines to return from the margins into the Rift basin. These returning brines were mixed with evaporated seawater existing in the basin, and precipitated gypsum and halite.

4. The Sr and S isotopic behavior confirms the conclusion based on field relations that the caprocks are residual rocks remaining after the dissolution of the halite members of the Sedom Formation.

5. The evaporites of the 'Amora Formation were deposited only from Ca-chloride brines, which were trapped in the Rift walls in the 'Sedom times' and flowed back into the Dead Sea basin later in the 'Amora times', after its final disconnection from the open sea.

6. The episodes of the formation of evaporites of different $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ with the same $\delta^{34}\mathrm{S}$ indicate an original seawater origin and subsequent modification through mixing. The delivery of the brines to the basin was a consequence of the tectonic activity along the Dead Sea graben

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GEOLOGICAL HISTORY OF PLIOCENE-PLEISTOCENE EVAPORITES, MT. SEDOM, ISRAEL

# <u>1Z-</u>	LOCATION	COORD.	FM	MBR.	POSITION IN SECTION
29	Give ot Karbolet, southern section	1865/0538	Sedom	Sk	350 m above base of section
48	'Atlit Quarry, southern section	1857/0552	Sedom	Sm	150 m above base of member
49	'Atlit Quarry, southern section	**	Sedom	Sm	150 m above base of member
63	'Atlit Quarry, southern section	**	Sedom	Sm	157 m above base of member
76	'Atlit Quarry, southern section	**	Sedom	Sm	166 m above base of member
135	Eastern slope, northern section	1870/0574	Sedom	Smc	10 m above base of member
136	Eastern slope, northern section	**	Sedom	Smc	10 m above base of member
137	Eastern slope, northern section	**	Sedom	Smc	base of member
179	Eastern slope, northern section	64	Sedom	Sb_2	38 m above base of member
198	Eastern slope, northern section	••	Sedom	Sb ₂	20 m above base of member
364	Eastern slope, northern section	1867/0573	Sedom	Sic	top of section
375	Nahal Perazzim	1875/0602	Sedom	SI	lower third of section
377	Nahal Perazzim	**	Sedom	Sì	lower third of section
442	Eastern slope, northern section	1870/0572	'Amora	Ame	35 m above base of member
451	Eastern slope, northern section	1	'Amora	Ame	60 m above base of member
465	Eastern slope, northern section		'Amora	Amc	85 m above base of member
478	Eastern slope, northern section		*Amora	Ame	105 m above base of member
485	Eastern slope, northern section		'Amora	Amc	112 m above base of member
486	Eastern slope, northern section	\checkmark	'Amora	Amc	112 m from base of member
489	Eastern slope, northern section	1871/0572	'Amora	Amc	117 m above base of member, 20 m from top
504	Eastern slope, northern section	1872/0572	'Amora	Ama	13 m above base of member
532	Eastern slope, northern section		'Amora	Ama	65 m above base of member, 6 m from top
538	Eastern slope, northern section	1872/0572	'Amora	As	near base of member
544	Eastern slope, northern section	**	'Amora	As	middle of member
547	Eastern slope, northern section	**	'Amora	As	top of member
567	Eastern slope, northern section	1870/0567	'Amora	Am	15 m above base of member
529	Eastern slope, northern section	1871/0568	'Amora	Am	15 m above base of member
597	Eastern slope, northern section	1872/0568	'Amora	Am	85 m above base of member
600	Eastern slope, northern section	**	'Amora	Am	100 m above base of member
601	Eastern slope, northern section	1872/0686	'Amora	Am	100 m above base of member
620	Eastern slope, northern section	**	'Amora	Am	130 m above base of member

Appendix 1a.Geographic and stratigraphic provenance of the samples in Har Sedom (For the names of the members designated by a symbole see Figure 4; for a detailed map: see Zak, 1967)

Sedom

Sm

190 m above base of member

= its top

1875/0552

627

'Athit quarry, southen section

RAAB, FRIEDMAN, SPIRO, STARINSKY, AND ZAK

Appendix 1b.Geographic and stratigraphic provenance of the samples in Har Sedom (For the names of the members designated by a symbole see Figure 4; for a detailed map: see Zak, 1967)

