Solar Lake (Sinai). 1. Physical and chemical limnology[1]

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Abstract

In Solar Lake, a basin at the edge of the sea filled with brine and shielded from the wind, a pycnocline builds up in September due to seepage of seawater to the surface. Solar heating produces a mesothermic temperature curve with a maximum up to 60.5°C at 2.5–3-m depth and decreasing temperatures toward the bottom (40°C at 5 m). The temperature profile together with a supply of nutrients from seepage leads to the development of several bacterial plates and a benthic cyanobacterial bloom. A rapid development of anoxic conditions with up to 39 ppm H_2S, a decrease in pH from top to bottom (8–6.9), redox potential gradients (+390 to –185 mV), and extremely pronounced light absorption are observed during the period of stratification which lasts from Sepember to July. With increasing solar energy, the seawater supply no longer compensates for the evaporation rate of 3.0 m yr^{-1} and the mesothermy becomes unstable. During a short period of holomixis, lasting from 4–13 weeks, the temperature is 27°C throughout the water column. The sediments of Solar Lake preserve a record of the last 4,600 years from the conditions of a marine lagoon to the development of the limnological cycle presented here.

Differential heating of the lower layers of saline lakes has long attracted attention (Beadle 1943; Kaleczinsky 1901; Schaffarczik 1908). Examples studied in different, relatively inaccessible parts of the world include Lakes Vanda (Wilson and Wellmann 1962) and Bonney in Antarctica (Angino et al. 1964), Hot Lake in Washington (Anderson 1958), "Red Pond" and "Green Pond" in Arizona (Cole et al. 1967), an artificial lake in the Panama Canal Zone (Bozniak et al. 1969), and Lake Mahega in Uganda (Melack and Kilham 1972). In many cases, the limnological cycle with periods of inverse temperature profile has not been described in detail, leaving it uncertain whether the lake being described was meromictic or monomictic.

Solar Lake is a small pond (140 × 50 m) 18 km south of Elat (Israel) on the Sinai coast of the Gulf of Elat. It is 4–6 m deep, depending on the time of year. A mountain ridge (100 m above sea level) protects it from winds. The lake is separated from the sea by a 60-m-wide gravel bar (Figs. 1, 2) and is fed by seawater seeping through the bar. The arid climatic conditions together with variations in seawater supply allow for a special type of monomixis with solar heating. Solar Lake was first described by Por (1968, 1969) and later by Mazor (1969) and Eckstein (1970). Friedman et al. (1973) surveyed carbonates in the algal sediments of the shallow parts of the lake, and Krumbein and Cohen (1974) described biogenic and abiogenic sediment accumulation. A detailed study of the limnology of Solar Lake during 1969–1974 is presented here.

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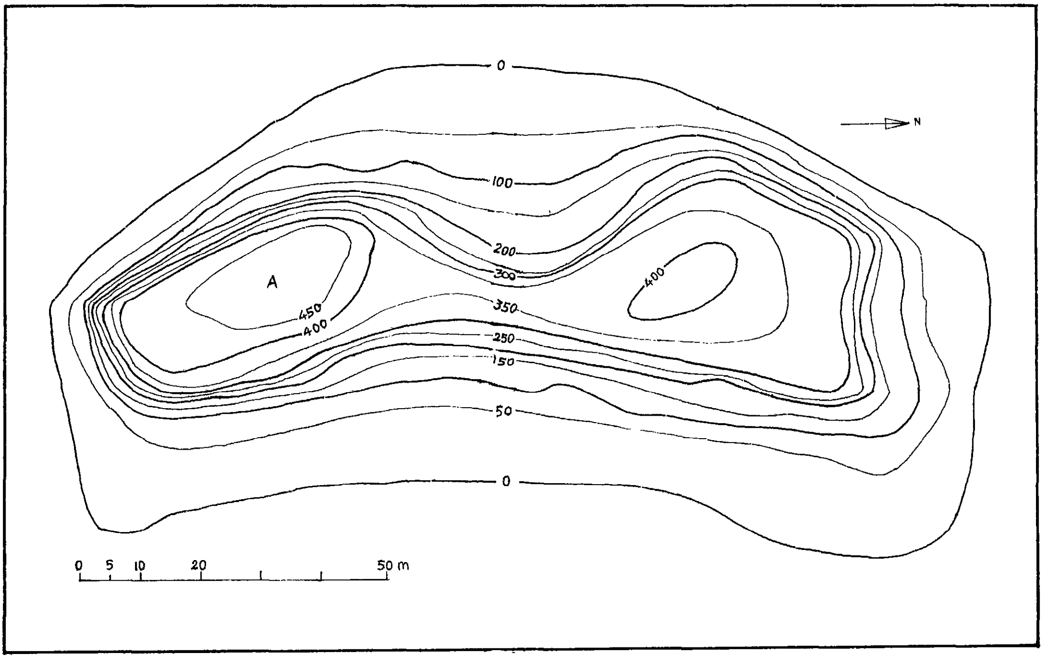

Fig. 1. Bathymetric map of Solar Lake, contour intervals in cm. A—Hydrological and biological sampling station.

