UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

# The Heliothermic Lake--
# A Direct Method of Collecting
# and Storing Solar Energy

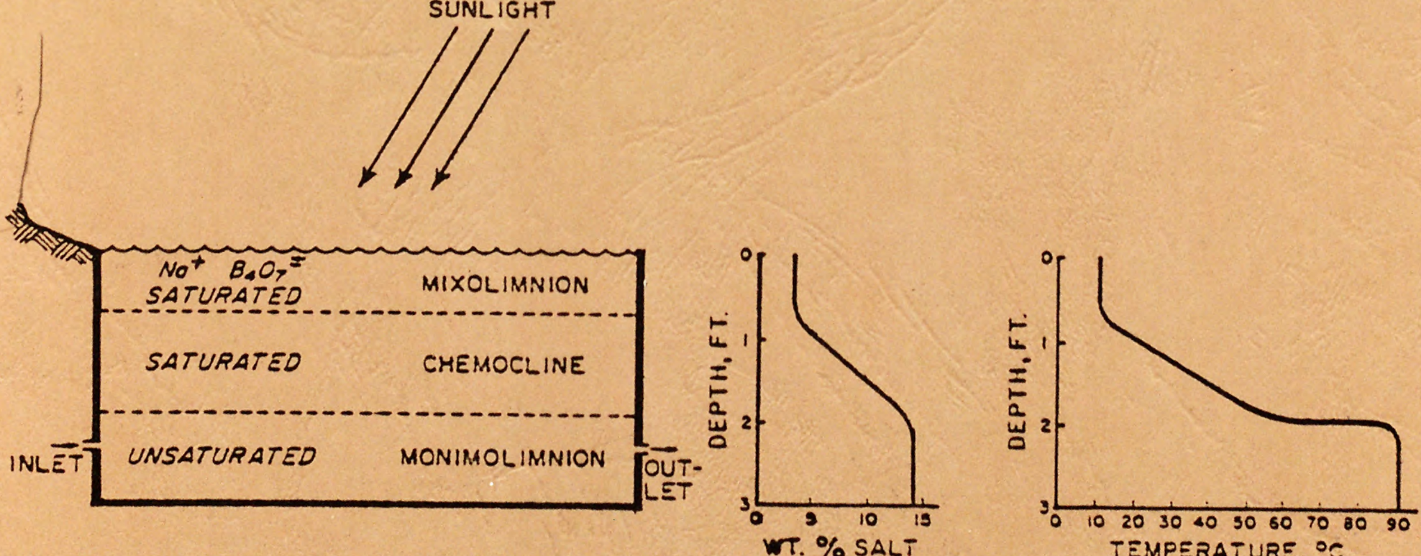
By

Douglas W. Kirkland,

Mobil Research and Development Corporation,

and by J. Platt Bradbury and Walter E. Dean,

U.S. Geological Survey



(200)
R29o



U.S. GEOLOGICAL SURVEY
Reston, VA 22092

Memorandum

Date Nov 19, 1980

To: Staff Production Controller, Geologic Div.

From: Chief, Office of Scientific Publications

Subject: New USGS open-file report

The following report was authorized by Henry Spall for the Director on 5/9/80 for release in the open files: (9760-01767)

TITLE: The heliothermic lake: a direct method of collecting and storing solar energy

AUTHOR(S): Douglas W. Kirkland, J. Platt Bradbury and Walter E. Dean

CONTENTS: 133 p., ______ over-size sheets (i.e., larger than 8½ x 11 inches)

Map scale: ______

**Depositories:**

(NC) USGS Library, Room 4A100, 12201 Sunrise Valley Dr., Reston, VA 22092
(Da) USGS Library, 1526 Cole Blvd. at West Colfax Ave., Golden, CO
(Mail address: Stop 914, Box 25046, Federal Center, Denver, CO 80225)
(M) USGS Library, 345 Middlefield Rd., Menlo Park, CA 94025



| PRICE: | ORIGINATING OFFICE | |
|---|---|---|
| Fiche $ ______ | Name: USGS, DTRU, Stop 902 | Release date: DEC 1980 |
| | Address: Denver, CO | |
| Paper $ ______ | | Area: ______ |
| | Telephone: FTS- 234-2445 | OFR No. 80-807 |

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

# The Heliothermic Lake--
# A Direct Method of Collecting
# and Storing Solar Energy

By

Douglas W. Kirkland,
Mobil Research and Development Corporation,
and by J. Platt Bradbury and Walter E. Dean,
U.S. Geological Survey

Open-File Report 80-807
1980

CONTENTS

## APPENDIX I

Page



## APPENDIX II

TABLES

## LIST OF ILLUSTRATIONS

# THE HELIOTHERMIC LAKE--A DIRECT METHOD OF COLLECTING AND STORING SOLAR ENERGY

by

Douglas W. Kirkland[1]

J. Platt Bradbury[2]

Walter E. Dean[2]

ABSTRACT

Heliothermic lakes contain a sun-heated layer of warm, saline water beneath a surface layer of cooler, less saline water. The two layers are separated by a chemocline, a stratum in which salinity increases progressively with depth. The chemocline, the position of which varies from lake to lake, functions as a heat trap. Most sunlight that penetrates this stratum is transformed into heat, which cannot escape by radiation because water is opaque to infrared light, and which cannot escape by convection because the specific gravity of the dense water below the chemocline is not significantly decreased by the increasing temperature. Heat can escape only by conduction through the chemocline, and water or brine is a very poor conductor. As a result, the temperature within and commonly below the chemocline rises. Under ideal conditions of a clear solution, high isolation, and a suitable salinity distribution, the temperature of the chemocline will increase to the boiling point. The lower part of the chemocline in a shallow (0.8-m) manmade heliothermic lake at Sedom, Israel, for example, reached a temperature of 96°C (205°F) in spite of a brine with poor light transmissibility.

[1]Mobil Research and Development Corporation, Dallas, Texas 75221.
[2]U.S. Geological Survey, Denver, Colorado 80225

About 30 natural heliothermic lakes have been reported. The best known, Lake Ursului, occurs in Transylvania, Romania (latitude, 46°35'N). During four consecutive summers, 1899 to 1902, this lake had temperatures of 60-70°C (140-158°F) at a depth of 1-2 m. Heliothermic conditions have persisted in this lake for at least 28 and probably for more than 77 years. The most unusual, Lake Vanda, Victoria Land, Antarctica (latitude, 77°35'S), has a temperature of 26°C near the base of the chemocline at a depth of 61 m despite a mean atmospheric temperature of -20°C. Sunlight penetrates into the chemocline through 5 m of remarkably clear ice.

Maintenance of the chemocline is the chief problem preventing commercial use of manmade heliothermic lakes for the collection and storage of solar energy. The most effective means of preserving this stratum from destruction by diffusion and wind mixing may be the use of salts, such as sodium sulfate and sodium borate, whose solubilities are markedly influenced by temperature. The chemoclines of ponds constructed with such salts, in theory, would persist indefinitely and could be of great size.

# INTRODUCTION

The direct conversion of sunlight into a low-cost source of power is a major technological challenge. That it has not been met is mainly because two characteristics of sunlight present formidable obstacles: sunlight is very diffuse; and the intensity of solar radiation is variable, changing at a particular locality with the extent of cloudiness, the seasons and, of course, with the time of day. Because of these obstacles, solar collectors must be immense if large amounts of energy are to be collected, and the radiant energy that is collected must be stored if continuous supplies of power are to be maintained.

Heliothermic lakes contain an internal zone of warm water derived from the absorption of sunlight. These limnological oddities have received little attention in spite of the probability that artificial heliothermic lakes may become a relatively inexpensive means of exploiting solar energy (Tabor and Matz, 1965). Natural heliothermic lakes have been investigated in North America, Europe, Asia, Africa and Antarctica, yet an integrated account of the limnology of such lakes has not been previously attempted. The absence of such a synthesis is difficult to understand in light of the intriguing thermal history of heliothermic lakes. Textbooks on limnology (e.g. Ruttner, 1952, Hutchinson, 1957; Wetzel, 1975) devote only a few sentences to this unusual lake type.

The first part of this report is a synthesis of the basic physical limnology of natural heliothermic lakes. We then review basic problems involved with production of hot water within manmade heliothermic lakes and recommend a simple method of constructing heliothermic lakes that avoids their major problem--maintenance of the heat-trapping mechanism. Descriptions of various natural heliothermic lakes and of the limonology of several artificial heliothermic lakes (chiefly those constructed by scientists with the National Physical Laboratory of Israel) are included in Appendixes I and II.

## WHAT IS A HELIOTHERMIC LAKE?

Any lake that shows a subsurface maximum on a profile of temperature vs. depth is called mesothermic (Hutchinson, 1957, p. 479). Mesothermy may be a permanent feature of a lake or may occur only during rare, short periods of time as after a heavy rain or under thin ice. A heliothermic lake is a special type of mesothermic lake in which a sun-heated layer of warm water exists beneath a layer of cooler water, a stratification that may be permanent. Temperatures attained in the zone of warmer water can be extraordinary; the maximum recorded within a natural lake is 70°C (158°F) (Roth, 1899); the maximum reported within a man-made heliothermic lake is 96°C (205°F) (Tabor and Matz, 1965).

Most heliothermic lakes are also meromictic; that is, they are stratified with a lower, stagnant, more saline water mass called the monimolimnion and an upper, less saline water mass called the mixolimnion that undergoes periodic circulation. The transition zone between these two layers is called the chemocline and acts as a heat-trap in heliothermic lakes. Within the chemocline, salinity (usually imparted by sodium chloride) increases progressively and usually substantially with depth. Sunlight that penetrates into or through this zone is either reflected back into the atmosphere from particulate matter or from the bottom of the lake or is absorbed and transformed into heat. A relatively small amount of solar energy may be tied up as chemical energy by photosynthetic organisms. Escape of this heat is greatly impeded. Loss of heat by convection through the chemocline will be retarded because the salt-induced increase in specific gravity with depth compensates for any decrease in specific gravity resulting from the increase in water temperature. In addition, the hot water within and beneath the salinity barrier (the chemocline) will lose little heat by radiation because water is virtually opaque to long-wavelength infrared radiation corresponding to the peak of thermal radiation at 30-90° C.

The chemocline of a heliothermic lake is analogous to the glass panes of a greenhouse in that it prevents loss of heat by suppressing convection and radiation. Thin glass panes, however, provide little protection from loss of heat by conduction. Virtually the only way that heat can escape from the "hot zone" of a heliothermic lake is by conduction; loss of heat by conduction, however, proceeds at a slow rate through the chemocline because water, even when saturated with sodium chloride (Kaufmann, 1960), is a poor conductor (1 m of nonconvecting water is about as good an insulator as 5 cm of styrofoam (Rabl and Nielsen, 1975)).

Discrete strata of water sometimes many meters thick commonly overlie the chemocline. Convection can occur in both of these zones if they are of uniform density. Heat can be lost from the upper stratum to the atmosphere by radiation, conduction, and evaporation. Heat is lost from the lower stratum only by conduction through the chemocline and to the sides and bottom of the lake.

If pronounced heliothermic conditions are to arise, it is important that the chemocline be penetrated by a substantial proportion (generally >3 percent) of the solar energy that impinges on the surface of the lake. Thus, the salinity barrier must occur within several meters of the surface unless the waters of the lake are unusually transparent.

# PHYSICAL LIMNOLOGY OF NATURAL HELIOTHERMIC LAKES

## Salinity

The role of salinity within heliothemic lakes is passive. Dissolved salts are important primarily because of their effect on specific gravity. Heliothermic conditions are apt to arise in a lake whenever a near-surface layer of relatively fresh water floats on a brine. The difference in specific gravity between the layers need not be large in order to preserve stability; the increase in specific gravity that results from the dissolved salt usually more than compensates for the decrease in specific gravity that results from any increase in temperature. In Espevick Pond, Norway, for example, the difference in salinity between the upper and lower strata is only about one percent.

The salt dissolved within the water of most natural heliothermic lakes is sodium chloride. Other highly soluble salts are effective; magnesium sulfate, for example, is the chief salt of Hot Lake, Washington, and calcium chloride is the principal salt of Lake Vanda, Antarctica.

### Types of Salinity Zonation

The zonation of salinity within heliothemic lakes is usually tripartite as shown in figure 1. The upper layer, the mixolimnion, is a zone of uniform salinity in which currents (generated either by wind or differences in water temperature) are free to circulate. If the mixolimnion is too thick (or too highly colored), sunlight cannot enter the monimolimnion and a "hot zone" will not form. This was the situation in Lake Negru, Romania, in late July 1901.

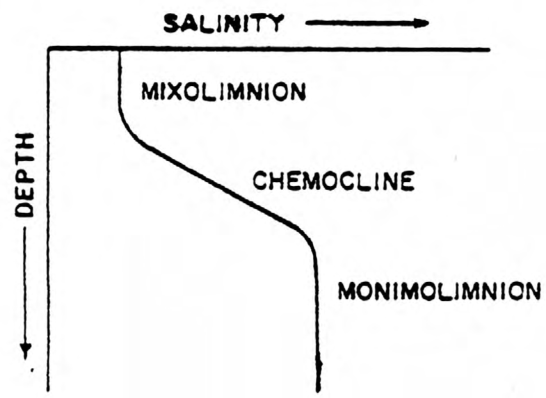



Figure 1.--Tripartite zonation of salinity found in most heliothermic lakes Examples include Lake Bonney, Antarctica; Solar Lake of Elat, Israel; and Devil's Kettle, Bahamas.

The middle layer, the chemocline, is the zone that is responsible for the trapping and retention of heat. Salinity increases progressively with depth within the chemocline, and this zone forms a transition between the mixolimnion and the underlying layer, the monimolimnion, which like the mixolimnion is essentially isohaline. The monimolimnion is a chemically stabilized zone of relatively dead water in the lower part of a heliothermic lake. Water sometimes circulates slowly within the monimolimnion, but this water does not mix with water of the mixolimnion (or, for that matter, with water of the chemocline). The mixolimnion and the monimolimnion are fundamentally different zones, each having distinct chemical, physical and biological properties. It is almost as if there were two separate lakes, one above the other, with the chemocline acting as a boundary zone. The mixolimnion, for example, may be rich in dissolved oxygen and usually supports abundant life, the monimolimnion, on the other hand, is almost always rich in dissolved hydrogen sulfide and usually supports only microbial life.

Other distributions of salinity may develop within heliothermic lakes. The chemocline, for example, may prevail from top to bottom as shown in figure 2.

Heliothermic lakes must <u>always</u> have a chemocline, but either the mixolimnion or the monimolimnion may be absent as shown in figure 3.

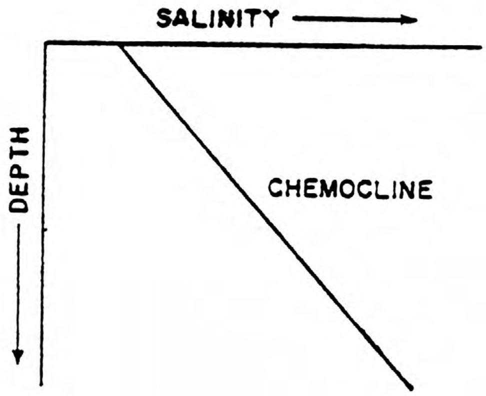



Figure 2.--Linear distribution of salinity in heliothermic lakes that lack both a mixolimnion and a monimolimnion. Examples include Lake St. Ioan, Romania; Red Pond, Arizona; Hot Lake, Washington, and Cape Evans Pond, Antarctica.

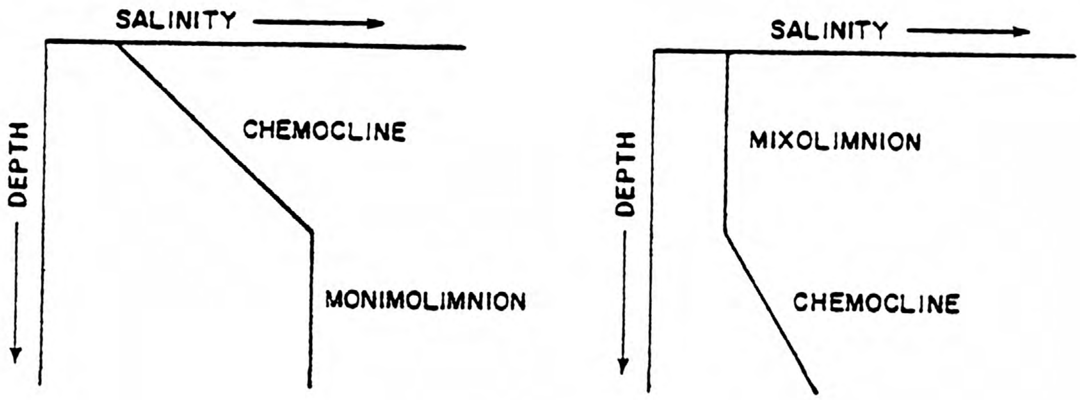



Figure 3.--Distribution of salinity in heliothermic lakes that lack a mixolimnion (left) or a monimolimnion (right). Left example, Lake Ursului, Romania; right example, Lake Vanda, Antarctica.

Multiple sets of chemoclines and monimolimnions are possible but are rarely found in heliothermic lakes; an example of such a salinity distribution is shown in figure 4.

A large number of different salinity profiles are possible; however, in nature, the observed salinity distributions of heliothermic lakes fall into the five general classes illustrated (Figs. 1-4).

Destruction of Salinity Zonation

The salinity zonation may be ephemeral or perennial. The longevity of heliothermic conditions depends on the degree of protection from processes that tend to destroy the salinity stratification and (or) gradient and thus permit convection. Four processes of this nature are considered below.

Increase in temperature:

If the temperature of the monimolimnion or of the chemocline were to increase substantially, the specific gravity of these zones might decrease until it was less than that of the overlying mixolimnion. The lake would then become unstable, and the various zones would mix. Such an inversion is probably uncommon because only a slight difference between the concentration of salt in the mixolimnion and moninolimnion is required in order to prevent complete circulation despite a substantial increase in the temperature of the monimolimnion. A layer of fresh water at 20°C overlying a solution of sodium chloride with a concentration of only 3.5 percent (35 $^{o}/oo$), for example,

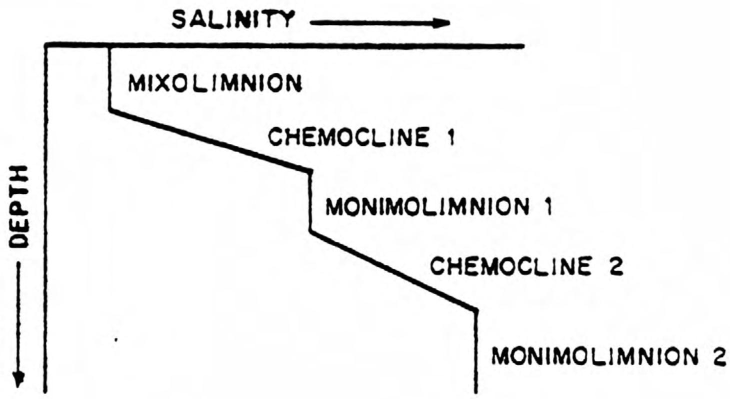



Figure 4.--Distribution of salinity in a heliothermic lake that has multiple sets of chemoclines and monimolimnions. Example: Lake Avran Iancu, Romania.

would not invert until the temperature of the saline layer reached 55-65°C. Man-made heliothermic lakes are stable up to the boiling temperature (117°C) if a nearly saturated solution of $MgCl_2$ is used in the monimolimnion (Tabor and Matz, 1965); a saturated solution of sodium chloride will also present convection up to the boiling point if there is a lower layer in which mixing can occur (a monimolimnion) (Tabor and Matz, 1965).

Increase in salinity:

Inversion would occur if the salinity of the mixolimnion were to increase until it equaled or exceeded that of the monimolimnion. The salinity of the mixolimnion increases slowly as water evaporates from its surface. In lakes in which there is insufficient influx of fresh water to replace that lost by evaporation, isohaline conditions will ultimately prevail. Such is the case for Red Pond, Arizona, and for Solar Lake of Elat, Israel; in both lakes a salinity stratification is established annually in winter and persists until late summer or fall, when isohaline conditions arise.

Diffusion:

Within heliothermic lakes there is continual movement of dissolved ions in the direction of lower concentration, that is, upward. The rate of diffusion, however, is remarkably slow. Experimental heliothermic ponds, for example, have been operated for months without being affected adversely by diffusion (Tabor, 1963). The rate of diffusion within Lake Vanda, Antarctica, has been calculated by Wilson (1967); the concentrated brine, about 10 times the salinity of seawater, in the lower part of the chemocline, diffuses upward at a rate of about 2.5 cm per year. A more rapid rate of diffusion would occur if the bottom water were warmer than 26°C, the present temperature.

Wind mixing:

A mixolimnion that has a thickness on the order of centimeters may be thickened substantially by waves in a matter of hours. As the mixolimnion gets progressively thicker, the strata within a lake exhibit greater and greater stability. Ultimately, if thick enough, energy imparted by wind-generated currents will be dissipated entirely within the mixolimnion, and underlying zones will not be significantly affected.

Wind moving across the surface of a lake with a mixolimnion several meters thick results in currents in the upper part of the mixolimnion. These currents are deflected at the shore, and commonly a counter-current becomes established in the lower part of the mixolimnion. These reverse currents erode the chemocline and ultimately result in a mixolimnion that is thicker and more saline. The extent of disruption depends chiefly on the velocity of the counter-currents, on the thickness of the chemocline, and on the difference between the specific gravity of the mixolimnion and that of the monimolimnion.

All heliothermic lakes that are essentially perennial have some type of natural protection from wind. Examples of such features are:

| | |
|---|---|
| cinder cone | Cinder Cone Pool, New Mexico |
| oak trees, topography | Lake Ursului, Romania |
| permanent ice | Lakes Vanda and Bonney, Antarctica |
| sink hole | Mead Salt Well, Kansas |
| topographic depression | Hot Lake, Washington |
| cliffs, gravel barrier | Solar Lake of Elat, Israel |

Trees provide a degree of protection from wind mixing for the heliothermic lakes of Romania and Norway. Near-surface windspeeds are markedly reduced by trees; shelter from wind is provided for a distance of about 20 times tree height (Critchfield, 1966, p. 292).

With the exception of the ice-covered heliothermic lakes of Antarctica, all perennial heliothermic lakes are small (surface area <1 $km^2$). Given identical salinity profiles and conditions of wind (velocity, duration, etc.), the salinity distributions of large lakes have a greater chance of being disrupted by waves and currents than the salinity zonation of small lakes. Distinct salinity stratification does exist in some large ice-free lakes, but wind mixing has increased the thickness of the mixolimnion at the expense of the monimolimnion to such an extent that the chemocline is now well below the depth of penetration of significant amounts of radiant energy. The chemocline in the Dead Sea, for example, lies at a depth of about 30 m.

## Preservation of Salinity Zonation

Ultimate preservation of the salinity distribution requires the addition of fresh water to the mixolimnion and the removal of salts from the mixolimnion.

### Addition of fresh water:

The mixolimnion may be diluted by springs, streams, or precipitation directly onto the lake. The mixolimnion of Lake Ursului, Sovata district, Romania, receives the inflow from two small permanent streams. This lake, in addition, has an outlet; consequently, excess salts are continually flushed from the mixolimnion.

Spring water freshens the mixolimnions of Red Pond, Arizona and Solar Lake of Elat. The mixolimnion may also be freshened by melt water (e.g., Hot Lake, Washington, and Red Pond, Arizona) and commonly by rain water (e.g., Cinder Cone Pool, New Mexico).