627	'Atlit quarry, southen section	1875/0552	Sedom	Sm	190 m above base of member = its top
621	En Ashlag (Ein Mumila)	1871/0583	Sedom	Sm	base of member
632	Northern quarry (Shukri Dib)	1871/0586	Sedom	Sm	20 m above base of member
638	Giv'eot Karbolet, southern section	1863/0538	Sedom	Ske	15 m above base of member
640	Giv'eot Karbolet, southern section	**	Sedom	Skc	13 m above base of member
690	Me'arat Sedom, 1 km south of	1878/0543	Sedom	Sh	24 m above base of member
692	Eastern slope, southern section	1873/0552	Sedom	Smc	85 m above base of member
701	'Aruts Benot Lot, southern section	1872/0552	Sedom	Sb ₃	2 m above base of member
702	'Aruts Benot Lot, southern section		Sedom	Sb ₃	base of member
715	'Aruts Benot Lot, southern section	**	Sedom	Sb ₂	25 m above base of member
716	'Aruts Benot Lot, southern section		Sedom	Sb ₂	23 m above base of member
727	'Aruts Benot Lot, southern section	**	Sedom	\mathbf{Sb}_{2}	13 m above base of member
742	'Aruts Benot Lot, southern section	1872/0551	Sedom	Sb,	top of member, 60 m above base
781	'Aruts Benot Lot, southern section	1871/0551	Sedom	Sb,	middle of member,30 m above base
791	Aruts Benot Lot, southern section		Sedom	Sb	15 m above base of member
825	The Neck, southern part	1874/0555	Sedom	Sh	5 m above base of member
826	The Neck, southern part	"	Sedom	Sb	27 m above base of member
888	'Aruts Benot Lot, southern section	1872/0552	Sedom	Sb3	17 m above base of member
889	'Aruts Benot Lot, southern section	••	Sedom	Sb3	23 m above base of member
896	'Aruts Benot Lot, southern section		Sedom	Smc	base of member
897	'Aruts Benot Lot, southern section	**	Sedom	Smc	20 m above base of member
978	Sedom 1 borehole, core 9	1861/0533	Sedom	Sk	depth 1270 m
987	Sedom 1 borehole, core 11	**	Sedom	Sk	depth 1680 m
998	Giv'eot Karbolet, southern section	1865/0538	Sedom	Skc	5 m above base of member
999	Giv'eot Karbolet, southern section	••	Sedom	Ske	8 m above base of member
1005	Giv'eot Karbolet, southern section	**	Sedom	Sk	200 m above base of member

	No.	Cl	Br	Br/Cl		No.	Cl	Br	Br/Cl
Mbr.	17	WL%	Wt%	molarX1000	Mbr.	U	WL73	Wt%	molarX1000
Am	547	60.6	0.0104	0.0762	Sb3	348	56.0	0.0095	0.0749
	546	60.6	0.0111	0.0813		269	51.3	0.0126	0.1086
	545	60.2	0.0094	0.0693		83	58.6	0.0110	0.0833
	544	60.0	0.0100	0.0740		80	58.8	0.0146	0.1102
	543	59.3	0.0106	0.0794		79	58.0	0.0105	0.0804
	542	56.0	0.0170	0.1348		78	53.7	0.0089	0.0736
	540	53.4	0.0160	0.1330	នា	801	60.3	0.0048	0.0353
	538	58.6	0.0106	0.0803		699	60.9	0.0042	0.0306
	537	59.0	0.0090	0.0677		381	57.7	0.0060	0.0460
	536	58.6	0.0085	0.0644		380	59.9	0.0065	0.0483
Sh	826	59.2	0.0096	0.0720		379	55.8	0.0056	0.0446
	825	58.6	0.0114	0.0864		376	54.2	0.0069	0.0565
	690	55.7	0.0120	0.0957		37 5	56.2	0.0038	0.0299
Sm	83	42.9	0.0119	0.1232		371	52.5	0.0042	0.0354
	76	56.4	0.0117	0.0921	ļ	370	50.3	0.0050	0.0445
	73	59.3	0.0060	0.0446		369	55.4	0.0048	0.0381
	72	55.8	0.0157	0.1249	Sk	904	55.8	0.0086	0.0682
	69	48.3	0.0052	0.0475		907	58.0	0.00B4	0.0643
	60	57.8	0.0119	0.0919	1	921	57.0	0.0080	0.0623
	56	59.4	0.0213	0.1592		9 23	59.3	0.0088	0.0859
	53	59.1	0.0180	0.1351		934	59.1	0.0083	0.0624
	49	59.0	0.0189	0.1422	[948	56.3	0.0087	0.0687
	48	58.0	0.0217	0.1661		950	58.9	0.0084	0.0631
LEGE?	ND: Am-	'Amora	Salt; Sh-	Hof Shale and	1	965	57.0	0.0098	0.0760
Sm- Me'arat Sedom Salt; Sb3- Benot Lot Shale 978 59.2 0.0099 0.0									
SI- L	ot Salt:	Sk- Kar	bolet Salt	and Shale.		987	58.7	0.0191	0.1445

SI- Lot Salt; Sk- Karbolet Salt and Shale.

←Appendix 2a. Br/Cl ratios ions in the Sedom and 'Amora formations (based on Zak, 1964; Appendix C).

 \downarrow Appendix 2b. Br/Cl ratios in brines from boreholes in the Dead Sea Rift Valley and in the Dead Sea waters (based on Starinsky, 1974; appendices 10 and 12).

WELL/		Cl	Br	Br/Cl	
LOCALITY	No.	mg/1	mg/l	MolarX103	COORD.
'Arava l	BT84	202,245	3,670	8.1	1786/0325
Heimar 1	BT87	52,752	1,035	8.1	1816/0497
	BT89	137,841	2,750	8.9	
Lot i	D 16	28,356	510	7.9	1832/0602
	FG25	130,985	3,040	10.3	
	FG26	119,096	2,465	9.3	
Sedom 1	BT90	274,800	3,100	5.0	1861/0533
	BT91	255,500	2,870	5.0	
	D 35	269,960	3,120	5.1	
Sedom 2	D 59	106,600	1,790	7,4	
Dead Sea	D 52	196,940	4,600	10.3	1844/0506
	D 53	210,670	5,150	10.8	
	D 54	219,250	5,270	10.6	