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Methods

Routine sampling was at station A (Fig. 1), in the approximate midpoint of the southern basin of the lake, above the maximum depth. Water samples for chlorosity, salinity, dissolved oxygen, and H_2S determinations were taken with a modified 1-liter Nansen bottle at intervals of 50 cm.

Chlorosity was determined by the argentometric method (Am. Public Health Assoc. 1971). Salinity and density data were calculated from chlorosity by the equation of Strickland and Parsons (1968). Density was measured with a densitometer in samples brought to the in situ temperature. Temperatures were measured in situ with a Yellow Springs telethermometer (model 425C) and checked by measuring the temperature of a 1-liter water sample with a reference mercury thermometer immediately after collection. Oxidation-reduction potential (Eh) and pH were measured with a Knick Portamess pH meter with expanded scale (model 902) combined with gel-filled electrodes adapted to higher hydrostatic pressures (Ingold, Frankfurt, model Pt 4805 TPA and 405 TPA). The electrodes were lowered into the lake by coaxial cable. The pH values were corrected for in situ temperatures. Redox potentials were converted from platinum-calomel to platinum-hydrogen values.

Oxygen was determined by the azide modification of the Winkler method (Am. Public Health Assoc. 1971). Immediately after sampling, duplicate 130-ml BOD bottles were filled and fixed; they were titrated in the laboratory within 2 h. Sulfide was determined according to the titrimetric method (Am. Public Health Assoc. 1971). Samples taken with the oxygen samples were placed in 130-ml BOD bottles with 1 ml of 2% $CdCl_2$ solution for immediate

Table 1. Precipitation (p, in mm) and evaporation (e, in mm) for meteorological station of Elat from 1968–1974. Columns start with September (representing beginning of stratification). Cloudbursts are underlined.

	'67-'68		'68-'69		'69-'70		'70-'71		'71-'72		'72-'73		'73-'74	
	p	e	p	e	p	e	p	e	p	e	p	e	p	e
Sep	-	-	-	352	-	386	-	365	-	367	-	353	-	356
Oct	-	-	-	(250)	0.8	258	-	278	-	277	-	260	-	266
Nov	-	-	19.7	(200)	3.2	208	1.4	171	-	187	20.7	168	27.2	174
Dec	-	-	-	141	-	146	0.3	130	84.2	121	-	141	-	152
Jan	0.8	132	23.6	126	2.0	140	14.0	144	3.7	133	-	143	8.5	114
Feb	2.9	178	-	160	-	170	0.8	146	4.2	171	-	158	5.4	140
Mar	2.8	247	22.5	226	-	259	7.5	249	5.2	195	-	288	12.8	202
Apr	24.0	289	3.1	259	-	328	5.1	274	0.9	293	5.1	296	0.3	297
May	11.6	390	-	396	-	425	-	368	-	357	-	403	-	394
Jun	-	449	-	459	-	467	-	407	-	404	-	429	-	438
Jul	-	473	-	(450)	-	441	-	437	-	422	-	443	-	472
Aug	-	436	-	473	-	460	-	403	-	406	-	436	-	407
Total			68.9	3492	6.0	3688	29.1	3372	98.2	3333	25.8	3518	54.2	3412

fixation and titrated within 2 h. The results were corrected for pH, salinity, and temperature according to Platford (1965). When the sulfide concentration was lower than 1 mM, the methylene blue visual color matching method (Am. Public Health Assoc. 1971) was used.

Results

The water budget of the lake is governed by evaporation, seepage of seawater, and precipitation. Evaporation and precipitation data for the Elat area over the period 1968–1974 are summarized in Table 1. The evaporation is extremely high in this region with maximum values of 473 mm month^{-1} (July 1968) and a minimum of 114 mm (January 1974). The annual average evaporation of seawater in the gulf is 3.5 m; pan evaporation experiments with Solar Lake brine gave a value of 3.0 m. Precipitation in the Elat area is low and irregular with a coefficient of variation of 84.0% for the last 40 years. The variation in annual precipitation during the period of our survey was between 6 (1969–1970) and 98.2 mm (1971–1972). Although precipitation is low, it influences the water balance of the lake for several reasons. Rainfall in this region is usually limited to occasional showers, 40% of which are collected as runoff (D. Sharon pers. comm.). The ratio of the catchment area to the surface area of the lake reaches 21.8. The addition of rainwater on top of the Solar Lake brine (180‰ salinity) is much more effective in establishing a stable pycnocline than the addition of seawater via seepage. The annual average rainfall (measured from 1930 to 1963) of 25 mm can add a volume of about one-fifth of the mean volume of the lake (10,244 m^3: Eckstein 1970). During our investigation the contribution

Table 2. Annual variations in limnological cycle of Solar Lake and maximal water temperature. s—Stratification; h—holomixis. Examinations made four times monthly, each indicated by a symbol.