Removal of salts:

The mixolimnions of some heliothermic lakes contain substantial quantities of dissolved salts (e.g., Hot Lake, Washington, and Red Pond, Arizona). When the surfaces of these lakes freeze, salts are wholly or partially excluded from the ice and are forced into the lower part of the mixolimnion or into the chemocline. When the ice melts, a layer of relatively fresh water results. Under unusually frigid conditions, the freezing-out may be the dominant mechanism by which a salinity zonation is established. (See discussion regarding formation of the salinity gradient in Cape Evans Pond, Antarctica.)

## Light

Most events within a lake, whether of the heliothermic class or otherwise, are directly or indirectly determined by radiation the lake receives. Radiation that impinges upon the surface of a lake comes directly from the sun and indirectly from scattering of sunlight by the atmosphere. The diffuse solar radiation constitutes approximately 20 percent of the total (Hutchinson, 1957, p. 423). A varying proportion of solar radiation impinging on the surface of a lake is reflected back into the atmosphere; the specific proportion depends particularly on the angle of incidence, on the salinity of the surface water, and on the turbulence of the surface. Some light that penetrates the water is reflected back into the atmosphere by particulate matter and, possibly, from the bottom of the lake. Most of the rest is absorbed by the water, the solutes, the suspended material, and the bottom of the lake and is transformed into heat. Photosynthetic organisms fix a relatively small proportion of the radiant energy as chemical energy.

## Light Absorption in Pure Water

The extent of absorption of light in pure water varies with the wavelength of the light; the miminum absorption is from blue light (about 470 nm) (Hutchinson, 1957, p. 423). Percentages of radiant energy for various wavelengths of light (in the vicinity of the visible spectrum) that are transmitted through a layer of distilled water one meter thick are shown in figure 5. This figure shows that such a stratum of water is much more transparent to violet, blue and green light than to yellow, orange and red; only a small fraction of the red light that falls on the surface of a body of pure water is able to penetrate through one meter.

Consider the absorption of sunlight in seawater, a process that is similar to the absorption of light in waters of lakes and a process for which more data are available. Most of the red end of the spectrum is absorbed readily by pure seawater so that only 39 percent of the light that impinges on the surface is transmitted through one meter (61 percent being absorbed). Radiant energy that is transmitted through the second meter will be primarily light with wavelengths in the violet end of the spectrum. Because such light is not readily absorbed by water (Fig. 5), only about 5 percent of the total light that impinges on the surface will be absorbed between depths of 1 and 2

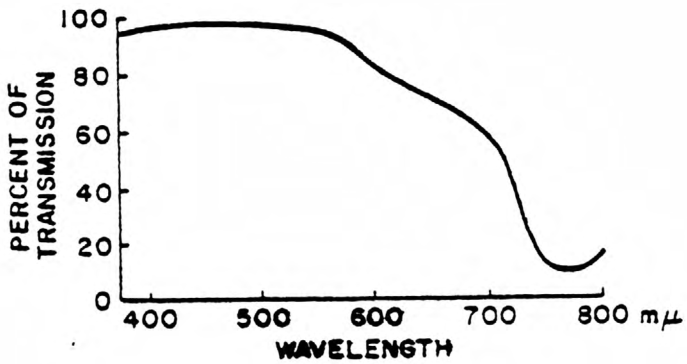



Figure 5.--The transparency of a stratum of distilled water 1 m thick with respect to different regions of the spectrum (after Ruttner, 1953).

meters (compared with 61 percent in the first meter). In fact, 28 percent of the total radiant energy at the surface will pass through 5 m and 22 percent through 10 m of pure seawater. The percentage of radiant energy impinging on the surface that penetrates to various depths in pure seawater, in extremely clear seawater, and in seawater of average clarity is shown in table 1.

Most natural lakes do not have water as transparent as average ocean water. Two ice-covered heliothermic lakes in Antarctica, Vanda and Bonney are notable exceptions; waters of these lakes are among the clearest in the world and compare in transparency with distilled water. Three main factors contribute to the great clarity of these two lakes: there is no influx of colloidal or humic substances, biological productivity is low, and particulate material settles rapidly because there are no wind-generated currents.

## Materials Affecting Transparency

The absorption of light by distilled water containing uncolored inorganic salts in solution does not differ appreciably from that of distilled water alone (Weinberger, 1964). The water of heliothermic lakes, however, commonly contains dissolved organic substances in addition to dissolved inorganic salts. These organic substances include humic acids, which if present even in slight amounts adversely affect transmission of light. Solutions containing humic acids readily absorb light with short wavelengths. Lakes containing high concentractions of humic compounds can completely absorb ultraviolet, blue, and green wavelengths in less than one meter (Wetzel, 1975, p. 55).

Table 1.--Percent of surface illumination penetrating to various depths in pure seawater, extremely clear seawater, and seawater of average clarity.

[Data from Sverdrup, Johnson, and Fleming (1942, p. 107)]

| Depth (m) | Pure seawater | Extremely clear seawater | Seawater of average clarity |
|---|---|---|---|
| 0 | 100 | 100 | 100 |
| 1 | 38.9 | 37.7 | 35.2 |
| 2 | 33.7 | 31.6 | 28.0 |
| 5 | 28.0 | 23.1 | 17.3 |
| 10 | 22.0 | 16.1 | 9.5 |

Light is also absorbed by materials in suspension, but this absorption is about the same for all wavelengths (Wetzel, 1975, p. 57). Suspended materials include tripton, the non-living suspended matter in a lake, as well as organisms. The inorganic fraction of tripton consists chiefly of clay- and silt-sized minerals. Particles of organic matter will either sink to the bottom or come to rest in the water column at a level corresponding to their specific gravity. Settling of particulates is accelerated by incorporation into zooplankton fecal pellets. If the salinity of the monimolimnion is high, many particulates may come to rest within the chemocline. The depth of penetration of light in heliothermic lakes can be affected greatly by suspended particulates. In the mixolimnion, phytoplankton and zooplankton are commonly prolific; light that is relected upward or absorbed by organisms in this zone cannot contribute to heliothermic conditions.

An optical measurement that is commonly made in lakes is the "Secchi disk transparency," or the depth at which a white disk 20 cm in diameter is just visible. The light intensity at the depth of disappearance of the disk is about 5 percent of that at the surface (Hutchinson, 1957, p. 424). The depth of disappearance of the Secchi disk in a number of heliothermic lakes occurs close to the depth of maximum temperature (e.g., Cinder Cone Pool, New Mexico; Hot Lake, Washington). This is because red or green sulfur bacteria occur in such great profusion within the hot zone that they form a barrier to deeper transmission of light. The colored sulfur bacteria use hydrogen sulfide as an oxygen acceptor in the photosynthetic reduction of carbon dioxide. They are present in most heliothermic lakes and frequently form a substantial proportion of the biomass. Sulfur bacteria commonly occur in such great numbers that the water in certain zones is distinctly red or green. The presence of these bacteria results in enhanced absorption of light, some of which becomes fixed within organic compounds as chemical energy.

Environmental factors controlling the distribution of sulfur bacteria are not entirely known, hence their concentration within the "hot zone" of heliothermic lakes cannot be fully explained. The bacteria may prefer the high temperatures of the zone of hot water, or they may contribute directly to the temperature rise in the "hot zone" through absorption of light. The sulfur bacteria are photosynthetic and, although they have "rather feeble photic requirements" (Hutchinson, 1957, p. 757), their demands for light may contribute to their distribution. A thin zone in which there is a great concentration of these bacteria, a so-called "bacterial plate", sometimes occurs within the uppermost part of the chemocline. Within this thin zone hydrogen sulfide from below and low concentrations of oxygen from above are available to the microbes.

## Temperature

Most radiation that penetrates into or through the chemocline of a heliothermic lake is transformed into heat whose loss is greatly impeded. Heat is not lost by radiation from the "hot zone" because water is virtually opaque to infrared radiation (800nm to 1 mm). Also, convection cannot occur within the chemocline if the salinity gradient is sufficiently large, and therefore heat is not transferred by convection from either the chemocline or the monimolimnion into the mixolimnion. A nonconvecting zone of water such as the chemocline creates an excellent layer of insulation. Thus, heat is transferred very slowly to the mixolimnion by conduction through the chemocline. The temperature in the chemocline and (or) the monimolimnion increases until loss of heat by conduction to the mixolimnion and to the sides and bottom of the lake balance the gain in heat from the absorption of sunlight.

## Types of Temperature Zonation

Several types of temperature zonation have been observed within heliothermic lakes. Kalecsinsky (1901) characterized a heliothermic lake as one enclosing a layer of warmer water between two layers of cooler water and, indeed, most heliothermic lakes have this thermal structure. A typical tripartite zonation of temperature is shown in figure 6. The "upper cool zone" occurs within the mixolimnion, the "warm zone" within the chemocline and sometimes within the upper part of the monimolimnion, and the "lower cool zone" generally occurs entirely with the monimolimnion.

In some lakes the hot zone may occur on the bottom. In lakes of this type, there is an upper cool zone, but the lower cool zone is absent. Examples are Lake Vanda, Antarctica, and Solar Lake of Elat, Israel.

Two hot zones rarely occur. This phenomenon was observed by Rózsa (1913) in both Lakes Rosu and Verde in the Sovata district, Romania, and by J. P. Bradbury (unpublished data, 1968) in Cinder Cone Pool, New Mexico. An example of a double hot zone is shown in figure 7.

Another temperature profile exhibited by heliothermic lakes is an approximately linear increase in temperature with depth; examples being Red Pond, Arizona, and Cape Evans Pond, Antarctica.

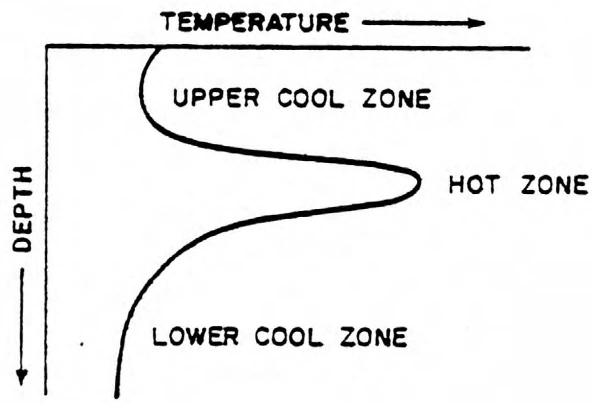



Figure 6.--Tripartite zonation of temperature found in most heliothermic lakes. Examples include Lake Ursului, Lake Avran Iancu, and Lake Rotund, Romania.

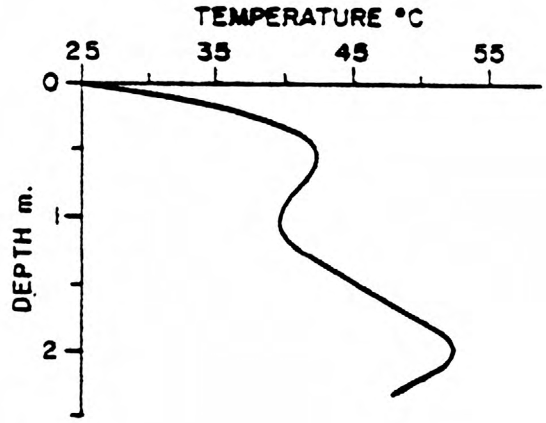



Figure 7.--Temperature profile showing two hot zones; Lake Verde, Romania (after Rózsa , 1913).

## Effect of Salinity on Temperature

Profiles of salinity and temperature for heliothermic lakes commonly show a striking positive correlation. This may extend over part or all of the profile. Examples include Red Pond, Arizona; Cape Evans Pond, Antarctica; Lake Vanda, Antarctica; and Devil's Kettle, Andros Island, Bahamas.

This relationship is due in part to the progressively decreasing specific heat of the lake water with depth through the chemocline. The specific heat of an aqueous solution decreases with increasing salinity. The specific heat of distilled water at 25°C is 1.0, whereas a saturated solution of sodium chloride has a specific heat of 0.780 at 50°C and 0.783 at 70°C (Kaufman, 1960, p. 619). For the same amount of heat input, a unit volume of water from the saline hot zone increases in temperature by up to 28 percent more than a unit volume of water from the less saline upper cool zone. Another reason for the observed correlation between temperature and salinity is that water temperatures rise as more insulation is provided (that is, as the thickness of non-convecting water increases). Thus, water in the upper part of the chemocline (which has a relatively low salinity and a relatively thin layer of insulation) will be at a lower temperature than water deeper within the chemocline (which has a relatively high salinity and a relatively thick layer of insulation).

## Annual Cycle of Temperature

The temperature of the upper cool zone of a heliothermic lake may fluctuate considerably throughout a year (Fig. 8). The mean temperature of the upper cool zone tends to be approximately the same as the mean annual air temperature. The temperature of the hot zone in high latitude lakes decreases markedly in winter, although it is always warmer than the near-surface zone (Fig. 8). The amount of sunlight absorbed by lakes at higher latitudes is reduced substantially in winter, and may be zero if the lake is covered by ice and snow. The depth to the hot zone may increase by one meter or more from spring to fall. The phenomenon has been observed in Lake Ursului, Romania, Hot Lake, Washington, and Cinder Cone Pool, New Mexico.

Within several heliothermic lakes in which temperature measurements have been made throughout the year, the temperature difference between the hot zone and the upper cool zone was observed to fluctuate slightly through the year. For example, the average annual difference between these two zones in Hot Lake, Washington, was 21.5°C, but a difference of only 15.9°C was observed in April 1955.

In those heliothermic lakes with a tripartite temperature distribution, the temperature of the lower cool zone is commonly less than that of the upper cool zone in summer and greater in winter (Fig. 8).

A lake that has two turnover periods each year is termed dimictic. Such lakes are prevalent in northern temperate regions, and their thermal properties have been thoroughly investigated. Figure 9 illustrates the annual cycle of temperature of a typical dimictic temperate lake. Note that the temperature profiles of the dimictic lake change markedly in shape with the seasons compared to the profiles of the heliothermic lake.

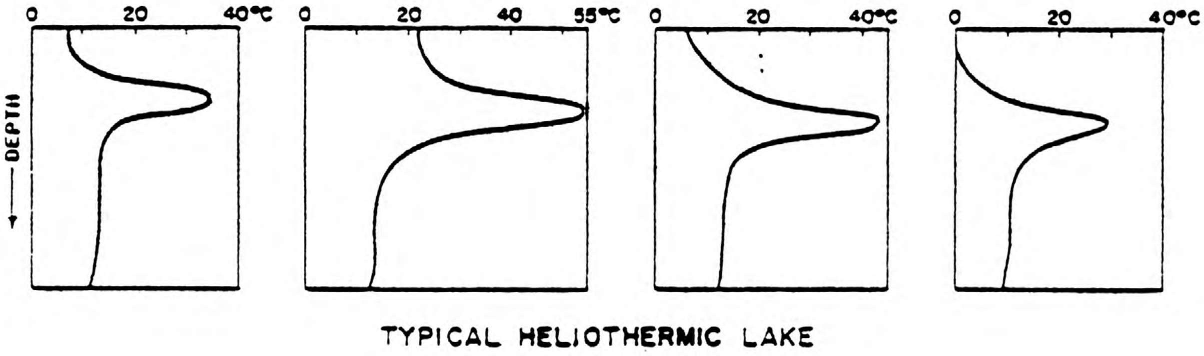



Figure 8.--Annual cycle of temperature in a typical heliothermic lake.

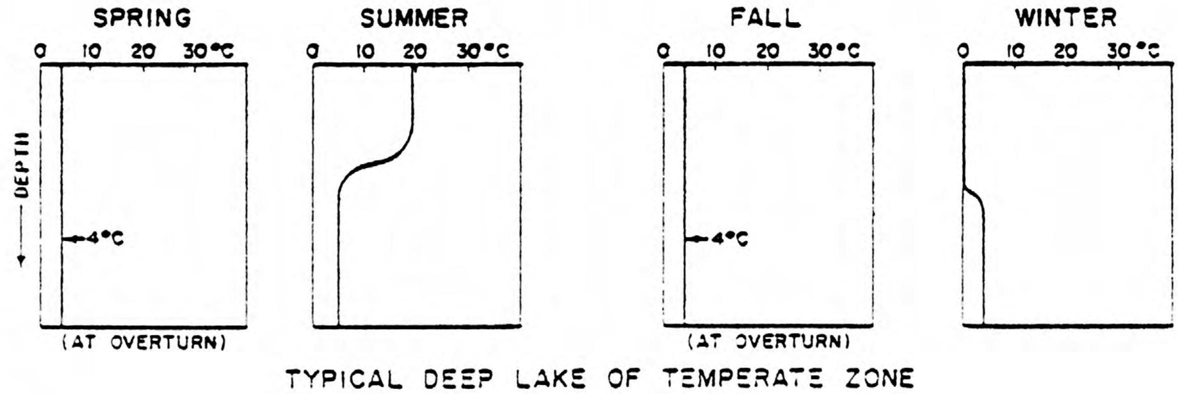



Figure 9.--Annual cycle of temperature in a typical deep, dimictic lake of the temperate zone. Depth scale not directly comparable with that of Figure 8.

## Maximum Temperatures Observed

The maximum temperatures that have been observed within various heliothermic lakes of the world are shown in Table 2. Only a few measurements have been made in most of these lakes and the maximum temperature that has occurred in a particular lake is probably greater than the observed maximum. The maximum temperatures observed within Lake Ursului are 10 and 15°C higher than maximum temperatures observed within other heliothermic lakes. During four summers (1899 to 1902), maximum temperatures in this lake ranged between 60 and 70°C; these higher temperatures resulted because of nearly ideal limnetic conditions for trapping solar energy.

All lakes listed in table 2 are in the northern hemisphere except for three from Antarctica. Heliothermic lakes undoubtedly occur in lower latitudes (the saline crater lakes of the Galapagos Islands are good possibilities), but because the great majority of published limnological surveys are on lakes of the northern temperate regions there are no reports, to our knowledge, of the occurence of heliothermic lakes in subtropical or equatorial regions.

Table 2.--Maximum temperatures encountered in natural heliothermic lakes.

| Lake | Maximum Observed Temperatures (nearest degree C) | Latitude |
|---|---|---|
| Lake Ursului, Romania | 70° | 46°35'N |
| Hot Lake, Washington | 55 | 48°58'N |
| Solar Lake of Elat, Israel | 54 | 29°20'N |
| Lake Rosu, Romania | 54 | 46°35'N |
| Lake Avran-Iancu, Romania | 53 | 46°00'N |
| Lake Rotund, Romania | 50 | 46°40'N |
| Lake Fara-Fund, Romania | 47 | 46°00'N |
| Red Pond, Arizona | 44 | 34°50'N |
| Solonowka "Creek", U.S.S.R. | 44 | 52°30'N |
| Lake Verde, Romania | 43 | 46°35'N |
| Lake St. Ioan, Romania | 42 | 46°00'N |
| Cinder Cone Pool, New Mexico | 40 | 34°27'N |
| Lake Alunis, Romania | 39 | 46°35'N |
| Espevick Pond, Norway | 36 | 60°00'N |
| Lake Negru, Romania | 35 | 46°35'N |
| Lake Roman, Romania | 34 | 46°40'N |
| Lake Vanda, Antarctica | 26 | 77°35'S |
| Lake Meggarine[1], Algeria | 26 | 33°12'N |
| Cape Evans Pond, Antarctica | 16 | 77°38'S |
| Lake Bonney, Antarctica | 8 | 77°55'S |
| Los Roques, Venezuelan Antilles | 45 | 11°58'N |

1/Temperature measurement made in winter.

PRODUCTION OF HOT WATER WITHIN MANMADE HELIOTHERMIC LAKES:

THE BASIC PROBLEMS

## Cleanliness

In order to function at maximum efficiency, waters of manmade heliothermic lakes must be exceptionally transparent. Organisms can be restricted readily by chemical agents (e.g., ozone, copper salts), and introduction of windborne organic materials can be controlled by locating lakes in regions of sparse vegetation (e.g., cleared land, deserts).

## Extraction of Heat

Heat can be extracted from heliothermic lakes either by pumping a heat transfer fluid through an array of pipes within the upper part of the moniomolimnion or by withdrawing brine from the hot zone and extracting heat in a heat exchanger (Tabor, 1964). In the latter method, brine is recycled for heating. Brine could be removed from and reinjected into the chemocline (or moniomolimnion) without disrupting stability. (See Elata and Levin, 1965).

## Seasonal Variations

In the United States the angle of altitude of the sun at solar noon is much higher, of course, in summer than in winter. As a result, less sunlight will be absorbed within the chemocline and monimolimnion of heliothermic lakes in winter than in summer. In addition, mean atmospheric temperatures are lower in winter than in summer, daylight hours are reduced, and weather is more often inclement. Because of these factors, the efficiency of heliothermic lakes in the United States in winter would be substantially reduced; in fact, throughout much of the country a cover of ice would further inhibit penetration of light.

In the southern, ice-free regions of the United States, hot water could be produced in heliothermic lakes in winter, although in lesser amounts and at lower temperatures than in summer. Seasonal climatic variations would obviously be less pronounced in most equatorial and subequatorial regions.

In Canada, Alaska, and northern parts of the contiguous United States, large volumes of hot water for use during winter could be stored within the monimolimnions of heliothermic lakes that were covered with exceptionally thick chemoclines.

## Maintenance of Stability

The major problem preventing commercial use of manmade heliothermic lakes for the collection and storage of solar energy is maintanance of stability. Can the chemocline be preserved for years or even decades so that it will efectively collect and retain radiant energy? In manmade heliothermic lakes, diffusion and wind mixing would ultimately cause destruction of stability. In the small experimental pond at Sedom, Israel, neither wind mixing nor diffusion were considered to be serious problems (Tabor, 1964), yet it is clear from natural heliothermic lakes that the meromixis would have been ephemeral at Sedom.. Ultimately the chemical stratification would have broken down. Upward movement by diffusion is slow, but relentless wind-generated currents flow along the boundary between the mixolimnion and the chemocline and ultimately result in substantial erosion of the chemocline. The extent of wind mixing is directly proportional to the surface area of a lake. Artificial heliothermic ponds with areas of several square kilometers, a size that would be essential if such ponds were to be used for the production of commercial amounts of electrical power, would be especially susceptible to wind mixing. Unfortunately, diffusion and wind mixing, if given enough time, will reduce the heat-trapping effectiveness of a heliothermic lake to zero. Several methods for maintaining stability are considered below.

## Locate the Chemocline at Considerable Depth

If the boundary between the mixolimnion and the chemocline were at a depth of 5-10 m, mixing along the boundary would be negligible, inasmuch as currents generated by wind diminish in velocity and duration as the thickness of the mixolimnion increases. Even with a thick (5-10 m) mixolimnion, if the lake were clear, as much as 16 to 23 percent of the sunlight reaching the surface could pass into the chemocline. Few natural heliothermic lakes have chemoclines that receive so large a fraction of incident light.

## Use Transparent Partitions

Rabl and Nielsen (1975) proposed that two transparent partions be used within heliothermic lakes; a plastic sheet at the top of the chemocline prevents wind-mixing and one at the bottom of the chemocline prevents diffusion. A relatively thin layer of fresh water, a mixolimnion, is placed above the upper partition (Fig. 10); this layer, however, is not necessary. Also the lower partition may be unnecessary (Rabl and Nielsen, 1975). A salinity gradient within the chemocline is maintained artifically (Fig. 10). Lakes Vanda and Bonney are analogous to the system of Rabl and Nielsen; instead of a plastic sheet, the upper transparent partition in these Antarctic lakes is extremely clear ice.