Year	Max temp	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1968	54.0 °C	ssss	ssss	ssss	ssss	ssss	ssss	ssss	hhhh	hhhs	ssss	ssss	ssss
1970	56.6 °C	ssss	ssss	ssss	ssss	ssss	ssss	shhh	hhhh	hsss	ssss	ssss	ssss
1971	48.5 °C	ssss	ssss	ssss	ssss	ssss	ssss	hhhh	hhhh	hhss	ssss	ssss	ssss
1972	50.5 °C	ssss	ssss	ssss	ssss	ssss	ssss	sshh	hhhh	ssss	ssss	ssss	ssss
1973	48.0 °C	ssss	ssss	ssss	ssss	sssh	hhhh	hhhh	hhhh	ssss	ssss	ssss	ssss
1974	60.5 °C	ssss	ssss	ssss	ssss	ssss	ssss	shhh	hhss	ssss	ssss	ssss	ssss

of flash floods to the total water volume ranged between 7.5% (1969–1970) and 77% (1971–1972), strongly influencing the annual limnological cycles (Tables 1 and 2).

The main constant source of water to the lake is seepage of seawater through the bar, influenced by daily (tidal) and annual sea level changes in the Gulf of Elat. The annual cycle of average daily water levels (Meteorol. Surv. Israel 1968–1974) indicates generally high levels from November–May (max, 55 cm above MSL) and relatively low levels from June–October (min, 10 cm below MSL). Changes of water level in the open sea are not directly reflected in the lake, which shows only minor daily tidal changes. The influence of the tides generally decreases with increasing distance from the open sea. Tidal movements were measured for 6 days in 1972 in a well on the bar (30 m from the sea) and in a pool dug in beachrock close to the shore of the lake (60 m from the sea). One set of measurements is presented in Fig. 2: water level changes are reduced and delayed with increasing distance from the open sea.

Seepage of seawater into the lake is restricted to a zone above the summer level of Solar Lake. Water enters through 11 to 14 wells in the beachrock on the eastern shore of the lake and also from the western shore, indicating that seawater flows around the lake in a separate groundwater system. The lake itself is sealed off by beachrock, laminated cyanobacterial mats, and gypsum crusts.

As a result of capillary tension, combined with retarded hydrostatic pressure in the bar, the groundwater level in the bar sediments is higher than the lake and sea level (Fig. 2). When the cyanobacterial mat was perforated with a corer and the core removed, an artesian well was formed: this indicates that relatively high groundwater pressure is built up by tidal action pumping water through the bar. Though tidal changes are minimal in the lake itself, seepage rates change with the changing tidal levels of the gulf. The tides produce different artesian pressures and thus create different flow rates through the cracks in the beachrock. Generally more seawater seeps into Solar Lake in winter than in summer. We measured an average daily inflow of about 100 m^3 in September. According to the annual changes in average daily sea levels, inflow rates are lower in July and August and somewhat higher from October–May. Assuming an average daily inflow of 100 m^3, we calculate the annual inflow reaches 36,500 m^3. Precipitation may add not less than 500 m^3 and, in extremely rainy years, up to 4,000 m^3

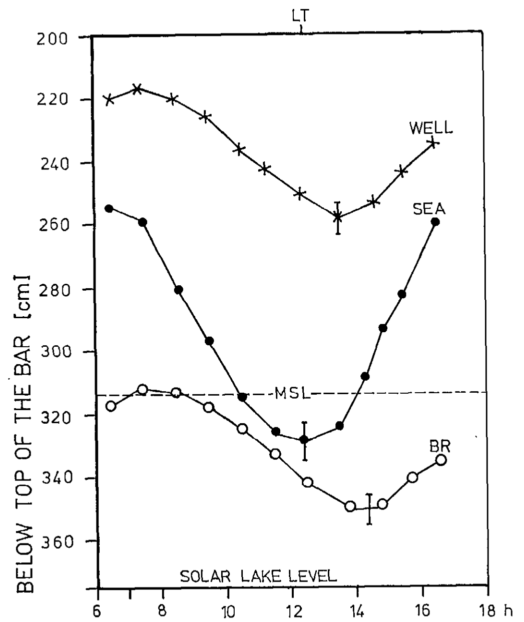

Fig. 2. Diurnal fluctuations in water levels related to tide at various points between sea and Solar Lake, 7 September 1972. Well-water levels measured in drillhole on top of bar; sea level of open gulf measured 20 m east of well; beachrock bore (BR) water level measured on seaward shore of Solar Lake; low tide (LT) according to predicted tides (Elat harbor).

yr^{-1}. Average values are difficult to give because of the high variability in rainfall.