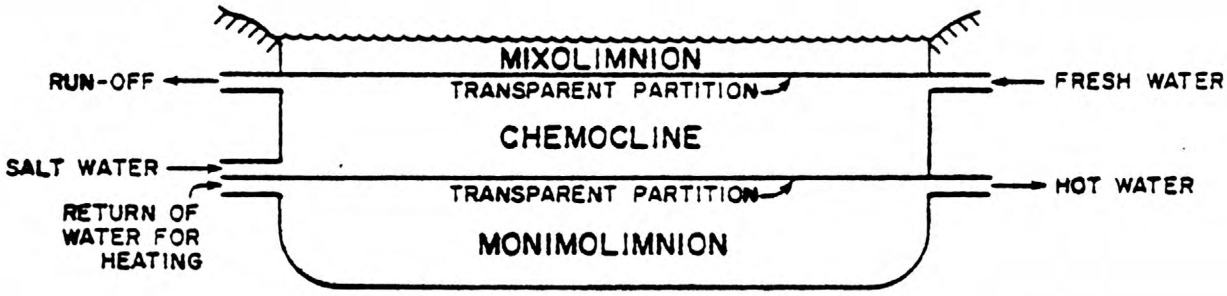



Figure 10.--Diagram of a heliothermic lake stabilized by transparent plastic partitions. (Modified after Rabl and Nielsen, 1975.)

Wash the Mixolimnion and Add Salt to the Monimolimnion

Stability can be preserved by adding salt (or a concentrated solution of salt) to the monimolimnion while streaming fresh water laterally across the mixolimnion (washing). A transition zone, a chemocline, will persist between the upper and lower strata. The great longevity of Lake Ursului (at least 28, and possibly 80 years) is a result of this process. (See appendix I.)

Use of a Salt Whose Solubility is Greatly Influenced by Temperature

A heliothermic lake with a self-correcting mechanism for maintenance of stability can be constructed using salts whose solubilities are markedly influenced by temperature. In such heliothermic lakes, neither wind mixing nor diffusion is likely to disrupt the chemical stratification, and it should therefore persist indefinitely with little or no maintenance.

Compounds whose solubilities are markedly affected by temperature and which would be suitable for this class of heliothermic lake include $NaCO_3.10H_2O$ (natron), $Na_2B_4O_7.10H_2$ (borax), $NaSO_4.10H_2O$ (mirabalite), KCL (sylvite), and $CaCl_2.6H_2O$. Natural reserves of each of these salts are considerable (Smith and others, 1973).

Consider a heliothermic lake in which tripartite chemical stratification is established by a salt whose solubility increases with increasing temperature. The salt may be a single-phase form such as sylvite or a double-phase form such as the borax-kernite pair (Fig. 11). The salinity

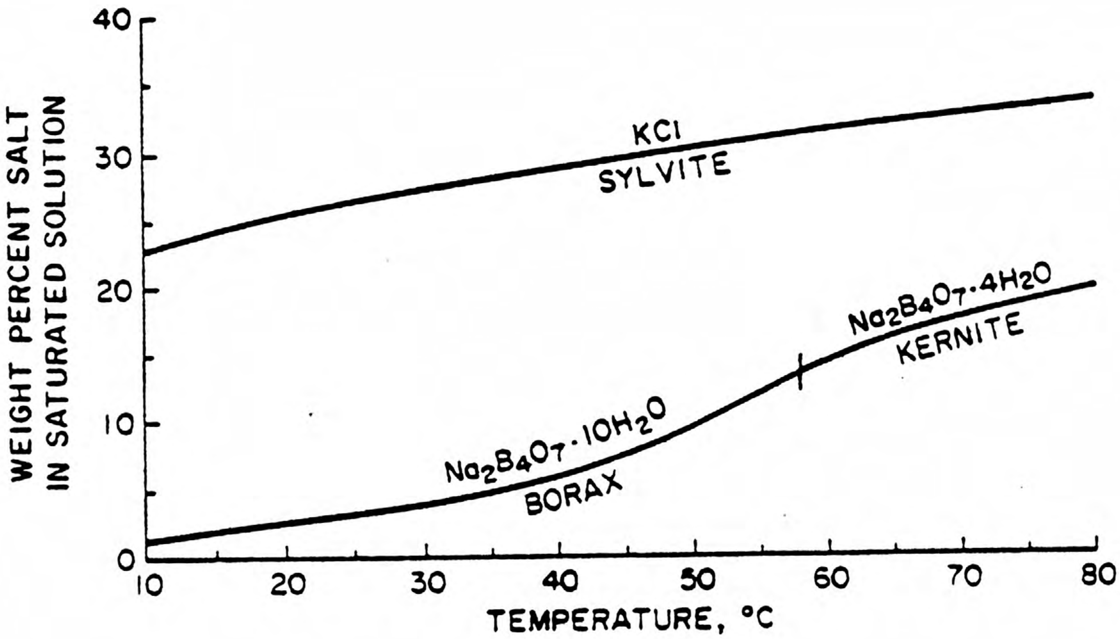



Figure 11.--Solubility curves for potassium chloride and sodium borate in water.

stratification would be constructed so that waters of the mixolimnion would be at saturation. Ions of the dissolved salt moving from the warmer waters of the chemocline to the cooler waters of the mixolimnion, by diffusion or because of wind-generated currents, would cause supersaturation and precipitation of the salt. The crystals would sink into the monimolimnion where they would dissolve. Ultimately an equilibrium would be achieved in which upward movement of ions in solution would be exactly matched by downward movement of atoms within crystals. The salinity-gradient would be preserved and the energy-absorbing capability of the pond assured over an extended period of time.

Within the chemocline, water temperature increases with depth (Fig. 12), allowing for progressively greater solubility of salt. Given sufficient concentration of salt within the monimolimnion, saturation could be achieved in the two upper layers, so that the diffusion and precipitation process would occur at or near the lower interface of the chemocline.

The quantity of salt chosen to charge the pond would be an amount that would allow the moniomolimnion to be undersaturated. The measured amount would be placed on the floor of a shallow pond of fresh water during a wind-free period. As dissolution proceeded, ionic diffusion and absorption of solar energy would allow stable salinity and temperature gradients to be established (Fig. 12).

The maximum temperatures in the pond would occur within the monimolimnion, and hot water for various applications could be (1) extracted from the lowest layer, (2) pumped through a heat exchanger, and (3) reintroduced into the monimolimnion (Fig. 12).

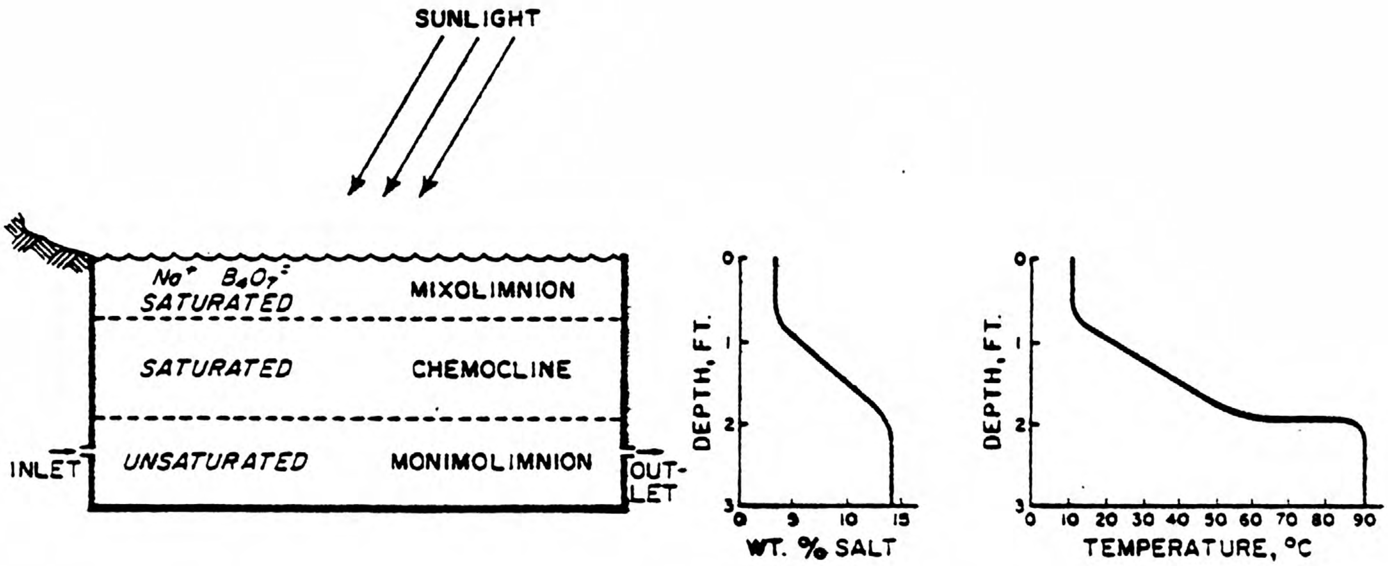



Figure 12.--Diagrammatic sketch of a heliothermic pond employing sodium borate. Dashed lines represent the boundaries between the three zones. Temperatures are approximations.

Permanently stable heliothermic lakes can also be constructed with a salt having two distinct phases: one in which solubility increases with increasing temperature, the other in which solubility decreases with increasing temperature. One pair of this type is $Na_2SO_4.10H_2O$ (mirabilite) and $NaSO_4$ (thenardite), and another is $Na_2CO_3.10H_2O$ (natron) and $Na_2CO_3.H_2O$. The solubility curves of these two salt pairs are nearly identical (Fig. 13).

In areas in which the minimum diurnal temperature of the uppermost waters in a pond is between 0° and 15°C, all that would be required to achieve permanent stability would be to put an excess of mirabilite ($Na_2SO_4.10H_2O$) or natron ($Na_2CO_3.10H_2O$) into a shallow pond of clear fresh water. The addition of a relatively small amount of a catalyst such as borax would prevent supersaturation undercooling (Telkes, 1952).

A pond in which stability has been achieved with mirabilite is shown diagrammatically in figure 14. The mixolimnion is absent or very thin. The chemocline extends from the surface or just below the surface to a depth at which the temperature of the water has risen to about 32°C. The water within the chemocline is saturated with mirabilite, but at the base of the chemocline, at a temperature of about 32°C, the water is saturated with thenardite ($Na_2SO_4$). Ions of sodium and sulfate moving by diffusion from the monimolimnion into the chemocline cause supersaturation, and crystals of mirabilite form, either to sink to the bottom or to dissolve in the monimolimnion. Even prolonged gales will not cause permanent disruption of the stratification because the layers are self-adjusting; after any displacement, they will revert to their original stratification.

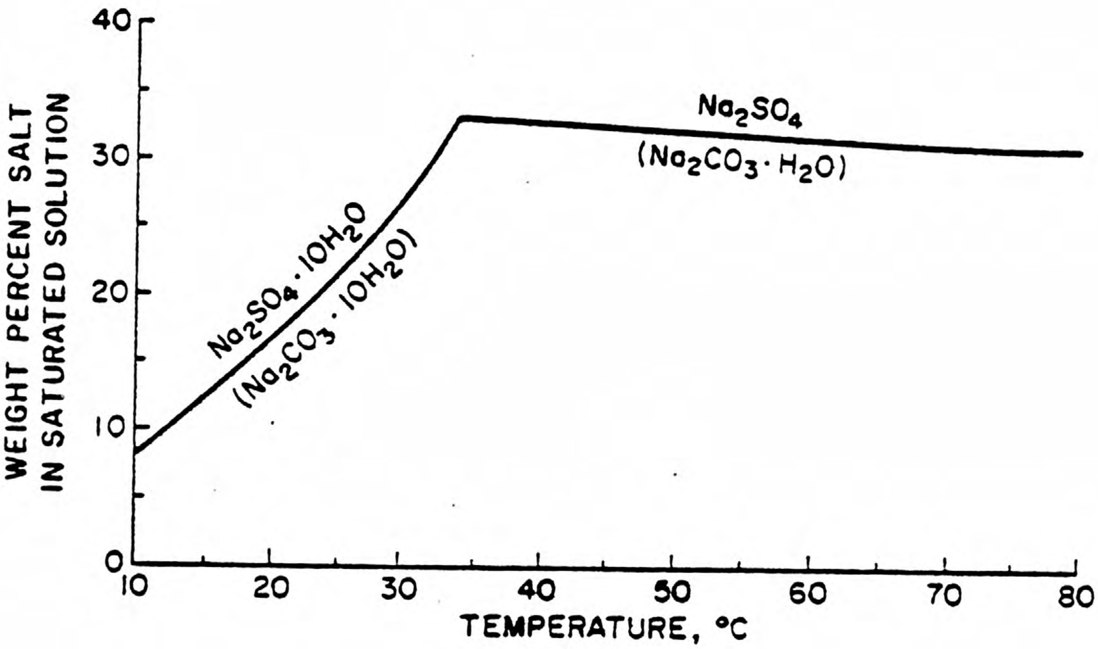



Figure 13.--Solubility curve for sodium sulfate and sodium carbonate in water.

The solubility of thenardite increases with decreasing temperature, and therefore, even though the monimolimnion may be saturated with salt, there will be no precipitation of thenardite when the hot water is removed from the pond and passes through a heat-exchanger unless the water is cooled to below 32°C. At that temperature, mirabilite would precipitate (Fig. 13).

The following advantages result from the collection of solar energy in lakes containing salts whose solubility is markedly influenced by temperature: (1)..No construction other than a shallow pond is required.

(2) The area of the pond is not limited.

(3) Salt is not lost from the pond; a single charge may be sufficient to last for tens of years.

(4) The salts used to achieve pond stability occur in abundant natural reserves.

(5) Stability can be preserved indefinitely with little or no upkeep.

(6) Severe weather conditions will, at most, only temporarily disrupt the efficiency of the collector.

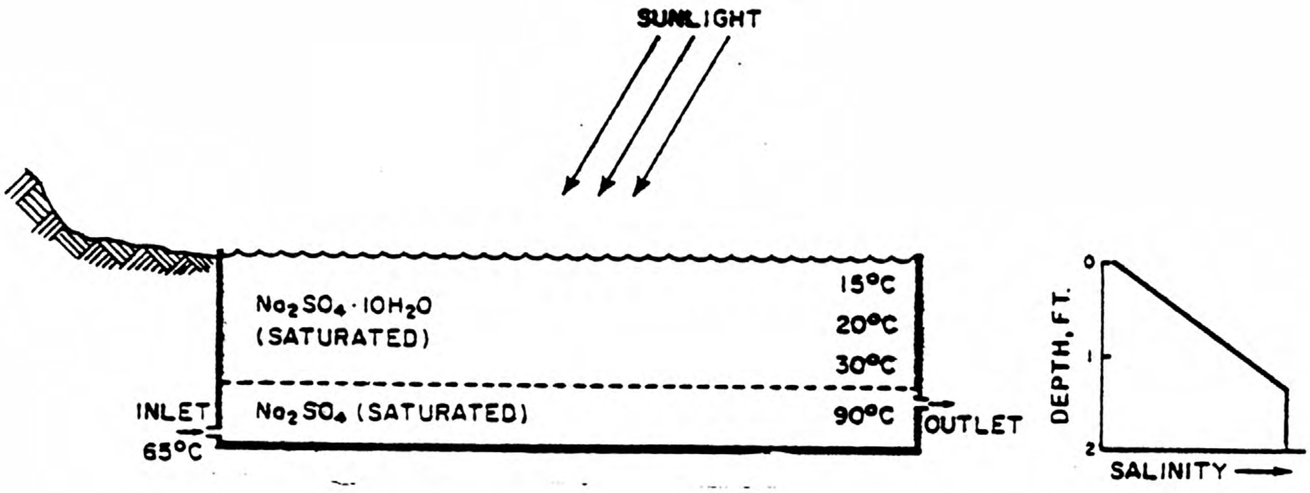



Figure 14.--Diagrammatic sketch of a heliothermic pond employing sodium sulfate. The dashed line represents the surface of phase transition between mirabilite and thenardite. The temperatures are approximate.

## REFERENCES CITED


Anderson, G. C., 1958, Some limnological features of a shallow saline meromictic lake: Limnology and Oceanography, v. 3, p. 259-270.

Angino, E. E., and Armitage, K. B., 1963a, A geochemical study of Lakes Bonney and Vanda, Victoria Land, Antarctica: Journal of Geology, v. 71, p. 89-95.

______1963b, Chemistry of three saline lakes, Victoria Land, Antarctica, and suggested geologic implications (Abs.): in Abstracts for 1963, Geological Society of America, Special Papers 76, p. 305.

Angino, E. E., Armitage, K. B., and Tash, J. C., 1964, Physicochemical limnology of Lake Bonney, Antarctica: Limnology and Oceanography, v. 9, p. 207-217.

Armitage, K. B., and House, H. B., 1962, A limnological reconnaissance in the area of McMurdo Sound, Antarctica: Limnology Oceanography v. 7, p. 36-41.

Ball, D. G., and Nichols, R. L., 1969, Saline lakes and drill hole brines, McMurdo Sound, Antarctica: Geological Society of America Bulletin, v. 71, p. 1703-1708.

Beadle, L. C., 1943, An ecological survey of some inland saline waters of Algeria: Journal of the Linnean Society of London, Zoology, v. 41, p. 218-242.

Bradbury, J. P., 1967, Origin, paleolimnology, and limnology of Zuni Salt Lake maar, west central New Mexico: Ph. D. Thesis, New Mexico University, Albuquerque, 247 p.

______1971, Limnology of Zuni Salt Lake, New Mexico: Geological Society of America Bulletin, v. 82, p. 379-398.

Brecht-Bergen, R. Von, 1908, Das Salz - und Bitterseengebiet zwiscen Irtysch und Ob: Globus, v. XCIII, no. 9, p. 133-139.

Cole, G. A., 1968, Desert limnology in Desert Biology, G. W. Brown, Jr. (Ed.), New York, Academic, p. 423-486.

Cole, G. A., and Whiteside, M. C., 1965a, Kiatuthlanna - A limnological appraisal. I. Physical factors: Plateau, v. 38, no. 1, p. 6-16.

______1965b, Kiatuthlanna - A limnological appraisal. II. Chemical factors and biota: Plateau, v. 38, no. 2, p. 36-48.

Critchfield, H. J., 1966, General climatology: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 420 p.

Daniels, Farrington, 1964, Direct use of the sun's energy: New Haven, Yale Univ. Press, 374 p.

Eckstein, Yoram, 1970, Physicochemical limnology and geology of a meromictic pond on the Red Sea shore: Limnology and Oceanography, v. 15, p. 363-372.

Edmondson, W. T., 1963, Pacific coast and Great Britain, in Limnology in North America, D. G. Frey (Ed.), Madison, Univ. of Wisconsin p. 371-392.

Edmondson, W. T., and Anderson, G. C., 1966, Some features of saline lakes in central Washington: Suppliment to vol. 10, Limnology and Oceanography, p. R87-R96.

Elata, C., and Levin, O., 1965, Hydraulics of the solar pond, 11th Congress of the International Association for Hydraulics Research, Leningrad (referenced in Tabor and Matz, 1965, and Rabl and Nielsen, 1975).

Friele, H. B. S., 1899, The oyster ponds on the west coast of Norway: Société pour l'encouragement des pêches norvégiennes à Bergen, Comptes rendus des Séances du Congrès international des Pêches réuni à a Bergen du 18 au 21 Juillet 1898, Bergen 1899. (Not seen; reference in Gaarder and Spärck, 1932.)

Gaarder, Torbjorn, and Spärck, R., 1932, Hydrographisch-biochemische Untérschungen in norwegischen Austern-Pollen: Bergens Museums Årbok, Naturvidenskapelig rekke Nr. 1, 144 p.

Goldman, C. R., Mason, D. T., and Hobbie, J. E., 1967, Two Antarctic desert lakes: Limnology and Oceanography, v. 12, p. 295-310.

Hankó, V., 1910, A szovátai melegvizü sóstavak hömérsékletének ingadozása: Magy. Balneologiai Ert. 111 évf. 6 sz Budapest 1910 (Not seen; referenced in Maxim, 1929.)

Helland, Amund, 1889, Temperaturen i østerstjernene: Norsk Fiskeritidende 1899, 8 sarg (referenced in Gaarder and Spärck, 1932).

Hoare, R. A., Popplewell, K. B., House, D. A., Henderson, R. A., Prebble, W. M., and Wilson, A. T., 1964, Lake Bonney, Taylor Valley, Antarctica: A natural solar energy trap: Nature, v. 202., p. 886-888.

Hollister, G. B., 1903, A curious salt pond in Kansas: The Journal of Geography, March issue, p. 155-159.

Hutchinson, G. E., 1957, A treatise on limnology, vol. 1, geography, physics, and chemistry: New York, John Wiley and Sons, Inc., 1015 p.

Jenkins, O. P., 1918, Spotted lakes of epsomite in Washington and British Columbia: American Journal of Science, v. 196, p. 638-644.

Kalecsinsky, Alexander, von, 1901, Über die ungarischen warmen and heissen Kochsalzseen als naturliche Warmeaccumulatoren sowie uber die Herstellung von warmen Salzseen und Warmeaccumulatoren: Annalen der Physik, v. 4, no. 7, p. 408-416. (The same paper appeared also in Ztsch. Gewasserkunde, v. 4, p. 226-248, and in Foldtani Kozlony, v. 31, p. 409-431.)

______ 1904, Über die Akkumulation der Sonnenwärme in verschiedenen

Flussigkeiten: Annalen der Physik, v. 14, p. 843-847.

Kaufman, D. W., 1960, Sodium chloride: The producton and properties of salt and brine: New York, Reinhold Publishing Corporation, 743 p.

Kohout, F. A., Rucker, J. B., Busby, F. R., Mertens, L. E., Caldwell, R. W., and Epler, Cyrus, 1968, The greenhouse effect on red bacterial water in a heliothermic Bahamian blue hole (abs.): in Abstracts for 1968, Geological Society of America Special Paper 21, p. 163.

Kopanev, I. D., 1960, Heat regime of the snow cover in the Antarctic: in Izvestiya (English Edition), no. 7, p. 1279-1284.

Maxim, I. A., 1929, Contributiuni la explicarea fenomenului de încălzire al apelor lacurilor sărate din Transilvania. 1. Lacurile dela Sovata: Revista Muzeului de Geologic - Mineralogic al Universita din Cluj, v. III, no. 1, p. 49-83.

______1930, Contributiuni la explicarea fenomenului de incălzire al apelor lacurilor sărate din Transilvania. 11. Lacurile dela Ocan-Sibiului. Revista Muzeului Geologic - Mineralogic al Universita din Cluj, v. VI, no. Cluj, p. 47-111.

______1937, Contrbutioni la explicarea fenomenolor de incalzire al apelor lacurilor sărate din Transylvania: Revista Muzeului Geologic - Mineralogic al Universita din Cluj, p. 209-320.

Nichols, R. F., 1963, Geological features demonstrating aridity of McMurdo Sound Area, Antarctica: American Journal of Science, v. 261, p. 20-31.

Por, F. D., 1968, Solar lake on the shores of the Red Sea: Nature, v. 218, p. 860-861.

Rabl, Ari, and Nielsen, C. E., 1975, Solar ponds for space heating: Solar Energy Journal, v. 17, p. 1-12.

Ragotzkie, R. A., and Likens, G. E., 1964, The heat balance of two Antarctic lakes: Limnology and Oceanography, v. 9, p. 412-425.

Rasch, H., 1866, 1879, 1880, 1881 (references listed in Gaarder and Sparck, 1932; papers not seen).

Rigler, G., 1903, Erdely nevesebb furdoi 1902-ben. Budapest, 1903, p. 150 (not seen; reference from Maxim, 1937).

Roth, Telegdi, von, 1899, A Szovátai ilyestó és kornyéke geologiai szempontból: Földtani Közlony köt , v. 29, p. 41-44.

Rózsa , Michael, 1911, Neuere daten zur Kenntnis der Warmen Salzseen: Berlin, R. Friedlander & Son, 32 p. (<u>see</u> review by Johnsen, 1911, Physikallische Zeitschrift XII, p. 735-736).

______1913, Über die periodische Entstehung doppelter Temperaturmaxima in den warmen Salzseen: Annalen der Hydrographie, v. 10, p. 511-513.

______1915, Die physikalischen Bedingungen der Akkumulation von Sonnenwarme in den Salzseen: Physikallische Zeitschrift, v. XVI, p. 108-111.