The average annual evaporation rate for Solar Lake is 3.0 m (calculated from pan evaporation experiments: Aharon 1974). The integrated values of monthly evaporation yielded a total of 32,530 m^3 yr^{-1}. We must therefore assume water losses of about 5,860 m^3 yr^{-1} by means other than evaporation. The only other possible means is by outflow through the bottom of the lake, probably through a tectonic crack system that runs north–south through the central part of the lake; the crack system has been mapped by SCUBA diving during summer.

The water balance can be formulated as follows:

$$\Delta V = V_{in} + V_p - V_e - V_{out},$$

where V_{in} = inflowing seawater, V_p = precipitation + runoff, V_e = evaporation, and V_{out} = outflowing brine. The calculation of the water balance by month yields a negative ΔV for the period from May–August and a positive ΔV for the period from September–March. In 1971–1972 the water level of the lake changed by 1.4 m over the year.

We calculated the residence time of the water in the lake to be 5.5 months. The geochemical water balance was calculated by Aharon (1974), based on the concentration of cations in the lake and the facts that precipitation of minerals in the lake is restricted to gypsum and carbonates and that no halite is found in the lake sediments. These calculations indicate that 5,881 m^3 flow out each year. The residence time calculated according to the geochemical balance was 5.5–6 months.

Because seawater and rainwater are added only at the surface, a pycnocline is rapidly built up in the lake in winter. During maximal stratification, the differences of water densities from top to bottom ($\Delta\sigma$) reach 0.578 g cm^{-3}, allowing a high degree of stability during winter.

Chlorosity and salinity—Water level and salinity profiles change throughout the year (Fig. 3) due to high evaporation in summer, continuous seepage of seawater, flash floods in winter, and reflux of brines to the open gulf. Chlorosity was highest in summer, reaching values of 90‰ throughout the water column. A recorded maximum of 100‰ (salinity 180‰) occurred at 3–4-m depth in October 1970. In winter chlorosity of the surface layers gradually decreased due to the continuous supply of seawater and flash floods, reaching a minimum of 35‰ (salinity 68‰).

Temperature—The annual changes of water temperatures are summarized in Fig. 4. During stratification an exceptionally steep temperature gradient built up: at maximal stratification, a difference of 34°C was measured within a vertical distance of 2 m. In 1970 a maximum of 56.6°C was reached at 2.5–3-m depth. During holomixis the temperature was 27°C throughout the water column.

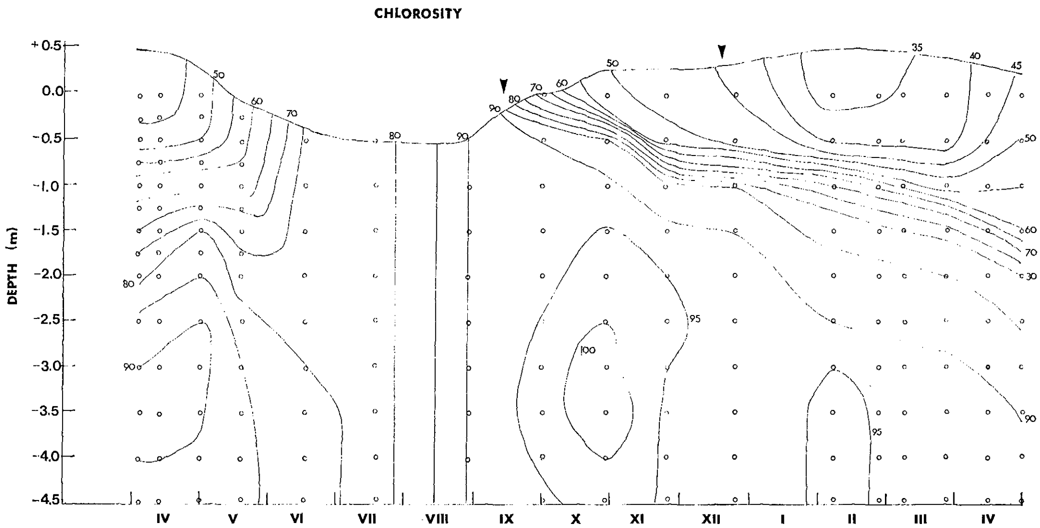

Fig. 3. Seasonal and vertical distribution of chlorosity (‰), April 1970–April 1971. Arrows—introduction of freshwater by flash floods.

The thermal stratification was disturbed by a flash flood in January 1971 and later rebuilt to a new maximum of 48.5°C. Temperatures have been recorded from 1968 (Eckstein 1970); Por 1969) to 1974; a maximal temperature of 60.5°C was measured in April 1974 (*see Fig. 4*).

pH and redox potential—The pH values of Solar Lake (Fig. 5) developed the highest relative gradient during stratification; pH ranged from 6.9 at the bottom to 8.0 at the surface in fall and from 8.1–8.2 in spring. In summer pH values were relatively high and uniform: 8.2–8.8 through-

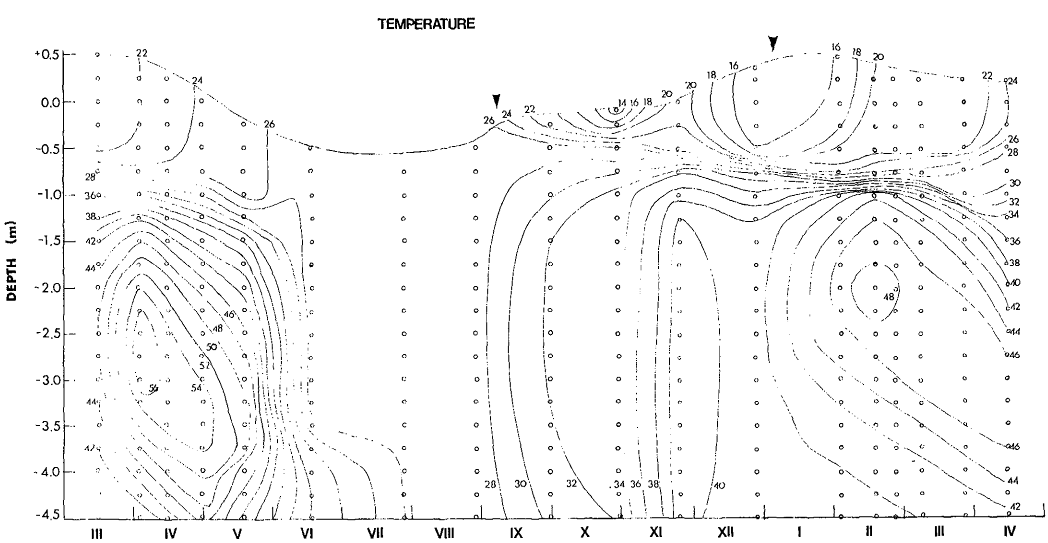

Fig. 4. Seasonal and vertical distribution of temperature (°C), March 1970–April 1971. Arrows as in Fig. 3.

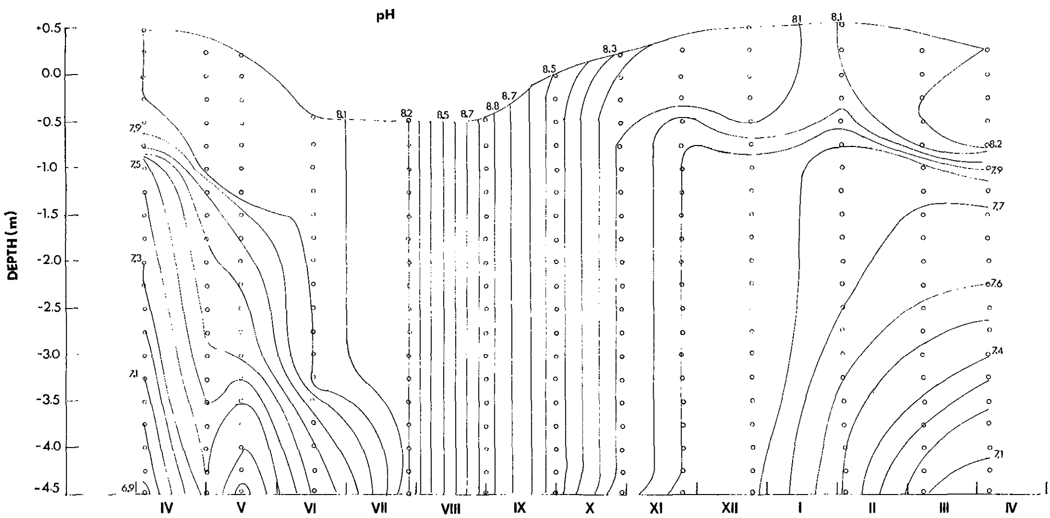

Fig. 5. Seasonal and vertical distribution of pH, April 1970–April 1971.

out the water column. The redox potential was not recorded continuously; Fig. 6 shows its vertical distribution during maximum stratification and holomixis in 1972. Several measurements in 1973 and 1974 showed a similar distribution. In summer the redox potential reached a uniform maximum value of +400 mV (corrected for hydrogen electrode). During stratification an extreme gradient built up, with a maximum of +390 mV at the surface and a minimum of –185 mV close to the bottom.