Ruttner, Franz, 1953, Fundamentals of limnology: Univ. of Toronto Press, 242 p.

Schafarzik, Franz, 1908, Uber die geologischen, hydrographischen und einige physikalische Verhaltnisse der durch isolation erwarmten Salzseen, insbesondere des heiszen Medveto - Sees bei Szovata: Foldtani Kozlony, v. 38, p. 437-455.

Shirtcliffe, G. L. and Benseman, R. F., 1964, A sun-heated Antarctic Lake: Journal of Geophysical Research, v. 69, p. 3355-3359.

Smith, G. I., Jones, C. I., Culbertson, W. C, Ericksen, G. E. and Dyni, J. R., 1973, Evaporites and brines, <u>in</u> United States Mineral Resources, Brobst, D. A. and Pratt, W. P. (Eds.): U.S. Geological Survey Professional Paper 820, p. 197-216.

Sverdrup, H. U., Johnson, M. W. and Fleming, R. H., 1942, The oceans - their physics, chemistry and general biology: New York, Prentice-Hall, Inc., 1087 p.

Tabor, H., 1963, Solar ponds: Large-area solar collectors for power production: Solar Energy Journal, v. 7, no. 4, p. 189-194.

______1964, Solar ponds: Electronics and Power, v. 10 (Sept.), p. 296-299.

Tabor, H. and Matz, R., 1965, Solar pond project: Solar Energy Journal, v. 9, no. 4, p. 177-182.

Telkes, M., 1952, Nucleation of supersaturated salt solutions: Industrial and Engineering Chemistry, v. 44, p. 1308.

Viski, I., 1911, A tordai sóstavak Földrajzi közlemények : Budapest (not seen, reference from Maxim, 1937).

Voitesti, I. P., 1925, Geology of the salt domes of the Carpathian region of Romania: American Association of Petroleum Geologists Bulletin,, v. IX, p. 1165-1206.

Walker, K. F., 1974, The stability of meromictic lakes in central Washington: Limnology and Oceanography, v. 19, p. 209-222.

Weinberger, Hershel, 1964, The physics of the solar pond: Solar Energy Journal, v. 8, no. 2, p. 45-56.

Wetzel, R. G., 1975, Limnology: W. B. Saunders Co., Philadelphia, 743 p.

Wilson A. T., 1967, The lakes of the McMurdo Dry Valleys: Tuatara, v. 15, p. 152-164.

Wilson, A. T., and Wellman, H. W., 1962, Lake Vanda: an Antarctic lake: Nature, v. 196, p. 1171-1173.

Ziegler, G., 1888, An den Herausgeber des Prometheus: Post: Jahrg. IX, no. 421, p. 79-80.

ZoBell, C. E., Sisler, F. D. and Oppenheimer, C. H., 1953, Evidence of biochemical heating in Lake Mead mud: Journal of Sedimentary Petrology, v. 23, p. 13-17.

# APPENDIX I

## Description of Natural Heliothermic Lakes

### Heliothermic Lakes of Romania

The most widely known heliothermic lakes occur in Transylvania, a region of Romania having a distinct geographical identity (Fig. I-1A). There are three heliothermic lake districts in Transylvania (Fig. I-1B), each of which occurs where large masses of halite have been brought to the surface by diapirism or by compressional deformation. (See Voitesti, 1925.) Depressions within the salt originated by natural solution and, in the Ocna-Sibiului and Turda districts, by ancient mining activity. These depressions have been filled with water to form small lakes. Some of these lakes, whose bottoms have been covered with clay, now contain fresh water (Schafarzik, 1908; Voitesti, 1925); most, however, are highly saline at depth.

#### Lakes of the Sovata District

Of numerous small lakes in the Sovata district, five are known to contain or to have contained hot water: Ursului, Alunis, Rosu, Verde, and Negru. The largest and most renowned, Ursului, is also known by the names Bear, Ursul, Medveto, and Illyes. The designation "Bear," and its Romanian equivalents, are derived from the configuration of the lake, which is like that of a bear skin (Fig. I-2). Lake Ursului was made famous chiefly by the study of the chemist Alexander von Kalecsinsky (1901, 1904), who showed conclusively that

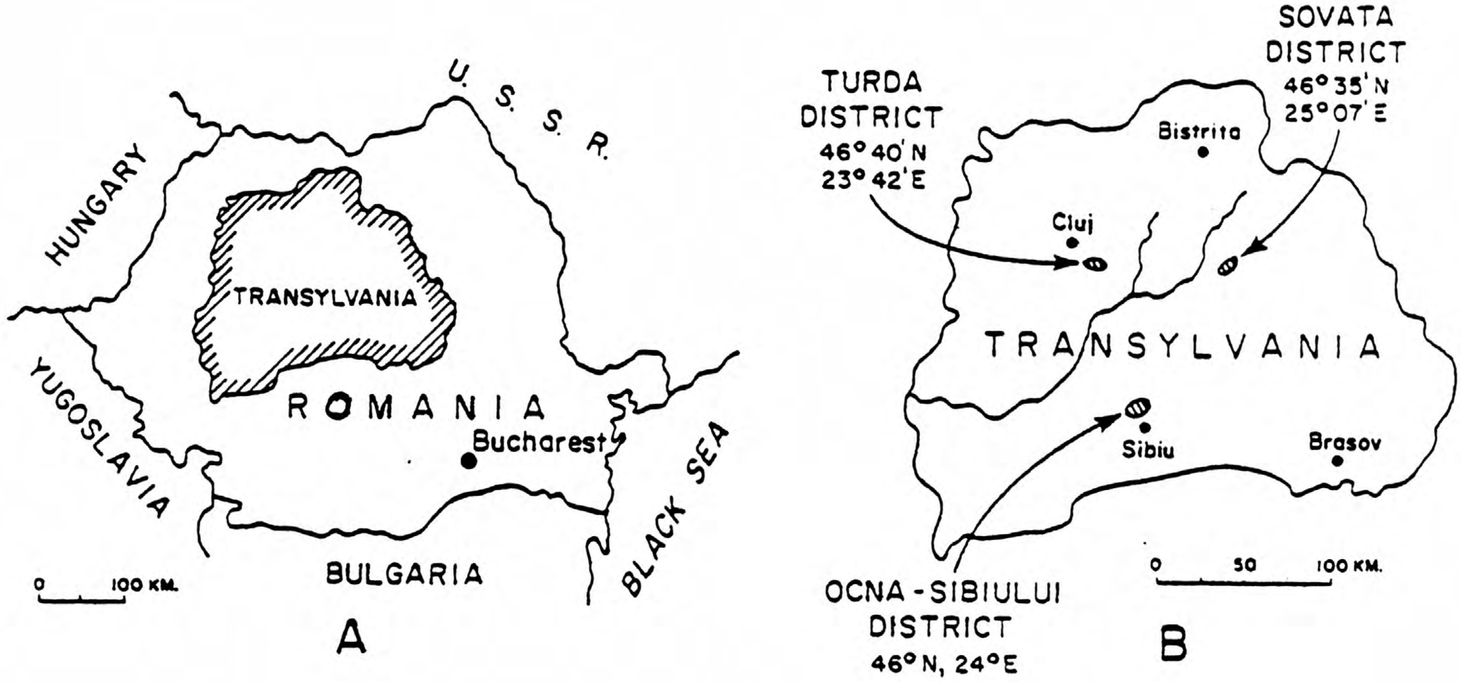



Figure I-1.--Location of Transylvania within Romania (A) and locations of its three heliothermic lake districts (B).

the unusually high temperatures within the lake were due to absorption of sunlight.

Lake Ursului lies 6 km from the village of Szovata. The lake originated in 1879 by the collapse of a cavern that resulted in a gaping opening whose walls were rock salt (Schafarzik, 1908). The depression filled with water to form a lake that had maximum depth of 23 m, a mean depth of about 10 m, an area of 45,696 $m^2$, and a volume of 308,921 $m^3$ in 1904 (Maxim, 1929). The bathymetry of the lake is shown in figure I-2.

Water in Lake Ursului is nearly saturated with sodium chloride from about 2 m below the surface to the bottom. The salt has been derived from solution of the rock salt that forms the bottom and sides of the lake; there is no evidence of saline springs. Between 1901 and 1910 the brine in the monimolimnion had a salinity of about 25 percent and a density of about 1.20 $g/cm^3$. (A saturated solution of sodium chloride has a salinity of 26.40 percent and density of 1.208 $g/cm^3$.) In 1926, when again measured, the salinity of the water at 13 m was 24 percent.

Throughout the early 1900's (and apparently through to the present) the mixolimnion of lake Ursului, (upper 1 to 2 m), was usually fresh. Schafarzik (1908), for example, found that the flora and fauna of the mixolimnion were characteristic of freshwater lakes. The freshness of the mixolimnion was maintained to some extent by rainfall and by freezing-out of salts, but mainly by inflow. Two small streams, Auris and Toplitza, flow into the pond (Fig. I-2). After heavy rains the streams may be torrents, but in dry periods they scarcely flow (Schafarzik, 1908). In the summer of 1901, the two streams had salinities of 4 to 5 percent, and the meager outflow of the lake was controlled by a sluice (Kalecsinsky, 1901).

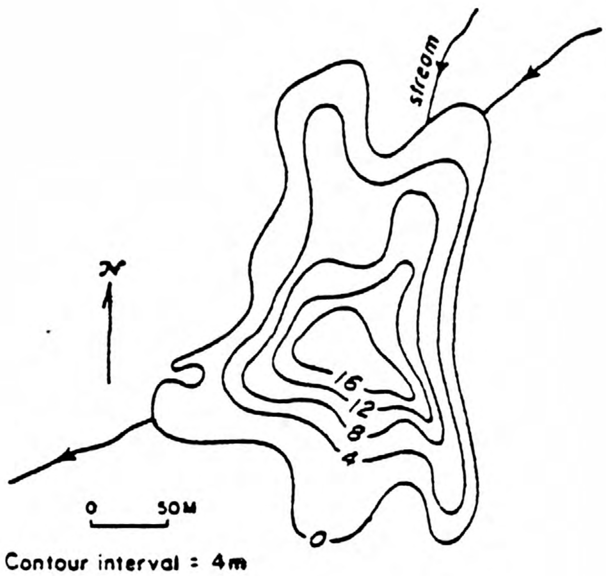



Figure I-2.--Bathymetry of Lake Ursului, Sovata district, Romania (after Schafarzik, 1908).

The salinity of the mixolimnion occasionally became unusually high. For example, on August 9, 1904, the water at the surface had a salinity of 17.08 percent (Schafarzik, 1908) perhaps because of diminished inflow, wind mixing, and (or) mixing caused by swimmers.

The lake is in a small topographic depression that provides protection from wind. In addition, the area surroundng the pond is heavily wooded with oak trees, which provide further protection.

The atmospheric temperatures in the vicinity of the lake during the 1920's had the following ranges (Maxim, 1929):

| | Maximum | Minimum |
|---|---|---|
| January | 13.8°C | 10°C |
| February | 18°C | 5°C |
| July | 28.9°C | 10.8°C |
| August | 25.4°C | 8.2°C |

According to Kalecsinsky (1901), the mean temperature of the mixolimnion in summer was about the same as the mean atmospheric temperature. The temperature of the mixolimnion in summer ranged from 20°C to about 30°C; the mean of 11 measurements was 23.2°C. The temperature of the lower part of the monimolimnion in summer (between 1901 and 1925) ranged from 19 to 26.2°C with a mean of about 22.5°C, a value that is approximately the same as the mean temperature of the mixolimnion in summer. The upper part of the monimolimnion, however, was heated to higher temperatures.

The first record of water of abnormally high temperature at the top of the monimolimnion in Lake Ursului was made by the chemist Lengyel B., who observed a temperature of 60°C in the summer of 1898 at a depth of several meters (Maxim, 1929). In September of the same year, the geologist Telegdi von Roth (1899) encountered the following maximum temperatures at a depth of about 1.3 m:

| | |
|---|---|
| September 22, 1899 | 66.2°C |
| September 23, 1899 | 67.5°C |
| September 24, 1899 | 69.5°C |

In the summer of 1901, von Kalecsinsky measured maximum temperatures as follows:

| | |
|---|---|
| July 22, 1901 | 55°C |
| July 23, 1901 | 56°C (see Fig. I-3A) |
| July 24, 1901 | 57°C |
| July 27, 1901 | 59°C |
| July 31, 1901 | 60°C |
| August 3, 1901 | 63°C |

L. V. Illyes measured maximum temperatures of 70-71°C in the summer of 1901 (presumaby in late August or September).

Variation of temperature, salinity, and density versus depth for Lake Ursului for July 23, 1901; July 6, 1910; and April 28, 1926, are shown in figure I-3; temperature variations for intermediate years are given in table I-1. Heliothermic conditions in Lake Ursului appear to have persisted for a period of at least 28 years (from September 22, 1898, to April 28, 1926). (According to the Romanian National Travel Office (1970), the summer temperatures in Lake Ursului presently vary between 30° and 40° at a depth of 1 m and between 40 and 50° C at a depth of 1.5 m.) The depth of maximum temperature during this period ranged from 1.0 to 2.5 m with mean of about 2 m. As the depths of maximum temperature increased, the values of maximum temperature decreased (Table I-1).

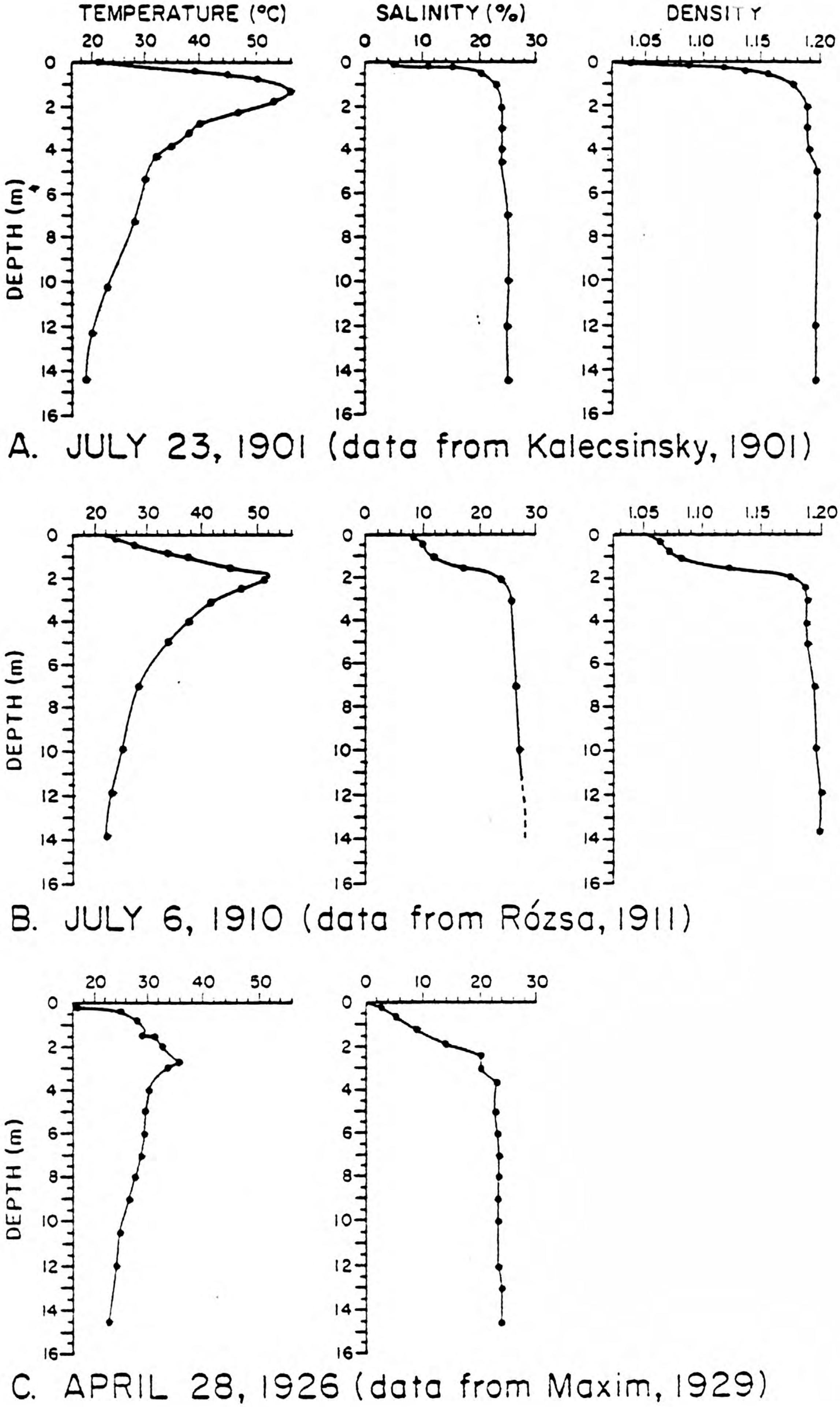



Figure I-3.--Temperature, salinity, and density with depth, Lake Ursului, Sovata district, Romania.

Table I-1.--Variation of temperature (°C) with depth, upper part of Lake Ursului, Sovata district, Romania; September 1898 to April 1926

[maximum temperatures underlined]

| Date of Measurement | Depth (meters) 0 | 0.5 | 1.0 | 1.3 | 1.5 | 2.0 | 2.3 | 2.5 | 3.0 | 4.0 | 5.0 | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sept. 23, 1898 | 20 | 46 | 60 | 70 | 65 | 60 | . | 43 | | | | Kalecsinsky, 1901 |
| July 23, 1901 | | | | 56 | (see Fig. 1-3A) | | | | | | | Kalecsinsky, 1901 |
| July 1902 | 36 | | 60.5 | 59 | 57.5 | 54 | | 48.5 | 42.5 | 37.5 | 34.0 | Rigler, 1903 |
| Aug. 9, 1904 | 26.3 | 27.0 | 33.0 | | 42.1 | 45.6 | | 44.5 | 41.9 | 35.1 | 32.0 | Schafarzik, 1908 |
| July 23, 1906 | 24 | 33.5 | 44 | | 48 | 50 | | | | | | Hanko, 1910 |
| Aug. 7, 1905 | 21.0 | 24.0 | 26.0 | | 31.0 | 37.5 | 41.0 | 40.5 | 38.5 | 35.0 | 32.0 | Maxim, 1929 |
| Aug. 28, 1907 | 25.0 | 25.5 | 26.0 | 26.5 | | 41.0 | 42.5 | | | | | Rozsa, 1915 |
| June 1908 | 27.0 | 33.0 | 37.5 | 43.0 | | 50.0 | | 45.0 | | | | Rozsa, 1915 |
| Aug. 4, 1909 | 27 | 28 | 31 | 34 | 37 | 40 | 41.5 | 41 | | | | Hanko, 1910 |
| July 6, 1910 | | | | | | 52.0 | | (see Fig. 1-3B) | | | | Rozsa, 1911 |
| May 3, 1921 | | | 24 | 25 | 26.5 | 29.5 | 29 | 28 | | | | Maxim, 1929 |
| Aug. 7, 1925 | 21 | 25.3 | 26 | 26.5 | 27.0 | 38.0 | | 40.8 | 39.8 | 37.2 | 32.8 | Maxim, 1929 |
| April 28, 1926 | | | | | | | | 36 | (see Fig. 1-3C) | | | Maxim, 1929 |

Figure I-4 shows the variation of temperature with depth to 2.5 m from August 28, 1907, to February 24, 1909. Measurements were made once each month between the 24th and 28th of the month for seventeen consecutive months. The minimum temperatures occured in February and March and the maximum in July. In 1908 the maximum water temperature decreased rapidly into the fall. From Rózsa's data (1915), the temperature at a depth of 2.5 m during winter ice cover ranged from 19.8° to 31°C with a mean of 24.4°C (n = 6). Maximum temperatures beneath the ice of 30° to 32°C were reported by Kalecsinsky (1904). In summer, the difference in temperature between the water at the surface and the water of maximum temperature ranged from 14.5° to 50°C, with a mean of 26°C (n = 11). Thus, it appears that the mean temperature at 1 to 2 m in Lake Ursului was about 25°C warmer than surface water throughout the year, at least for the period 1898 to 1926.

Lake Negru is a small pond approximately 0.4 km southwest of Lake Ursului. It has a length of 110 m, a mean width of 58 m, a mean depth of 1.6 m, and a maximum depth of about 6 m (Maxim, 1929). Kalecsinsky (1901) noted that water flowed into the pond intermittently in a stream that had almost as large a drainage area as the combined drainage area of the two streams that flowed into Lake Ursului (Maxim, 1929, pl. 1).

Variations in temperature and salinity in Lake Negru are shown for July 22-27, 1901, in figure I-5A and for August 2, 1925, in figure I-5B; Kalecsinsky (1901) found Lake Negru to be a "cold lake" (maximum temperature,

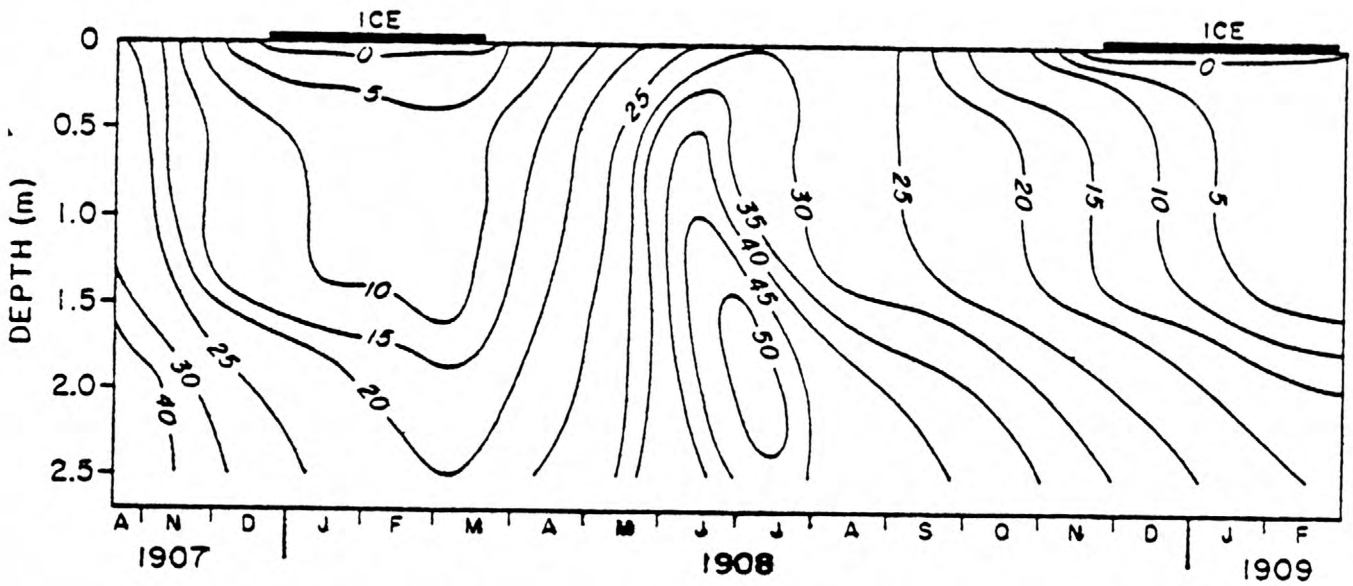



Figure I-4.--Isotherms (°C) between the surface and 2.5 m, Lake Ursului, Soyata district, Romania, from August 1907 to February 1909; data from Rózsa , 1915; contour interval, 5°C.

27°C), whereas Maxim (1929) encountered a warm layer (maximum, 34.5°C) between 2 and 3 m (Fig. I-5B). The chemocline was about 0.4 m shallower on August 2, 1925, than in late July 1901 (Fig. I-5).

In Lake Negru the depth to the chemocline was considerably deeper than in Lake Ursului (Figs. I-3 and I-5), and most of the sunlight entering Lake Negru was apparently being absorbed in the mixolimnion, which probably explains the lower temperatures. When investigated by Kalecsinsky on July 22-27, 1901, the dilute brine in the upper layer was colored (probably by sulfur bacteria) and little radiant energy was being transmitted into or through the chemocline.

Lake Alunis (also called Lake Magyarosito) is another small pond (area, 5700 $m^2$) about 50 m to the west of Lake Ursului that receives its outflow from Lake Ursului. On July 22-27, 1901, Kalecsinsky measured a maximum temperature of 38°C at 1.82 m, and in July 1910, Rózsa (1911) observed a maximum temperature of 39°C at a depth of 2.1 m.

Two other small ponds, Rosa and Verde, are located 50 and 100 m respectively northwest of Lake Ursului. Lake Verde had a maximum summer temperature of 54.1°C at a depth of 2 m, and Lake Rosu had a maximum temperature of 43.4°C at a depth of 2.5 m (Rózsa, 1913).

Lakes of the Ocna-Sibuilui District

A number of small heliothermic lakes occur in the district of Ocna-Sibuilui (Fig. I-1B). All are in depressions that formed from collapse of

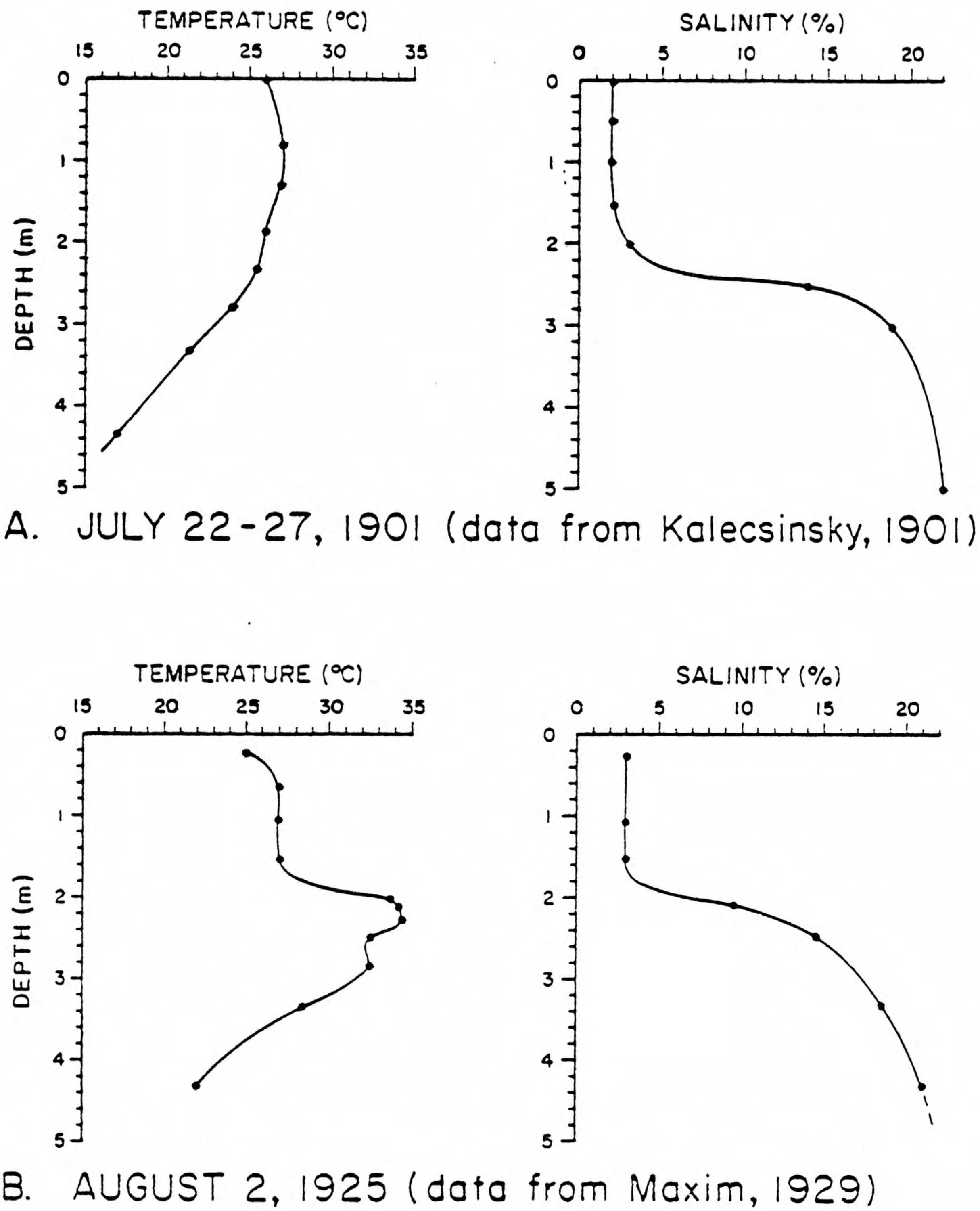



Figure I-5.--Temperature and salinity with depth, Lake Negru, Sovata district Romania.

ancient Roman salt mines. The lakes were investigated in 1926 and 1930 by Maxim (1930). He recorded the following maximum temperatures in three lakes in the district on the dates shown:

| | | |
|---|---|---|
| Lake Avram-Iancu | 53.0°C | June 27, 1930 |
| Lake Fara-Fund | 46.6°C | August 17, 1926 |
| Lake Fara-Fund | 46.4°C | June 27, 1930 |
| Lake St. Ioan | 40.6°C | August 2, 1926 |
| Lake St. Ioan | 42.3°C | June 29, 1930 |

The bathymetry of Lake Avran-Iancu is shown in figure I-6; note the depression more than 120 m deep in the center of the pond. Variations in temperature and salinity with depth for June 27, 1930, are shown in figure I-7. The maximum temperature (53.4°C) occurs at a depth of 1.25 m. The chemocline has two parts, the upper part between 0.25 and 1 m and the lower part between 2 and 4 m.

Lake St. Ioan has a length of 78 m, a mean width of about 30 m, and a maximum depth of about 16 m. Variations in temperature, salinity, and density with depth on August 2, 1926, are shown in figure I-8. There is no mixolimnion, and salinity increases almost linearly from 3 percent at the surface to 19 percent at 3 m. Temperature increases progressively from 18.5°C at the surface to a maximum of 40.6°C at a depth of 2.5 m.

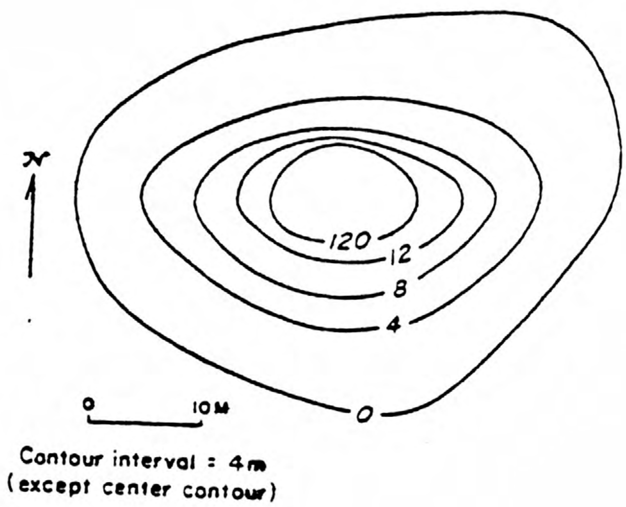



Figure I-6.—Bathymetry of Lake Avram-Iancu, Ocna-Sibiului district, Romania (after Maxim, 1930)

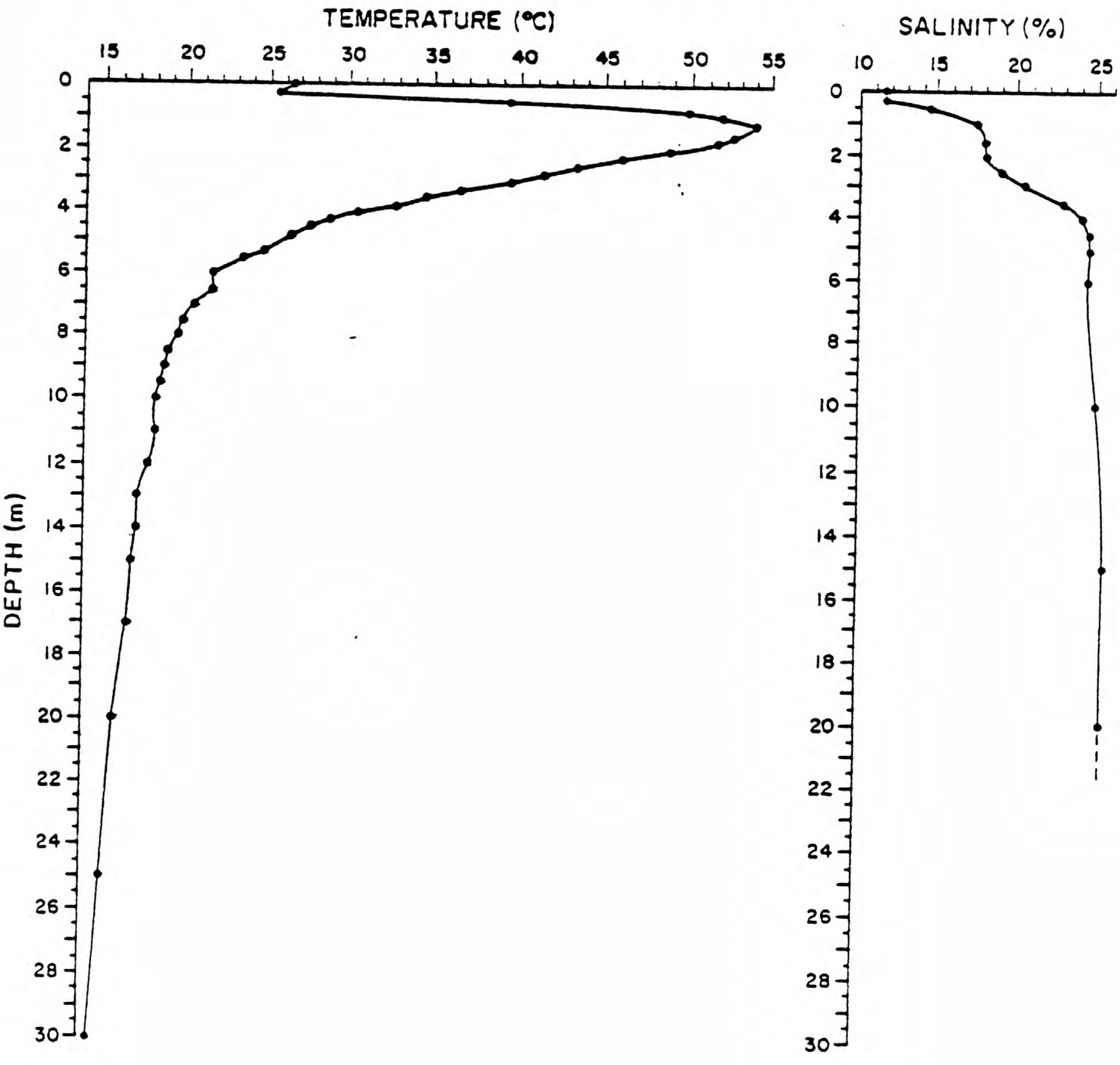



Figure I-7.--Variation of temperature and salinity with depth on June 27, 1930, Lake Avran Iancu, Ocna-Sibiului district, Romania (data from Maxim, 1930).

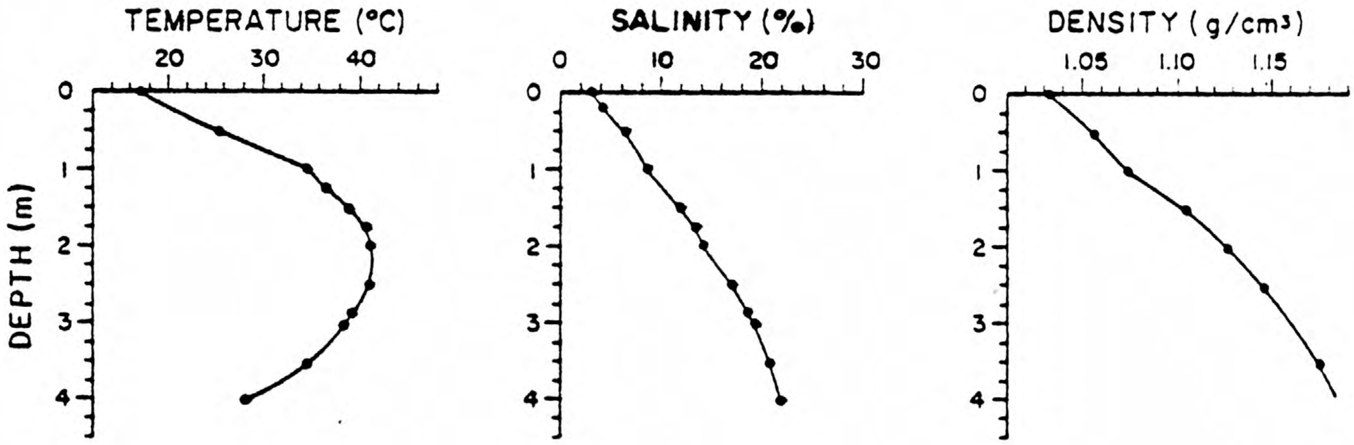



Figure I-8.--Temperature, salinity and density from surface to 4 m on August 2, 1926, Lake St. Ioan, Ocna-Sibiului district, Romania (data from Maxim, 1930).

In the heliothermic lakes of the Ocna-Sibiului district, Maxim (1930) found that a Secchi disk was no longer visible at a depth that coincided approximately with the depth of the hot zone.

Lakes of the Turda District

Two large salt domes occur near the city of Turda (Fig. I-1). There are a total of about 20 small ponds on the crests of these domes. The lake basins were created by ancient mining activity (Maxim, 1937). Almost all ponds in the Turda district had a zone of warm-to-hot water between the depths of 1 and 3 m when investigated by Maxim in the summers of 1926 and 1933.

Lake Rotund, one of the smaller ponds, has an area of 500 $m^2$, a maximum depth of 18 m and a mean depth of 4.1 m. The lake had a maximum temperature of 42.5°C at 2.2 m on August 11, 1910, when investigated by Viski (1911). Sixteen years later, on July 20, 1926, when first investigated by Maxim, the hot zone was only one degree warmer than the overlying water, although a pronounced salinity gradient from 15 to 23 percent occured between 2 and 3 m. At this time the upper waters of this pond were so highly colored that only a small percentage of the radiation falling on the surface of the lake was able to penetrate into the chemocline; a Secchi disk disappeared at 0.4 m! Nearly seven years later, when again measured by Maxim on July 3, 1933, the hot zone was several meters thick and had a maximum temperature of 50°C (Fig. I-9). The top of the chemocline at this time was within 0.5 m of the surface (Fig. I-9) and a Secchi disk disappeared at 0.95 m.

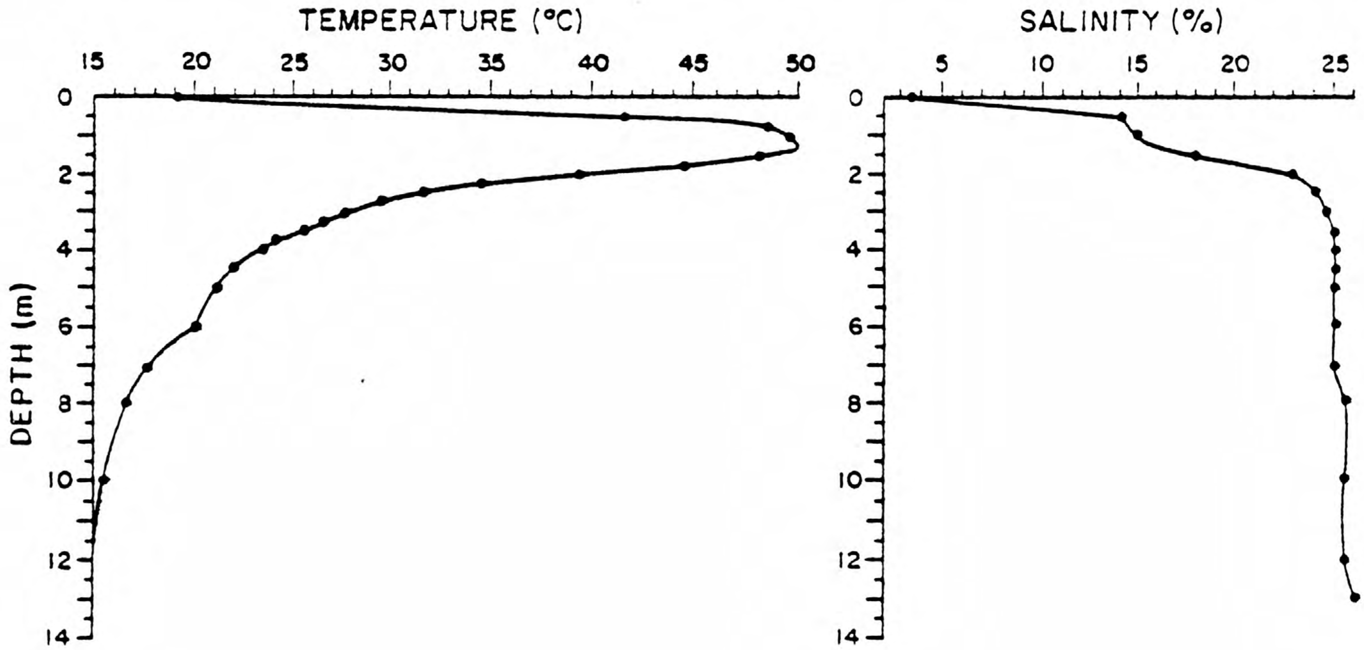



Figure I-9.--Variation of temperature and salinity with depth on July 3, 1933, Lake Rotund, Turda district, Romania. Data from Maxim (1937).

Lake Roman, one of the larger ponds in the Turda district, has an area of 3800 $m^2$ and a maximum depth of 5.2 m. The following temperatures were measured in the hot zone on different dates and by different investigators:

| | | | |
|---|---|---|---|
| 27.8°C | 1.1 m | July 1902 | Rigler, 1903 |
| 33.5°C | 2.2 m | July 9, 1910 | Viski, 1911 |
| 29.9°C | 2.1 m | May 27, 1926 | Maxim, 1937 |
| 30.5°C | 2.2 m | July 22, 1926 | Maxim, 1937 |
| 15.0°C | 3.6 m | January 7, 1933 | Maxim, 1937 |
| 29.5°C | 2.0 m | July 6, 1933 | Maxim, 1937 |

On July 22, 1926, a Secchi disk disappeared at 2.5 m, 0.3 m below the depth of maximum temperature, and on July 6, 1933, it disappeared at 0.65 m, 1.35 m above the depth of maximum temperature. In each of the six observations recorded above, the hot zone occurred entirely within the chemocline.

## Solar Lake of Elat, Israel

Solar Lake of Elat is 30 km south of Elat on the east coast of the Sinai Peninsula (Fig. I-10). The lake has an elliptical outline with dimensions of about 80 x 40 m. The maximum depth of the lake is 5 m. The thermal properties of the lake have been described by Por (1968) and in greater detail by Eckstein (1970). A maximum midsummer temperature of 54°C was observed by Eckstein (1970). Water seeps into the pond from small springs along the eastern shore of the lake (Por, 1968. The chlorinity of this spring water, 25.21-29.47$^{o}/_{oo}$, is slightly higher than that of water in the Gulf of Aqaba. Another possibility is that seasonal storm waves wash over the barrier between the lake and the sea to introduce saline water to the basin.

Whatever its source, the spring and (or) wash-over water forms a monimolimnion in winter and early spring, when evaporation is less than the inflow (Fig. I-11). A high ridge, which almost encircles the pond, restricts wind and thus retards vertical mixing. In summer, when evaporation exceeds inflow, the salinity of the mixolimnion increases progressively. As a result, the stability of the layers (Fig. I-11) diminishes, and ultimately, in late summer, wind mixing disrupts the stratifications. In August of 1968, the lake was essentially isohaline and isothermal, and currents were able to circulate through the entire water mass.

Five salinity-temperature-depth profiles for different dates during 1968 are shown in figure I-12. Measurements by Por (1968) for April 1968 are similar to those of Eckstein for June 19 (Fig. I-12); the maximum salinity measured was about 92 $^{o}/_{oo}$ at 3.5 m. With reestablishment of brine sratification (e.g., the profile for December 10, figure 20) conditions were again favorable for retention of heat, and in December the temperature at a depth of 2.5 m again approached 50°C.

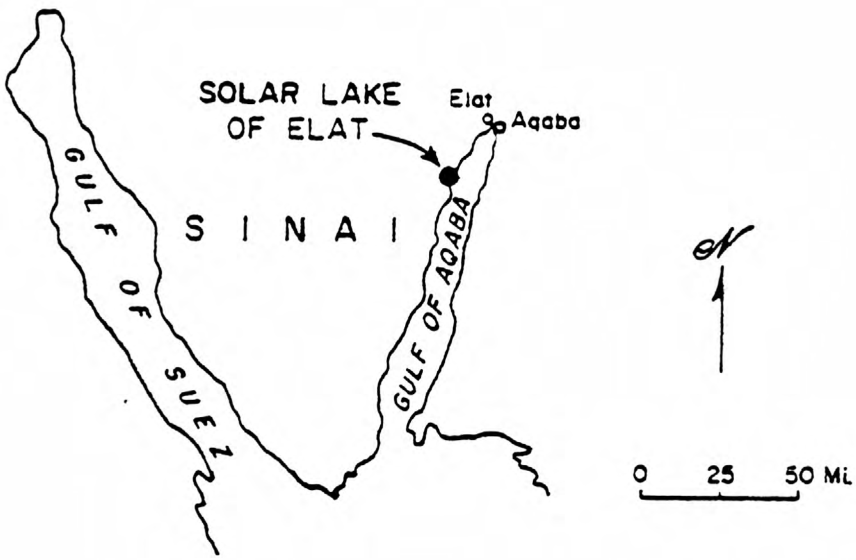



Figure I-10.--Location of Solar Lake of Elat, (29°20'N., 34°46'E.).

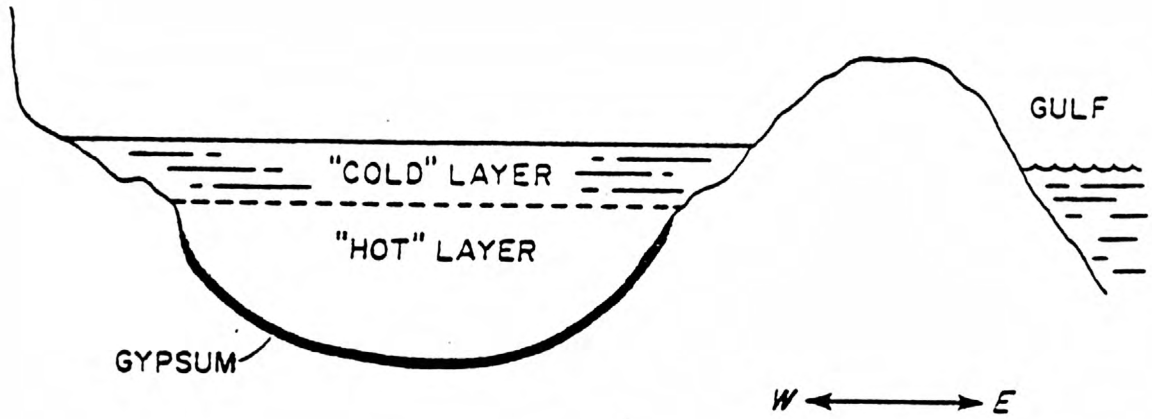



Figure I-11.--Diagrammatic cross section of Solar Lake of Elat winter and spring (modified after Por, 1968).