The low Eh values are caused by the accumulation of H_2S in the bottom layers of the lake. The annual development of oxygen and H_2S distribution in the water column is mainly governed by microbial activity (Cohen et al. 1977*b*). Figure 7 shows the vertical distribution of some limnological parameters during maximal stratification, including oxygen and H_2S distribution. Gradients were steep for all parameters recorded.

Discussion

Solar Lake is a mesothermic, hypersaline desert lake with extremely high solar heat accumulation and an unusual type of monomixis with summer overturn. Some of its unique features are caused by the facts that Solar Lake receives a constant supply of seawater seeping through beachrock and accumulating at the surface, that it is wind protected, and that it is subjected to extreme evaporation.

Because of the peculiar factors ruling the annual cycle, Solar Lake develops the highest solar-heated mesothermy so far recorded, with temperatures matched only by some geothermal hot lakes (Brock and Brock 1971). The vertical temperature in-

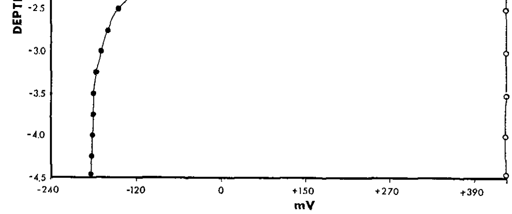

Fig. 6. Vertical distribution of redox potential at height of stratification, 8 March 1972 (●), and holomixis, 27 July 1972 (○).

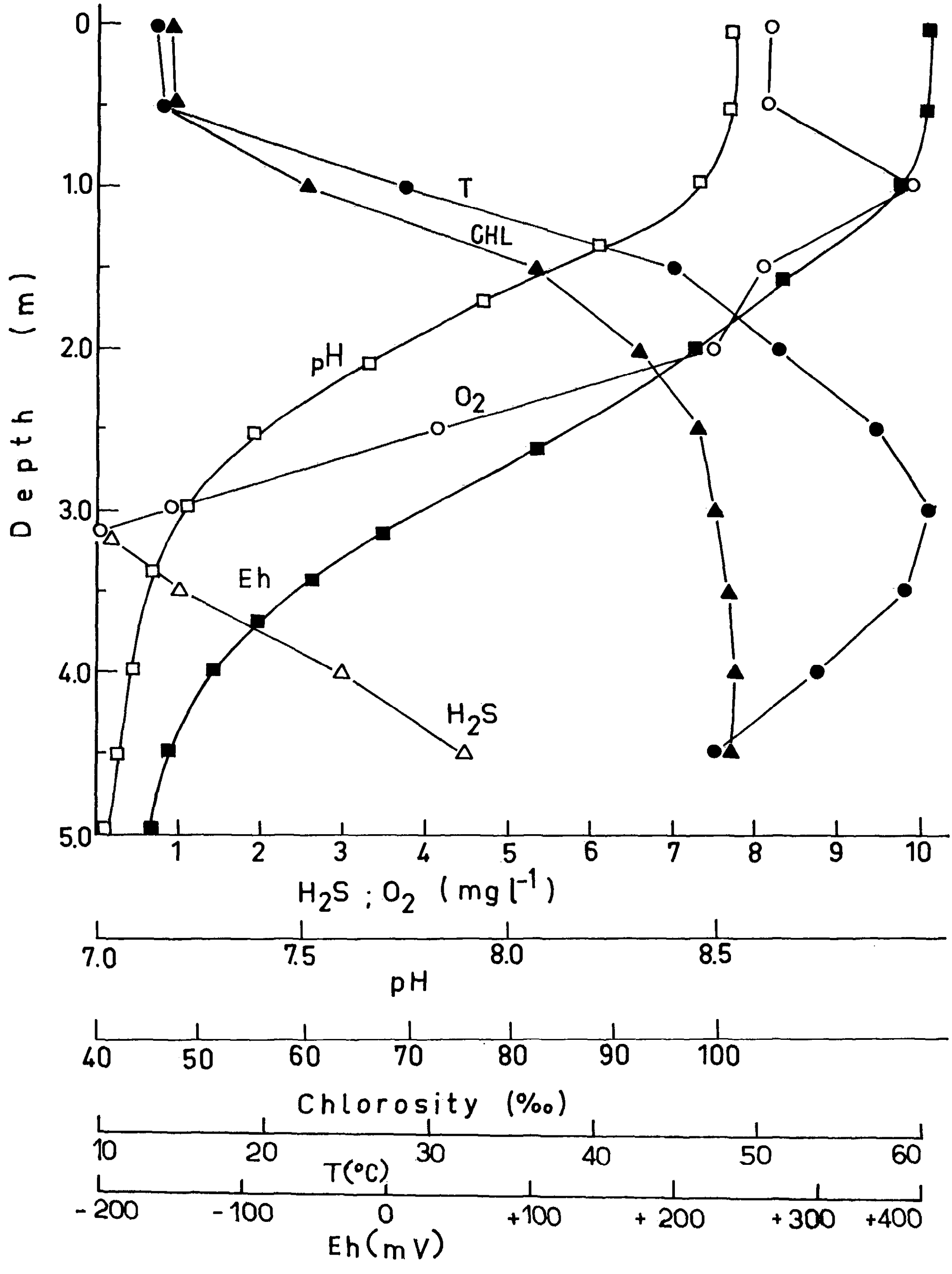

Fig. 7. Vertical distribution of temperature, chlorosity, H_2S, O_2, pH, and Eh at height of stratification, 4 April 1974.