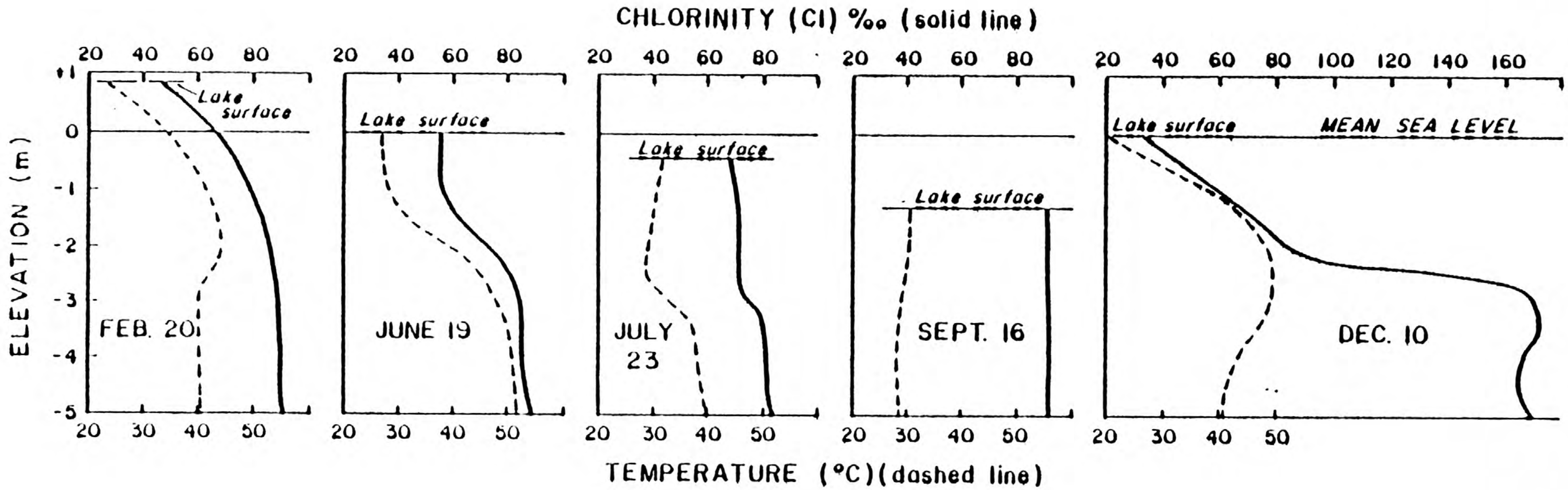



Figure 1-12.--Temperature and chlorinity with depth, Solar Lake of Elat, west coast of Sinai Peninsula, February 20, 1968 (left) to December 10, 1968; salinity = 0.03 + 1.805 chlorinity; after Eckstein, 1970.

The difference in temperature between the surface water and the hot zone changed substantially through 1968 as follows:

| | Por (1968) | Eckstein (1970) |
|---|---|---|
| February | 34°C | 21°C |
| April | 28 | 25 |
| July | 8 | 8 |
| August | 0 | |
| September | 0 | 1 |
| December | | 30 |

Hot Lake, Okanogan County, Washington

Four meromictic lakes that exhibit water of abnormally high temperature at depth occur in the semiarid region of north-central Washington (Edmondson and Anderson, 1966).. The most extraordinary of these, Hot Lake, has been studied by Anderson (1958). The location of the lake is shown in figure I-13.

Hot Lake is in a wind-protected depression of glacial origin. It has a length of 281 m, a mean width of 45 m, an area of 12,700 $m^2$, and a maximum depth of 3.25 m. An elongate depression with a width of about 16 m and an average depth of about 2.5 m extends for about 200 m along the axis of the lake bottom (Fig. I-14). This channel is apparently a result of mining for epsomite ($MgSO_4 \cdot 7H_2O$); prior to 1920 a 15-foot bed of epsomite is reported to underlie the lake (Jenkins, 1918).

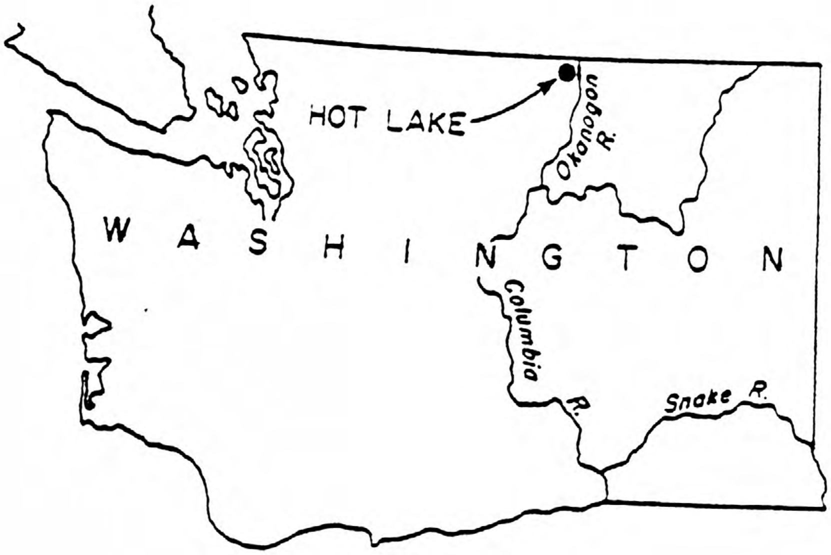



Figure I-13.--Location of Hot Lake, Washington (48°58'N., 119°29'W.).

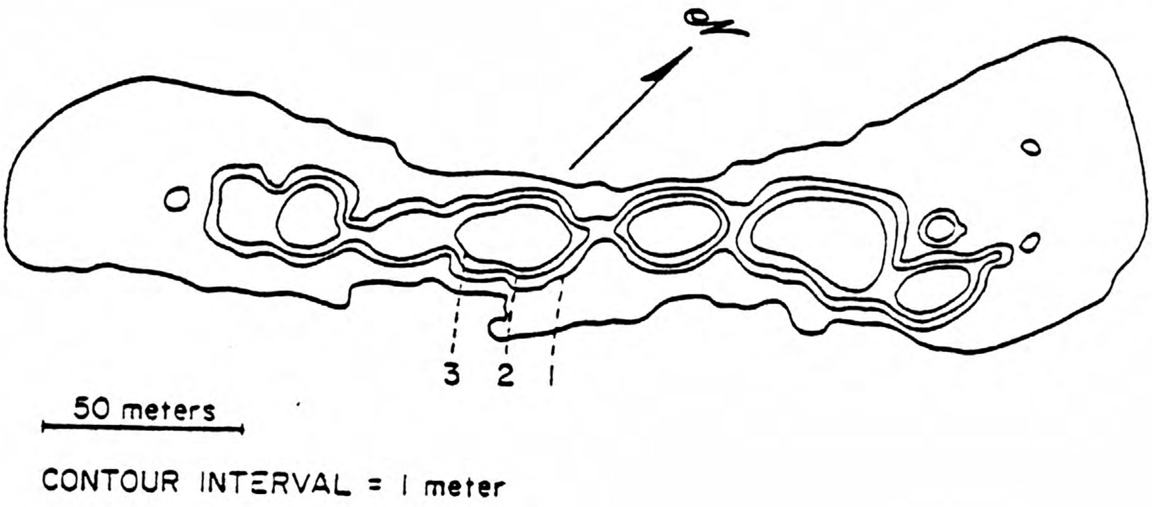



Figure I-14.--Bathymetry of Hot Lake, Washington; after Anderson, 1958.

Magnesium and sulfate ions form more than 75 percent of the ion concentration in the lake; the remainder consists of sodium, chloride, bicarbonate, potassium, and calcium ions. During the nearly two-year period of Anderson's study, the lake had an average salt concentration of about 100 g/l at the surface and 400 g/l at the bottom.

Hot Lake has neither an inlet nor an outlet. Fresh water, in the form of surface runoff and melt water from snow, enters the lake principally in early spring. This water forms a mixolimnion on top of the monimolimnion of highly saline brine; a chemocline forms between these layers (Fig. I-15). This well-stratified condition does not persist for long, however. The two strata lose their identity apparently because of gradual wind mixing, and a uniform salinity gradient develops (Fig. I-16). A uniform gradient without a distinct mixolimnion or monimolimnion was the usual condition throughout Anderson's investigation.

The surface water in the summer of 1955 had an average daytime temperature of 23°C. From the surface, this temperature increased progressively with depth to an average of about 48°C between 1.5 and 3 m. The temperature then decreased steadily with depth to an average of about 29°C at the bottom. The maximum temperature recorded by Anderson was 50.53°C on July 23, 1955.

Walker (1974) reported that on August 10, 1972, the lake level was very low and detailed observation could not be made easily "because of difficulty of access." At that time the lake had a surface temperature of 55°C and a surface salinity of 54 g/l; the salinity at 1.5 m was 268 g/l.

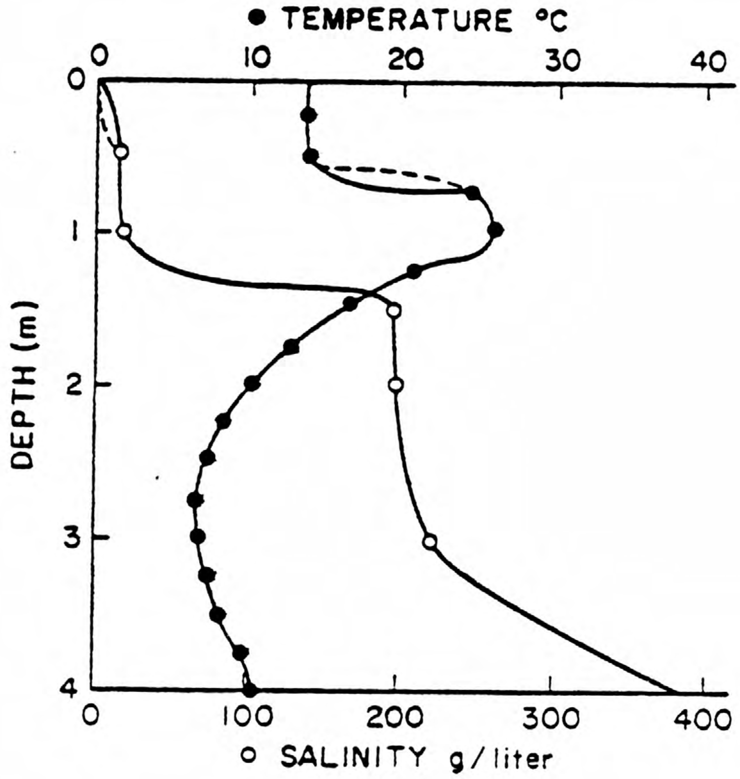



Figure I-15.--Variation of salinity and temperature with depth, Hot Lake, Washington, May 1, 1956. (Modified after Anderson, 1958; dashed lines indicate an alternate interpretation.)

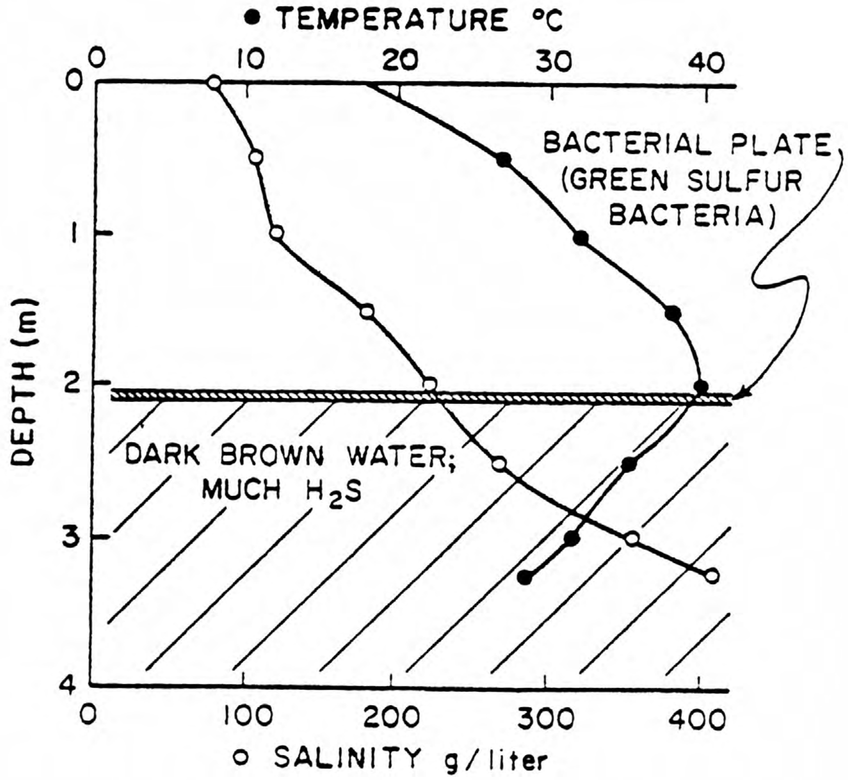



Figure I-16.—Variation of salinity and temperature with depth, Hot Lake, Washington, May 17, 1955 (after Anderson, 1958).

The variation of temperature with time and depth in Hot Lake for the period November 1954 to December 1955 is shown in figure I-17. The temperature of the water at 1.75 m increased from about 16°C during winter and spring to about 50°C in early July 1955. Figure I-17 also shows that the hot zone increased in depth through the summer and fall of 1954. The maximum temperature on July 23 for example, was at 2.1 m, whereas on September 28, the maximum temperature was at a depth of about 3 m.

The difference between the temperature of the surface water and the water of maximum temperature was remarkably constant throughout 1955 (Table I-2); the minimum difference was 15.9°C and the maximum was 28.7°C, but most values were clustered around 21°C.

Winter temperatures in Hot Lake can be substantial even though considerable heat is lost. Anderson encountered a maximum temperature of 33°C beneath the ice at a depth of 3.3 m.

The waters of Hot Lake in summer were virtually colorless down to the depth of maximum temperature. Anderson reported that a Secchi disk could be seen clearly at any depth in the upper cool zone, but the disk disappeared from sight after passing through the hot zone. This opacity was caused by a thin layer of dark-green water containing green sulfur bacteria, possibly Chlorobium. Below this bacterial plate the water was dark-brown and contained dissolved hydrogen sulfide. Light that was transmitted through the transparent layer of the lake was absorbed readily within the zone of sulfur bacteria and within the upper part of the underlying brown water (Fig. I-16).

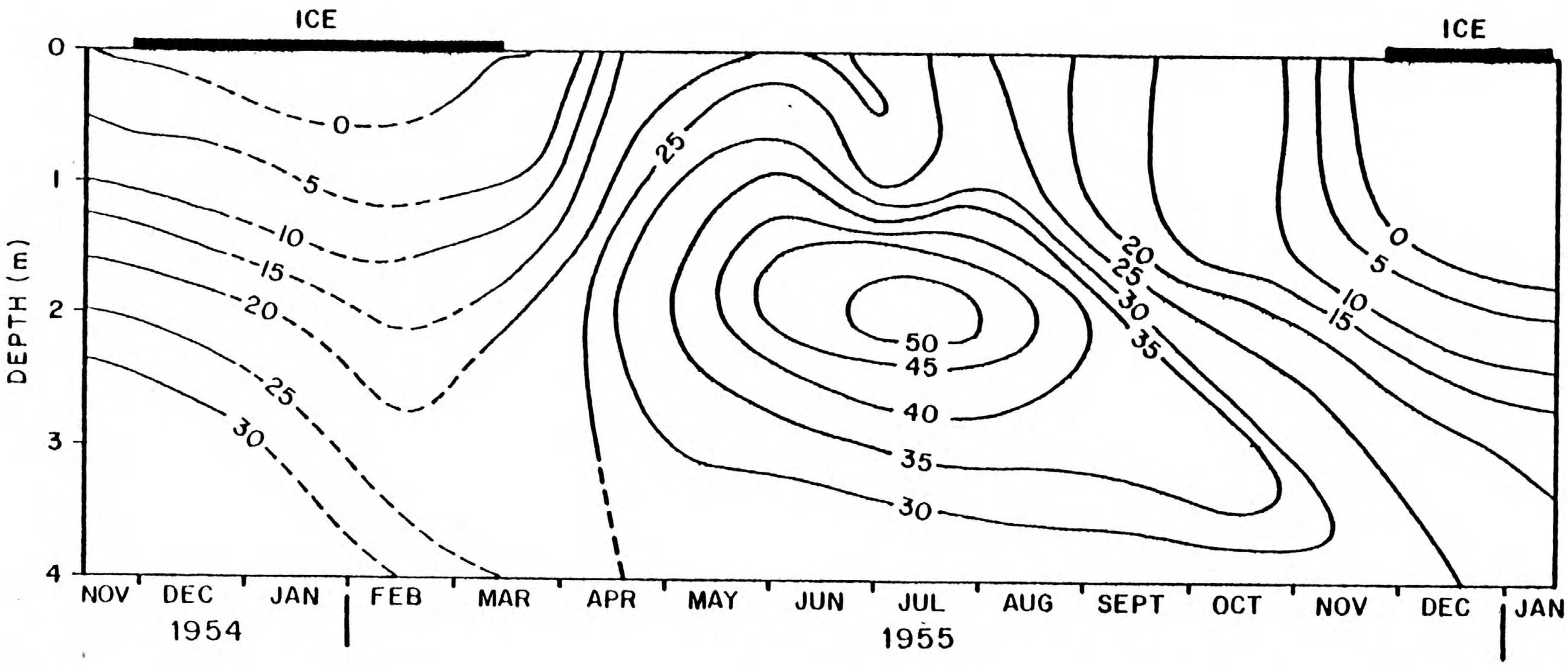



Figure I-17.--Variation of isotherms with depth and time in Hot Lake, Washington, from November, 1954 to January 1956; contour interval, 5°C; changes in the level of the surface of the lake are not shown. (Modified after Anderson, 1958.)

Table I-2.--Difference between surface water temperature and maximum water temperature, Hot Lake, Washington

[Data of Anderson, 1958]

| Date | Temperature Difference (°C) |
|---|---|
| March 12, 1955 | 21.0 |
| April 16, 1955 | 15.9 |
| May 17, 1955 | 22.1 |
| May 29, 1955 | 25.0 |
| June 25, 1955 | 28.7 |
| July 23, 1955 | 23.8 |
| August 22, 1955 | 21.7 |
| September 28, 1955 | 20.1 |
| October 18, 1955 | 18.0 |
| December 9, 1955 | 20.0 |

The position of the bacterial plate was not obviously controlled by the salinity gradient (Fig. I-16). The coincidence of the bacterial plate with the hot zone indicates to both Anderson (1958) and Edmondson (1963) that absorption of light by the plate was responsible for the maximum temperature. It is possible, however, that the bacteria prefer the high water temperatures.

Anderson found that the maximum transmission of light occurred in the yellow region of the spectrum. The intensity of light at 1.8 m (the depth to the bacterial plate) on August 23, 1955, was only 3.6 percent of the surface illumination. Using this value, Anderson calculated that the temperature of the zone with a thickness of 10 cm just beneath the top of the plate should be increasing by 2.92°C/day. On May 17, 1955 (3 months earlier), he had observed that this zone actually gained 2.2°C between 4:30 a.m. and 4:25 p.m.

Red Pond, Apache County, Arizona

Red Pond occurs about 32 km north and slightly west of St. Johns, Arizona (Fig. I-18), at an elevation of 1860 m. The bathymetry of the pond is shown in Figure I-19. Red pond had an "unusual temperature inversion" in the summer of 1964 (Cole and Whiteside, 1965a). In the early summer the temperature of the surface water was 20°C, whereas the temperature at 2 m was 44°C. In early March 1964, the difference between the temperature of the surface water and the maximum temperature was 21.5°C. A difference of 24°C existed on June 4-5, 1964, but by late August 1964 the pond was almost isothermal. At times the temperature gradient is very steep; Cole (1968) reports that in February (1964?) there was a change of 1.2°C within a vertical distance of 2 cm.

Red Pond is highly saline; the primary ions in the brine are sodium and chloride (Cole and Whiteside, 1965b). Variation in salinity with depth for early March 1964 is shown in figure I-20. On June 4-5, 1964, the following temperature, specific gravity, and salinity values were determined at the surface and at a depth of 1.5 m:

| Depth | Temperature | Specific Gravity | Salinity |
|---|---|---|---|
| 0 m | 20°C | 1.125 g/cm$^3$ | 165.9 g/l |
| 1.5 m | 44°C | 1.180 g/cm$^3$ | 258.45 g/l |

By August 17, 1964, Red Pond had become nearly uniform in temperature (Fig. I-21) and salinity (221 g/l).

Chemical stratification in Red Pond is established annually. A mixolimnion forms in winter and spring from melted snow, from fresh water springs that surround the pond and occasionally from freezing-out of salts. The fresher water layer is able to persist because of relatively low rate of evaporation in winter and spring.

In early March 1964, only a chemocline was present (Fig. I-20). but by early June a mixolimnion about 0.67 m thick had developed (Fig. I-21). By late summer, the high rate of evaporation had increased the salinity of the mixolimnion to such an extent that wind-generated currents were able to disrupt the stratification. By August 17-18, 1964, the temperature distribution was typical of holomictic lakes in summer in that a surface zone of warm water overlay cooler water (Fig. I-21).

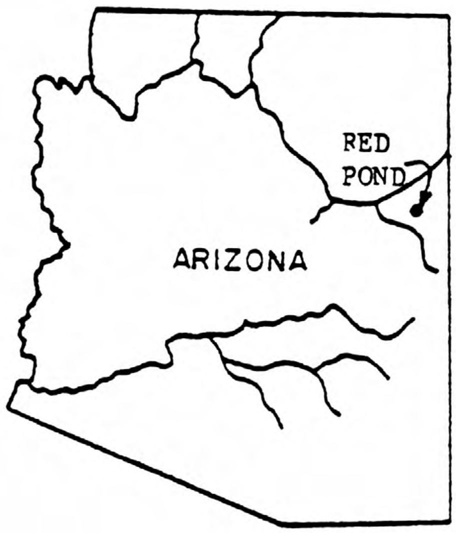



Figure I-18.--Location of Red Pond, Apache County, Arizona (34°50'N., 109°26'W.).

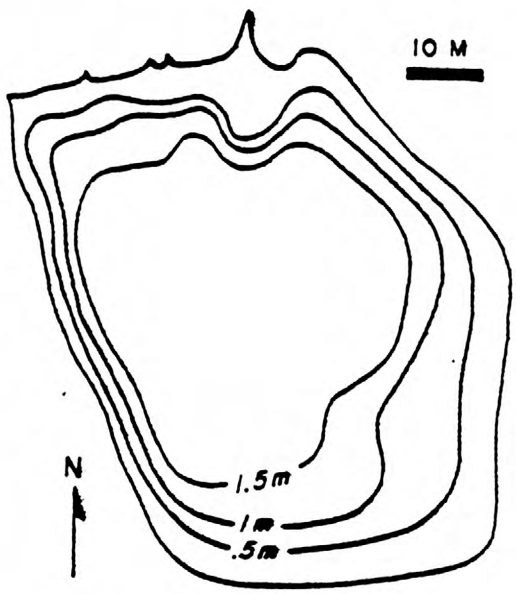



Figure I-19.--Bathymetry of Red Pond, June 1964 (after Cole and Whiteside, 1965a).

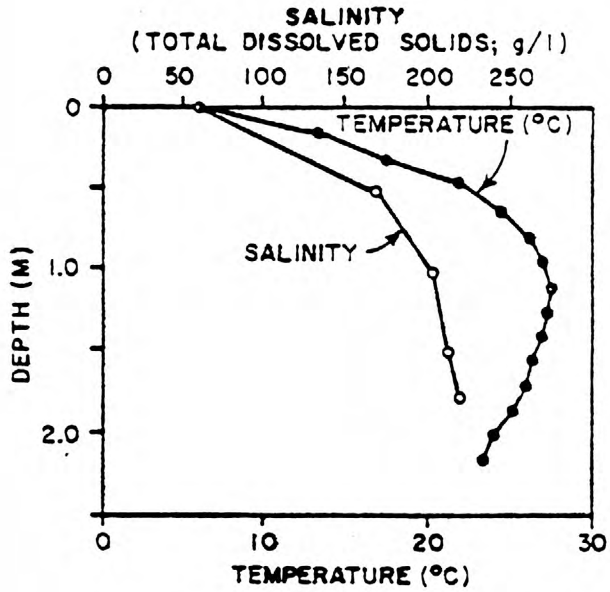



Figure I-20.--Variation of temperature and salinity with depth in Red Pond, Arizona. Observations apparently were made in early March 1964 (after Cole, 1968).

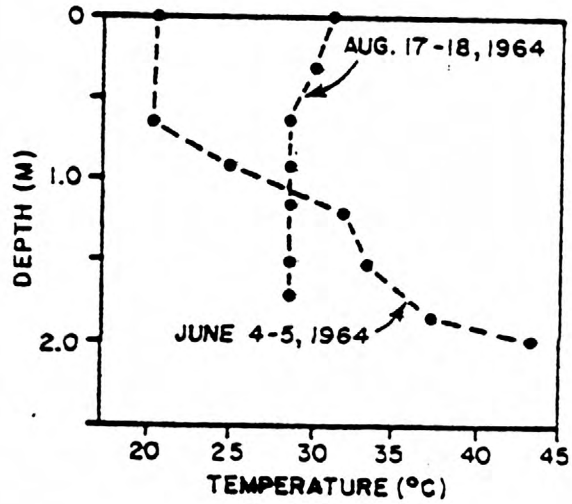



Figure I-21.--Variation of temperature with depth, Red Pond, Arizona (after Cole and Whiteside, 1965a).

The extent of penetration of light in Red Pond is shown in figure I-22. In June 1964, about 98 percent of surface radiation was absorbed before reaching a depth of 1.5 m (0.5 m above the bottom). The abrupt absorption of light between 1 and 1.5 m in early June 1964 (Fig. I-22) was caused by a "tremendous bloom" of purple sulfur bacteria that inhabited this zone. By August 1964, after overturn, the pond was yellow-green throughout.

Cinder Cone Pool, Catron County, New Mexico

Cinder Cone Pool is located 28 kilometers northwest of Quemado, New Mexico (Fig I-23), at an elevation of 1900 m. The pool occurs within the crater of a recently extinct volcano (Fig. I-24) that lies near the center of a maar[1] with a diameter of about 1.8 km. The northern part of the maar is occupied by Zuni Salt Lake, a shallow (mean depth, 0.7 m), saline lake with an area of about 0.6 $km^2$. The volcanic cone containing Cinder Cone Pool is on the southern shore of Zuni Salt Lake (Fig. I-24), but the two water bodies are not directly connected. This review is based on a number of visits to the pool between 1960 and 1964 by the authors, and on more detailed investigations by Bradbury (1967 and 1971).

1/A low-relief, coneless volcanic crater formed by a single explosive eruption.

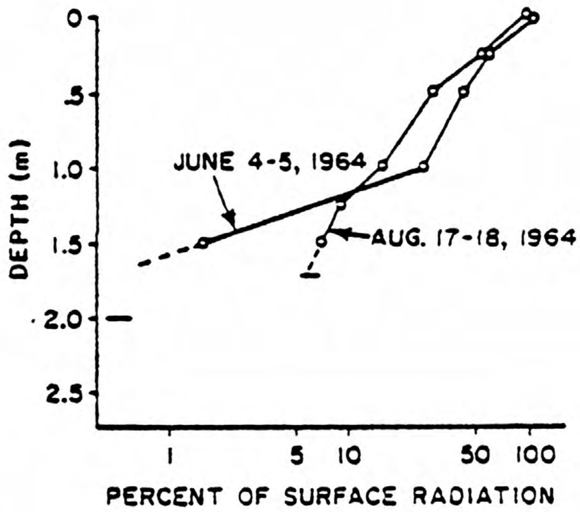



Figure I-22.--Light penetration in Red Pond, Arizona. Depths to bottom of the lake are shown by short horizontal lines (after Cole and Whiteside, 1965a).

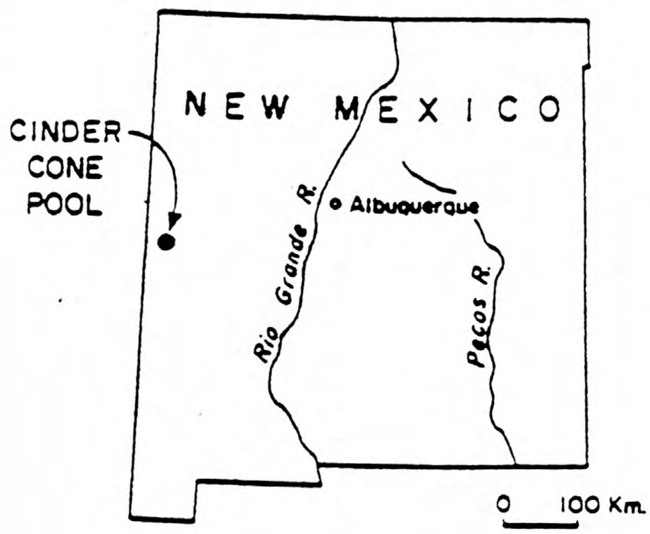



Figure I-23.--Location of Cinder Cone Pool, Catron County, New Mexico (34°27'N., 108°46'W.).

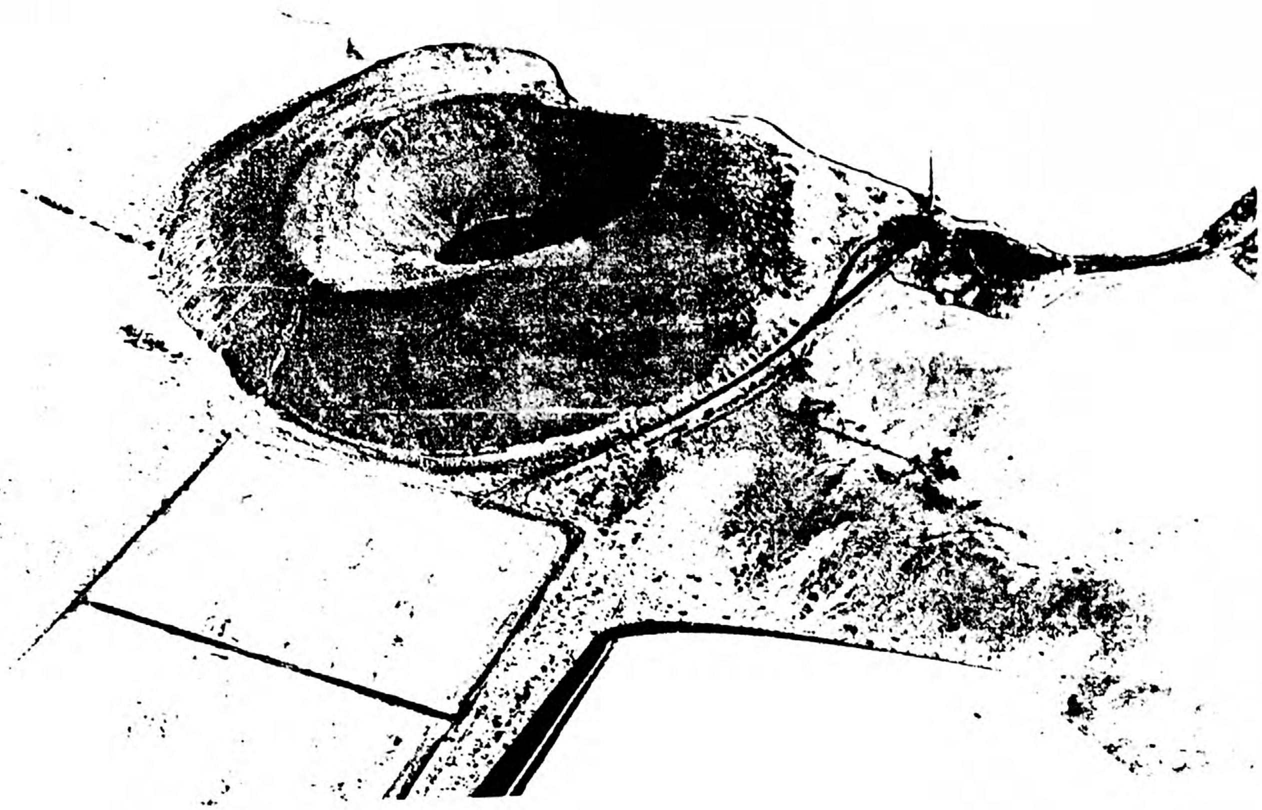


Figure I-[illegible].--View of Cinder Cone Pool, New Mexico, looking northwest.

The approximate bathymetry of Cinder Cone Pool is shown in figure I-25. The pool has a maximum depth of 7 m, a length of 58 m and a width of 37 m. The steep sides of the cinder cone protect the pool surface from wind, but, at the same time, reduce the amount of sunlight reaching the surface of the pool. Salt water enters Cinder Cone Pool from springs rising along the volcanic conduits of the crater. The sides of the cinder cone crater form a catchment basin, and fresh water from rain or snow is added to the top of the pool by runoff and seepage. The fresh water floats on top of the denser saline water and forms a chemical stratification that may persist for many months. Such a stratification was established in late August 1963, when heavy rains fell directly into the crater of the cinder cone, and persisted for 23 months, until June 1965. Before August 1963, the pond had been essentially isohaline. With the addition of fresh water, a mixolimnion and a chemocline were established, and the temperature of the underlying brine increased rapidly.

The variation of salinity within Cinder Cone Pool between July 1963 and November 1965 is shown in figure I-26. The contour values represent the percent of saturation of the brine with respect to sodium chloride. The mean density of the monimolimnion was about 1.084 g/cm$^3$ (Table I-3), which represents about 43 percent of saturation. From April 1963 to April 1964, chemical stratification was pronounced. During the winter of 1963-1964, the salinity ranged from somewhat less than 15 percent of saturation at the surface to somewhat more than 40 percent of saturation at a depth of about 2 m.

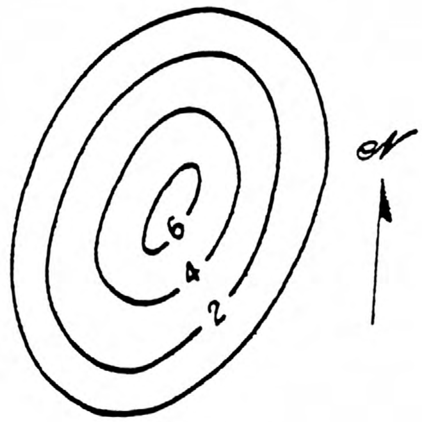



Figure I-25.—Bathymetry of Cinder Cone Pool, New Mexico, in 1963. Contour interval = 2 m.

The distribution of temperature with time and depth is shown in figure I-27. The maximum temperature recorded was 40°C on October 5, 1963. The depths to the hot zone increased from spring to fall (Fig. I-27), a condition that has also been observed in Hot Lake, Washington, and Lake Ursului, Romania.

Purple sulfur bacteria formed a bacterial plate in Cinder Cone Pool that closely coincided with the zone of maximum water-temperature. These bacteria were so abundant that they colored the water bright pink and greatly increased the capacity of the saline water to absorb radiation.

## Lakes of the McMurdo Region, Antarctica

The discovery of saline lakes in the McMurdo region of Antarctica (Ball and Nichols, 1969) resulted in a proliferation of investigations on the lakes. Two lakes in particular, Lakes Vanda and Bonney, have been studied in considerable detail. Armitage and House (1962) reported that the near-bottom water of one of these lakes, Lake Vanda, is maintained at 25.6°C in an environment with a mean annual air temperature of -20°C. The second of the two most studied lakes in this area is Lake Bonney, about 28 km southeast of Lake Vanda. The general locations of these two lakes are shown in figure I-28, and some features of the lakes and their environment are given in table I-4.

Table I-3.--Difference in temperature (°C) between water at the surface and water of maximum temperature, and difference in density between water at the surface and water at about 6 m, Cinder Cone Pool, New Mexico.

[Data from Bradbury, 1967]

| Date | Temperature of Water (°C) | | | Density of Water (g/cm$^3$) | | |
|---|---|---|---|---|---|---|
| | Surface | Maximum | Difference | Surface | 6 m | Difference |
| June 2, 1963 | 18 | 18 | 0 | 1.083 | 1.083 | 0 |
| September 14, 1963 | 21 | 31 | 10 | 1.035 | 1.088 | 0.053 |
| October 5, 1963 | 17 | 40 | 23 | 1.030 | 1.082 | 0.052 |
| October 24, 1963 | | | 1.030 | 1.083 | 0.052 | |
| November 9, 1963 | 11.5 | 32 | 20.5 | 1.031 | 1.081 | 0.050 |
| December 7, 1963 | 1 | 27 | 26 | 1.040 | 1.080 | 0.040 |
| January 16, 1964 | -2 | 24 | 26 | 1.040 | 1.081 | 0.041 |
| February 23, 1964 | 0.5 | 32 | 31.5 | 1.018 | 1.092 | 0.074 |
| March 22, 1964 | 8 | 37.5 | 29.5 | 1.040 | 1.083 | 0.044 |
| April 18, 1965 | 13 | 39 | 26 | 1.048 | 1.082 | 0.034 |
| May 23, 1964 | 20 | 36.5 | 16.5 | 1.059 | 1.082 | 0.023 |
| June 20, 1964 | 21 | 36 | 15 | 1.070 | 1.082 | 0.012 |
| July 25, 1964 | 24 | 36 | 12 | 1.070 | 1.083 | 0.013 |
| August 15, 1964 | 25 | 37 | 12 | 1.070 | 1.087 | 0.017 |
| September 13, 1964 | 23 | 32.5 | 9.5 | 1.072 | 1.084 | 0.012 |
| November 21, 1964 | 4 | 25 | 21 | 1.069 | 1.088 | 0.019 |
| June 21, 1965 | | | 0 | | | 0 |

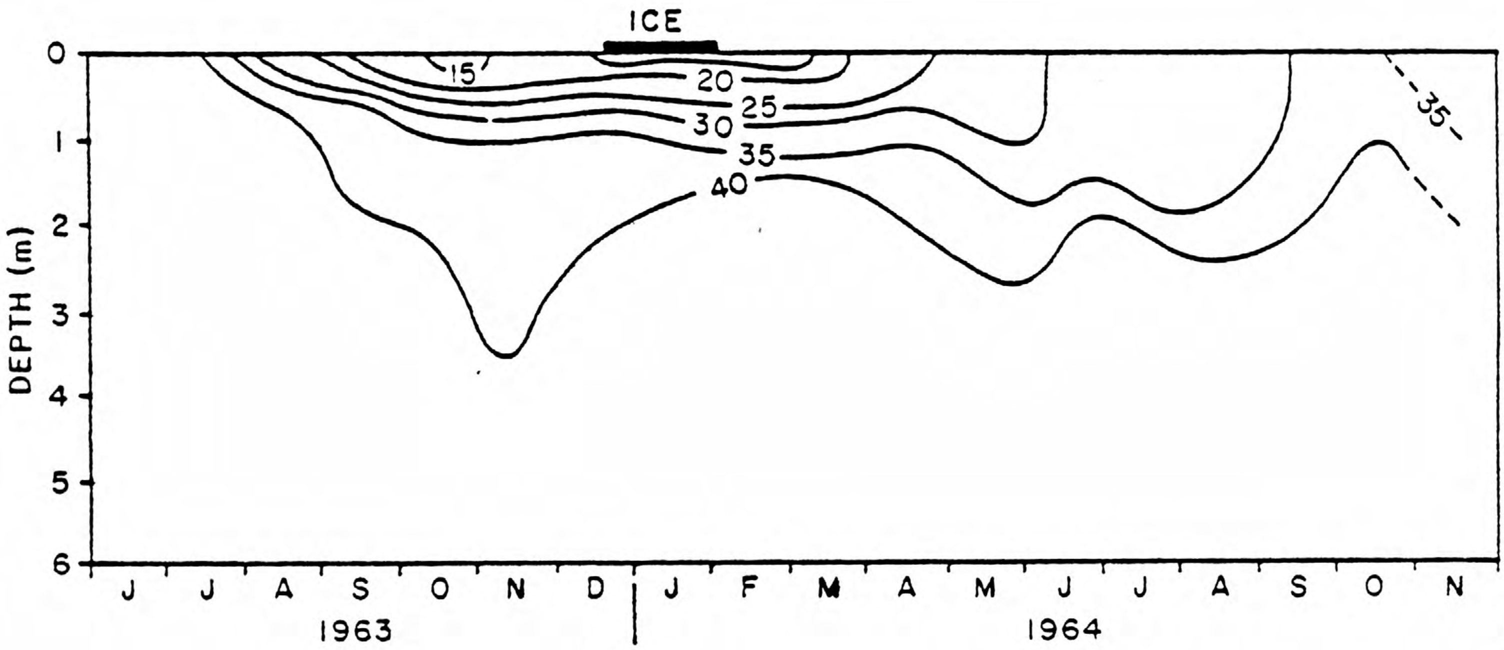



Figure I-26.--Variation of isosalinity lines with depth and time in Cinder Cone Pool, New Mexico, June 1963 to November 1964. Contour interval, 5% of saturation of sodium chloride. (Modified after Bradbury, 1971.)

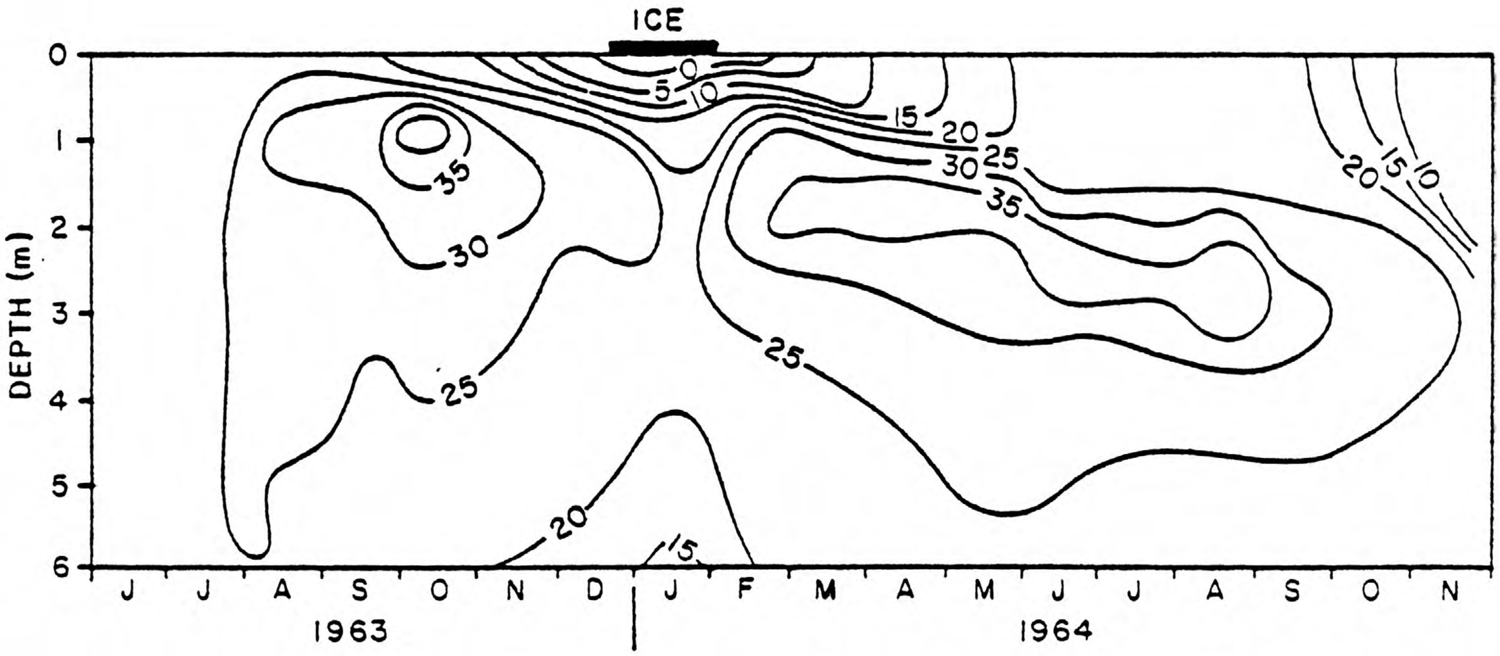



Figure I-27.--Variation of isotherms with depth and time in Cinder Cone Pool, New Mexico, June 1963 to November 1964. Contour interval 5°C. (Modified after Bradbury, 1971.)

Lakes Vanda and Bonney are located on the western side of McMurdo Sound in Wright Dry Valley, an ice-free area that is about 16-24 km wide and about 160 km long. The mean annual snowfall in this arid region is very small (Nichols, 1963). Most of the snow that does fall is lost by sublimation (Wilson, 1967). The climate is frigid; the mean temperature is below 0°C during all months of the year (Angino and Armitage, 1963a).

The influx of solar radiation in the vicinity of Lakes Vanda and Bonney is extraordinarily high (about 90,000 cal/$cm^2$/yr; Wilson and Wellman, 1962; Shirtcliffe and Benseman, 1964). The maximum solar radiation received in a summer day in Antarctica is about the same as that in southern California and Arizona in June (Daniels, 1964, p. 40 and 42). Indeed, because of the reduced content of dust and water vapor in the Antarctic atmosphere, "the influx of solar radiation may achieve values greater than [those] in equatorial latitudes" (Kopanev, 1960).

Profiles of temperature, density, and light penetration with depth for Lakes Vanda and Bonney are shown in figures I-29 and I-30. Note the remarkably high positive correlation between the profiles of density and temperature in Lake Vanda below about 20 m.

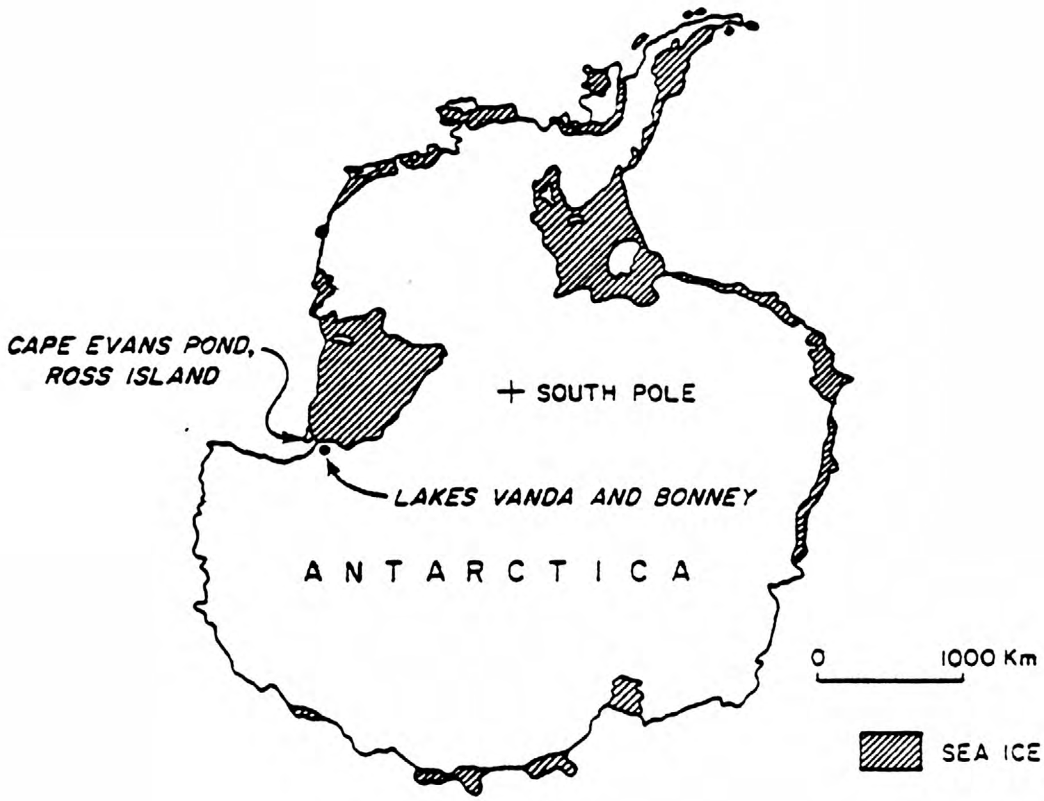



Figure I-28.--Locations of Lakes Vanda and Bonney and of Cape Evans Pond, Antarctica.