crement during stratification may reach values as high as 18°C m^{-1}. These extreme temperatures and steep thermogradients rapidly disappear in summer when the supply of seawater can no longer compensate for the high evaporation rate. Holomixis then occurs and lasts for several weeks, and the water level reaches a minimum. The holomictic lake has uniform salinities of 180‰ and a temperature of about 27°C. The brine is relatively clear and the Secchi disk can be seen to the bottom; 25.7‰ of the surface light intensity in the visible range reaches bottom.

With decreasing insolation at Solar Lake in September, along with maximal high tides and frequent southern storms, additional hydrostatic pressure is exerted on the groundwater system surrounding the lake (Krumbein and Cohen 1974). The seepage, restricted to the uppermost layers of the lake, leads to the establishment of a pycnocline at this time. Occasional rainfall in winter together with runoff from the catchment area and occasional floods from the southern wadis bring about additional dilution in the upper layers of the lake. A temporary distortion of the stratification may occur due to these floods (*see Figs. 3 and 4*).

Together with establishment of the pycnocline, a well defined thermocline develops. Solar energy is absorbed mainly at the pycnocline and in the brine below. Later, the development of communities of pigmented photosynthetic microorganisms in these layers enhances the process. Due to the high density of the brine, water expansion by heat is not sufficient to allow overturn. The high density gradient between the hypolimnion and the epilimnion allows mesothermy to increase from September to April and remain stable until June. In the Elat area, the monthly solar energy from October–February ranges from 5,500–8,800 g cal cm^{-2} (Neumann 1952). From February–March it increases from 7,100–10,000 g cal cm^{-2}, and it reaches a maximum of 13,250 in June. Thus the increasing evaporation rates first compensate for the diluting effect of seawater seepage into the lake and then lead to increasing salinities in the surface layer together with lowering of the water level. This process is accelerated during April and May. Toward the end of June, during maximal solar irradiation, chlorosity reaches 75‰ at the surface. Surface temperatures are kept relatively low as heat is lost by evaporation. At this time the density gradient disappears and mixing begins. By the end of July overturn is complete.

A pronounced biological cycle (Cohen et al. 1977*a,b*) accompanies the physicochemical cycle of this type of monomixis. Together with the physical establishment of the pycnocline and thermocline, the biological development in the water column produces other chemoclines and causes pronounced gradients of pH, Eh, and light penetration. The pH gradient during stratification is probably caused by the fermentation processes of highly active heterotrophic bacterial communities; the decrease of pH through fermentation overrides the increase which would be expected from *Desulfovibrio* activity. The sulfide oxidation by photosynthetic sulfur bacteria and cyanobacteria (Cohen et al. 1975) may contribute further to the observed pH decrease toward the bottom. The steep redox potential gradient is mainly controlled by the different communities of microorganisms ruling the O_2-H_2S concentrations in the water column during stratification (Cohen et al. 1977*a,b*).

The annual cycle, here described for 1970–1971, was also studied during the following 3 years and generally followed the same pattern. But such external factors as winter precipitation, differences in air temperatures, the occurrence of southern storms, and of low water levels due to tides in the Gulf of Elat modified the periods of stratification and the time of overturn. Cool and rainy weather in 1973–1974 resulted in prolonging stratification to more than 11 months (Table 2); the maximal water temperature of 60.5°C was then recorded (Fig. 7). In contrast, the relatively dry and warm winter in 1972–1973 caused a shorter period of stratification (<9 months), with a low maximum water temperature of 48°C (Table 1).

The record of several annual cycles of stratification and holomixis in this small lake shows a remarkably unusual limnological pattern, opposite to that of other subtropical warm monomictic lakes. The temperature profile is inverse. The thermocline builds up in winter instead of early summer and overturn is completed in July, which in normal monomictic lakes of the northern hemisphere is the time of maximum stratification. In addition, hypersaline and mesothermal conditions create an extreme environment that allows development of communities where prokaryotic organisms predominate.

The historical development of Solar Lake has been reconstructed by analyzing the sediments of the lake. Several cores with cyanobacterial laminites were taken at the shallow parts of the lake, the slope, and in the deep section. In addition two deep wells were drilled with commercial equipment on the bar separating the lake from the gulf (well 1 = 7.6 m), and on the shores of the lake itself (well 2 = 5.6 m). The presence of the cyanobacterial laminites allowed us to count annual layers. Reliable ^{14}C age determinations were possible because a high percentage of organic matter is preserved (Krumbein and Cohen 1974).

The bottom of these cores indicates that the lake was originally an open bay, similar to bays presently situated immediately north of it and in the southern parts of the Gulf of Elat. A bar was built up slowly, closing off the lagoon. This process was followed by development of a fringing reef at the seaward side of the bar; the drilling revealed no reef below the bar itself. Such processes can now be observed at other places along the Sinai shore of the Gulf of Elat. After the bar was substantial enough to slow seawater inflow and to create higher salinities in the lagoon, the faunal associations decreased in species diversity. The beachrock which developed at that time at the eastern shore of the lagoon contains only *Pirenella conica* and *Brachidontes* sp. This community—still found in the bays north of the pond—indicates a lagoonal environment. The organic matter and carbonates of the fossils in the beachrock yielded ^{14}C ages between 4644 ± 555 (organic compounds) and 3378 ± 172 B.P. ($CaCO_3$ of the fossils) (Friedman et al. 1973). A cleaned sample of *P. conica* and *Brachidontes* sp., analyzed by M. A. Geyh (pers. comm.), yielded an age of 3430 ± 90 B.P.

Thus the lagoonal stage was reached at about 3400 B.P. After this waters evaporated into a brine allowing precipitation of carbonates and gypsum. At about 2490 ± 155 B.P. a "shallow water" cyanobacterial mat (Golubic 1973; Krumbein et al. 1977) almost completely replaced the gypsum and carbonate precipitation in the entire lake. At the same time *P. conica* and *Brachidontes* sp. disappeared. The lagoon then closed off completely and cyanobacterial laminate formation prevailed throughout the lake. The cores from the center and slope of the lake show an intermediate stage of massive mats sandwiched between thick deposits of recrystallized gypsum (*see* Krumbein et al. 1977: figure 1). These organic deposits are gypsum-free owing to *Desulfovibrio* activity, whereas bacteriogenic carbonate precipitation continued (Krumbein et al. 1977). The uppermost cyanobacterial lamina of this stage in the two cores was dated 1935 ± 130 B.P. This marks the end of a shallow water mat stage (Golubic 1973) lasting about 555 years and indicates a sudden change in limnological conditions establishing the present conditions; the uniformity of the mat deposited from 2400 B.P. to 1935 B.P. can only be explained by shallow water conditions throughout the whole lake. We assume that the sudden change in limnology and depositional environment was caused by a subsidence of the central part of the bottom. With the establishment of the present Solar Lake, four different mat types (Krumbein et al. 1977) replaced the flat shallow mat, uniform throughout the lake. It is possible that a prolonged period of higher annual rainfall increased the deposition of clastic mate-

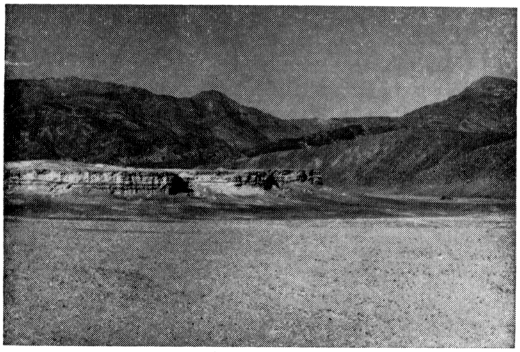

Fig. 8. Example of a fossil Solar Lake as witnessed by stromatolitic sediments 20 km south of Solar Lake.

rial and caused a subsequent decrease in cyanobacterial growth. Such a period of delivery of greater amounts of clastic material is especially obvious at 12–13-cm depth (1880 to 1890 B.P.). This silt layer can be attributed to a big flood entraining material from the wadi south of Solar Lake (Krumbein and Cohen 1974). The laminated mats can thus serve as a record of changes in climatic conditions in this area during the last 2,400 years. They might possibly be correlated to dendrochronological evidence (Fahn et al. 1963).

Processes similar to those occurring in Solar Lake are recorded for different sediments of other hypersaline environments along the shores of Sinai (Owen 1973; Por 1971). Some of these environments are still open to the sea and in the lagoonal stage, others are just starting to close.

Figure 8 shows an old lake which, after having been filled completely by gypsum and cyanobacterial mat sediments, and after compression and dehydration, has been partially eroded by a recent wadi. This sediment sequence is evidence both of the occurrence of fossil examples of such lakes along the shores of the Gulf of Elat and of sea level changes (decreasing in this case) in the late Pleistocene in this part of the world.

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