Table I-4.--Features of Lakes Vanda and Bonney, Victoria Land, Antarctica.

| | Lake Bonney | Lake Vanda | Reference |
|---|---|---|---|
| Location | 77°55'S 162°20'E | 77°35'S 161°39'E | Hoare and others, 1964 |
| Dimensions | The lake is made up of two basins, 2.56 km by 0.84 km and 4.8 km by 0.77 km, which are connected by a narrow channel. | 5 km by 1.45 km (maximum width) | Ragotzkie and Likens, 1964 |
| Area | Western part: 1.1 $km^2$ | 5.2 $km^2$ | Goldman and others, 1967 |
| Maximum depth | 32.15 m | 66.1 m | Ragotzkie and Likens, 1964 |
| Elevation of surface of ice | 91.5 m | 123 m | Armitage and House, 1962 |
| Depth of ice cover | 4.21 m | 3.51 m | Angino and Armitage, 1963a |
| Salinity of lower-most water | 10x seawater | 3x seawater | Angino and Armitage, 1963b |
| Maximum chloride ion concentration | 15.2% | 7.6% | Angino and Armitage, 1963b |
| Maximum density | 1.20 $g/cm^3$ | 1.09 $g/cm^3$ | Angino and Armitage, 1963b; Wilson and Wellman, 1962 |
| Maximum temperature | 8°C (at 15 m) | 25.6°C (at 66 m) | Angino and Armitage, 1963b; Shirtcliffe and Benseman, 1964 |

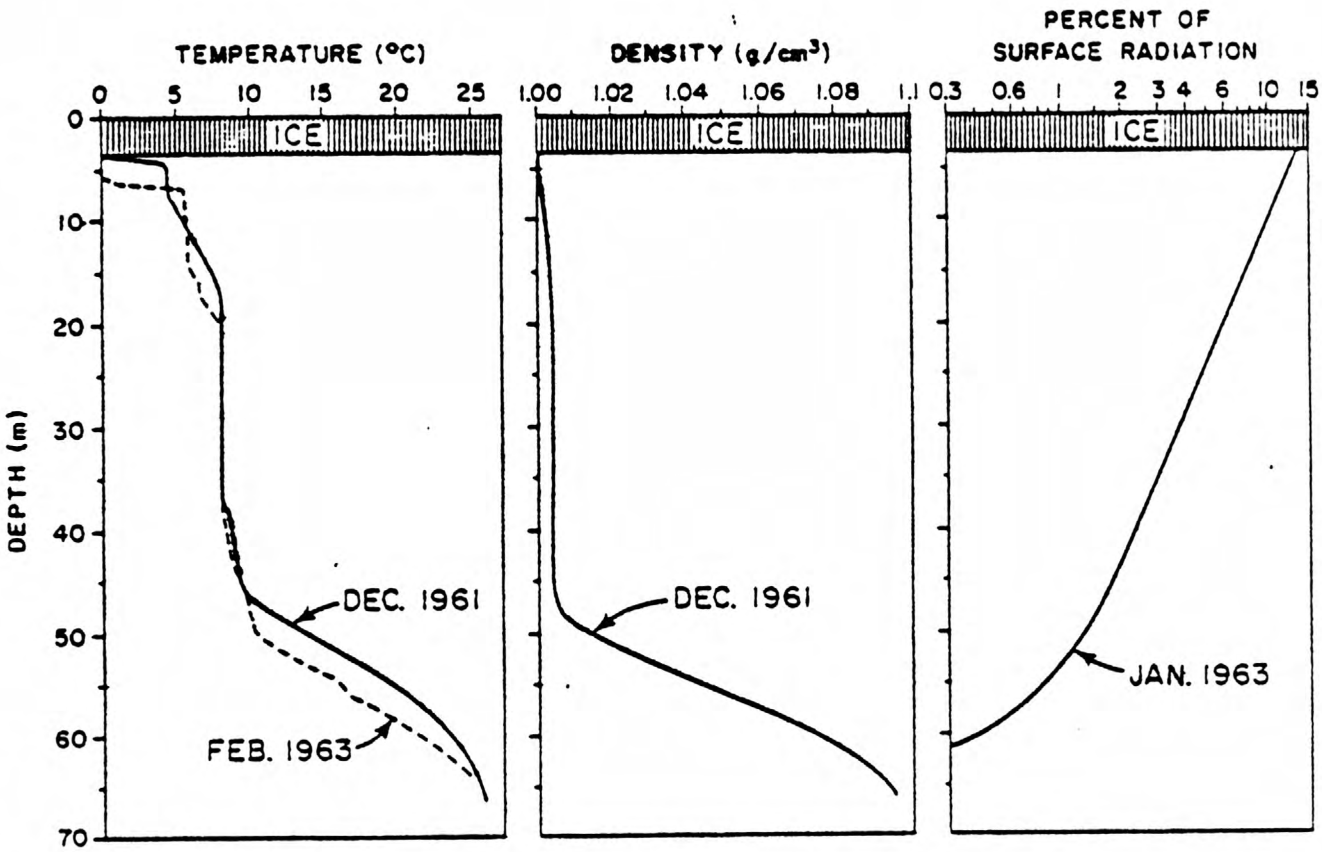



Figure I-29.--Temperature, density, and light penetration with depth, Lake Vanda, Victoria Land, Antarctica. Data from Wilson and Wellman (1962), and Goldman and others (1967).

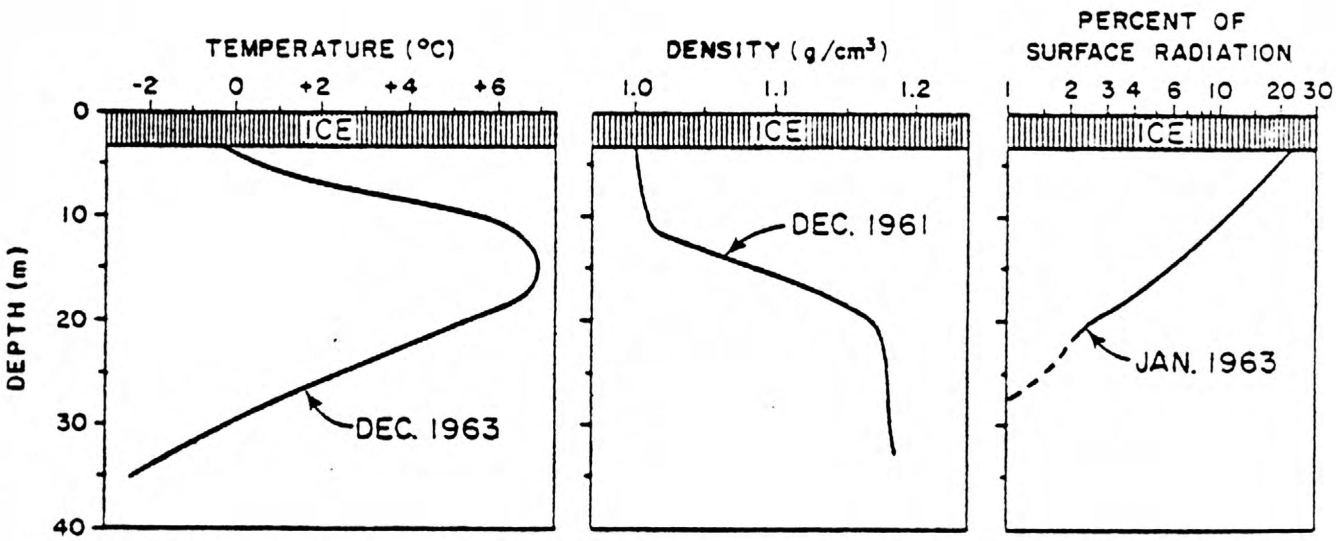



Figure I-30.--Temperature, density and light penetration with depth, Lake Bonney, Victoria Land, Antarctica (data from Hoare and others, 1964, Angino and others, 1964, and Goldman and others, 1967).

As much as 21 percent of the incident light in January passes through approximately 4.6 m of ice covering Lakes Vanda and Bonney (Goldman and others, 1967). The light transmissibility of the ice approaches that of distilled water (Goldman and others 1967). Quoting Wilson (1967)

> "The high light transmission of this ice is due to the fact that for hundreds of year the ice has been growing on the bottom of the ice and ablating from the top. The ice now contains large crystals several square cms. in cross section and 12 feet long with the X-axis arranged vertically. These crystals act as light pipes. The light energy from the sun passes through the ice and into the water where it is absorbed."

After passing through the ice, the remaining light penetrates to great depths. The upper waters of Lake Vanda are among the clearest in the world (Goldman and others, 1967). The percentages of surface radiation penetrating to various depths in Lakes Vanda and Bonney are shown in figures I-29 and I-30, respectively.

The phenomenal clarity of the water within these lakes occurs notwithstanding the presence of numerous types of planktonic organisms less than 20 $\mu$m in size that extend throughout the water column. Although the variety of organisms is great, the standing crops and primary productivity are low (Goldman and others, 1967). In Lake Vanda some heat is derived from the anaerobic oxidation of the remains of these organisms (see ZoBell and others, 1953), but the amount is small compared to the total heat retained in the bottom waters. Armitage and House (1962) noted a "strong odor of hydrogen sulfide" from 66 m in Lake Vanda, which is circumstantial evidence of anaerobic decomposition.

The fact that Lakes Bonney and Vanda are only 28 km apart but have very different thermal characteristics (figures I-29 and I-30) suggests that the sources of heat may be different in these two lakes. The maximum temperature in Lake Bonney occurs within the water column whereas the maximum temperature in Lake Vanda is at the bottom. This suggests that Lake Vanda may be receiving at least some of its heat from the bottom of the lake. Indeed, Ragotzkie and Likens (1964) measured a positive heat flow from the bottom of Lake Vanda. They concluded that Lake Vanda receives about twice as much heat from solar radiation than from conduction from the bottom. Wilson and Wellman (1962), on the other hand, concluded that solar radiation was the only source of heat in Lake Vanda. The bulge in the temperature profile for Lake Bonney (Figure I-30) is apparently due entirely to solar heating.

Below about 48 m in Lake Vanda and between 11 and 20 m in Lake Bonney there is a rapid increase of specific gravity with depth (Figs. I-29 and I-30) produced by a corresponding increase in the amount of salt dissolved in the water. These salinity gradients (chemoclines) completely suppress convection, and heat escapes through the chemoclines only by conduction.

Bottom water of Lake Bonney is nearly saturated with sodium chloride and contains small amounts of magnesium chloride. These two salts account for 98 percent of the dissolved salts in the deeper waters (Table I-5). In contrast, the bottom water of Lake Vanda is chiefly a solution of calcium chloride with much smaller amounts of sodium and potassium chloride (Table I-5). Calcium and chloride ions account for 86 percent of the salinity in the bottom water of Lake Vanda. The physical environments of the two lakes are similar, and they are in proximity (28 km); hence, the fact that their bottom waters differ so widely in chemical composition is puzzling. The origin of the salts has not been unequivocally determined, but the consensus is that the saline waters in both Lake Bonney and Lake Vanda are essentially seawater that has been modified to differing degrees by evaporation, freshwater influx, and, possibly, volcanic hot springs.

An associated problem is the origin and maintenance of the chemocline. Wilson (1964, 1967) believed that some thousands of years ago the lake level of Lake Vanda had dropped until only about a meter of concentrated calcium chloride remained. When the climate changed, freshwater flowed onto the top of the concentrated solution, the lake basin filled up, and calcium chloride began to diffuse upward. Because all lakes occupying the lowest parts of various enclosed drainage basins in the McMurdo "Dry Valleys" have a similar chemical stratification, this process would have had to have been widespread.

The observations by Goldman and others (1967) of small ponds on Ross Island (Fig. I-28) suggest that another mechanism may have been responsible for the chemical stratification. Figure I-31 shows the variations in temperature and electrical conductivity with depth in a small pond near the south shore of Cape Evans, Ross Island (77°38'30"S, 166°24'00"E). This pond was about 1 m deep, 20 m long, and 10 m wide. A very thin layer of ice (about 5 mm thick) covered the lake on January 16, 1962, during the investigation by Goldman and others (1967). The bottom of the pond was dark volcanic rock. Goldman and others state,

Table I-5.--Chemical composition of water at various depths in Lakes Vanda and Bonney, Antarctica (after Angino and Armitage, 1963a).

| (Percent) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Depth | Na+ | K+ | Ca++ | Mg++ | $Cl^-$ | $SO_4^{--}$ |
| **Lake Bonney** | | | | | | | |
| 11.3m | .15 | .02 | .00 | .00 | .08 | .01 | |
| 30.5 | 4.33 | .30 | .11 | 2.63 | 14.33 | .05 | |
| **Lake Vanda** | | | | | | | |
| 6.1m | .00 | .00 | .00 | .00 | .02 | | |
| 6.6 | .01 | .00 | .02 | .00 | .06 | | |
| 61.0 | .51 | .07 | 2.05 | .70 | 6.45 | | |
| 66.2 | .68 | .08 | 2.42 | .77 | 7.59 | .08 | |

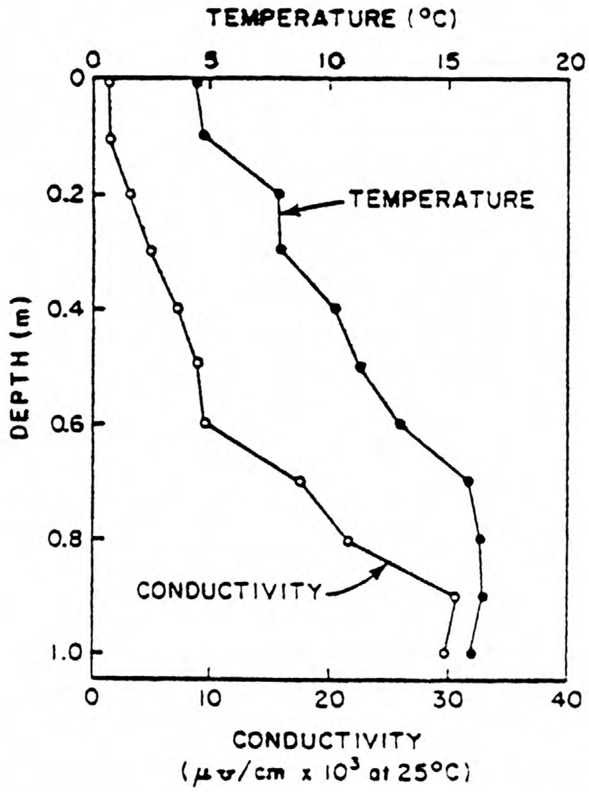



Figure I-31.--Temperature and electrical conductivity with depth, Cape Evans Pond. A layer of ice with a thickness of about 5 mm covered the pond. (After Goldman and others, 1967.)

"The water temperature increased from 4.4°C just below the surface to 16.0°C at 1 m. A concomitant increase in conductivity indicated that the thermal structure was stabilized by increases in salinity with depth...."

This small pond illustrates how a salinity gradient can form by freezing-out. As the pond froze, salts were forced downward out of solution. "As freezing continued downward, an ice layer was formed in which the salinity increased toward the bottom" (Goldman and others, 1967, p. 301). During the spring and early summer the general rise in temperature in the pond caused melting of the ice on the margins and near the bottom before the surface ice melted. With continued melting a salinity gradient was created with fresh water at the surface and concentrated brine at the bottom. Summer insolation then developed a thermal gradient.

It seems unlikely that Lake Vanda, with a maximum depth of 66.1 m, could have been frozen to the bottom. Both Lakes Vanda and Bonney are continuously covered by ice except at the margins, "where summer melting produces a short moat one to several meters wide" (Ragotzkie and Likens, 1964). Perhaps the freezing-out process described by Goldman and others (1967) for the small pond on Ross Island operated in the shore zones of Lakes Vanda and Bonney. Each winter as the edge ice froze and each spring as the edge ice melted, a concentrated brine might have flowed as a density current along the bottom. Ultimately the chemoclines that are observed in both Lakes Bonney and Vanda developed. Solar radiation passing through the ice heated the underlying water and decreased its density.

Espevick Pond, Norway

The culture of oysters in Norway is difficult because of cool water temperatures. The chief problems are that oysters will not spawn and young oysters, if introduced, cannot survive. During a search for a solution to these problems, Rasch (1866-1881) was surprised to find that some coastal ponds were inhabited by abundant oysters. He found that these ponds were only occasionally flooded with seawater. The water near the surface was nearly fresh, but water at a depth of 1-2 m was almost as salty as the sea. Rasch found that the surface water was cool in summer, but the deeper water had a temperature approaching 30°C. He speculated that the heat was produced by the microbial degradation of organic matter in the bottom sediments.

Espevick Pond, one of these heated coastal ponds, is about 120 km north of Stavanger on the island of Tysnes and near the opening to the sea of Hardanger Fjord (Fig. I-32). The pond has a maximum dimension of about 325 m (Gaarder and Spärck, 1932, fig. 4). Espevick Pond is separated from the sea by a low barrier about 50 m wide that prevents seawater from entering the pond except during some spring tides. The pond has a maximum depth of about 5 m. In August of 1885, a maximum temperature of 36°C was observed in the pond (Gaarder and Spärck, 1932).

Helland (1889) observed that the maximum temperature in Espevick Pond did not occur at the bottom of the pond but at a depth of 2-3 m, and he concluded correctly that the heat was not derived from oxidation of organic matter but from absorption of solar radiation.

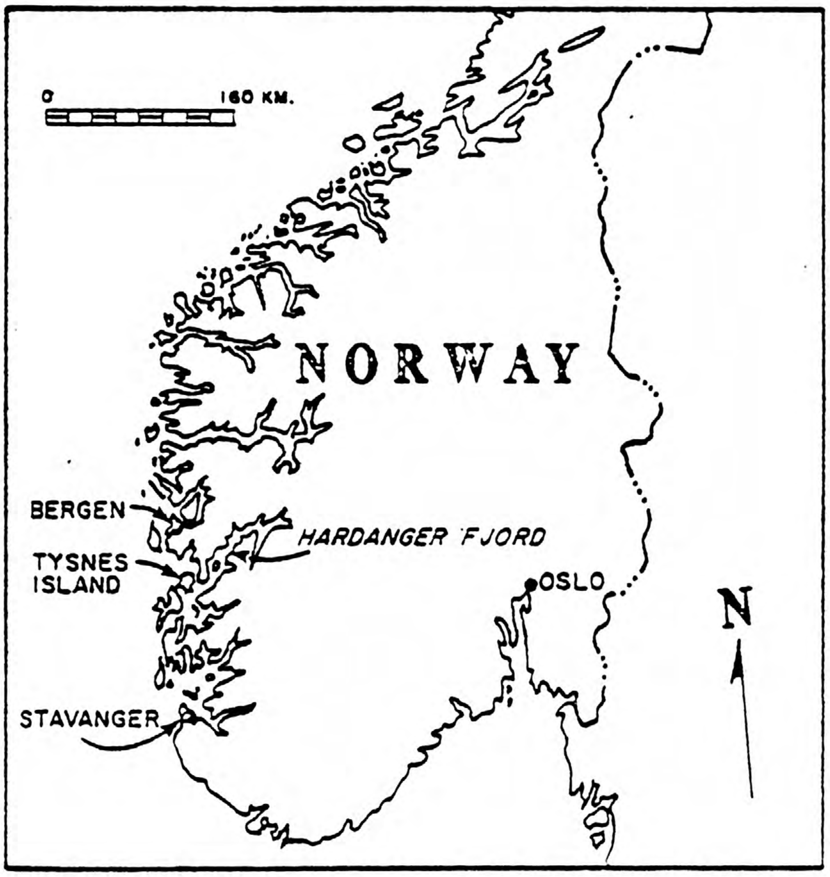



Figure I-32.--Location of Tysnes Island, Norway (60°N., 5°36'E.), the site of Espevick Pond.

Friele (1899) showed that the temperature of the water at a depth of 2 m correlated closely with the number of hours of daylight (Fig. I-33). His data show also that the temperature at 2 m is markedly reduced during winter (Fig. I-33).

Figure I-34 shows variation of salinity ($^{o}/oo$) with depth and time in Espevick Pond in the summer of 1927. Salinity measurements were taken by Gaarder and Spärck (1932) at approximately weekly intervals. They found a rather pronounced salinity gradient between the surface and a depth of 1 m, but only a slight gradient (from 27 to 28 $^{o}/oo$) between the depths of 2 and 4 m. The mean increase in salinity between the surface and 1 m was 10.16 $^{o}/oo$.

Figure I-35 shows the gradual development of the hot zone in Espevick Pond during the summer of 1927. The maximum temperature recorded was 28°C on August 8th. Favorable conditions for the development of a hot zone in Espevick Pond are attained when there is enough rain in spring for the formation and maintenance of a brackish water layer at the surface; in the summer of 1927, sufficient rainfall occurred in late June.

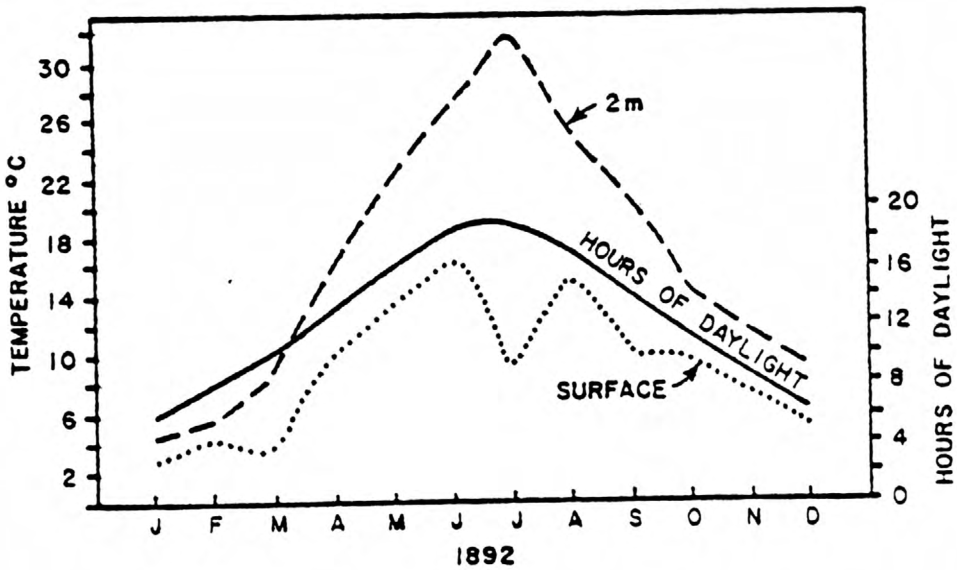



Figure I-33.--Variation of temperature with time in Espevick Pond (at the surface and a depth of 2 m) and variation in the number of hours of daylight with time (after Friele, 1899).

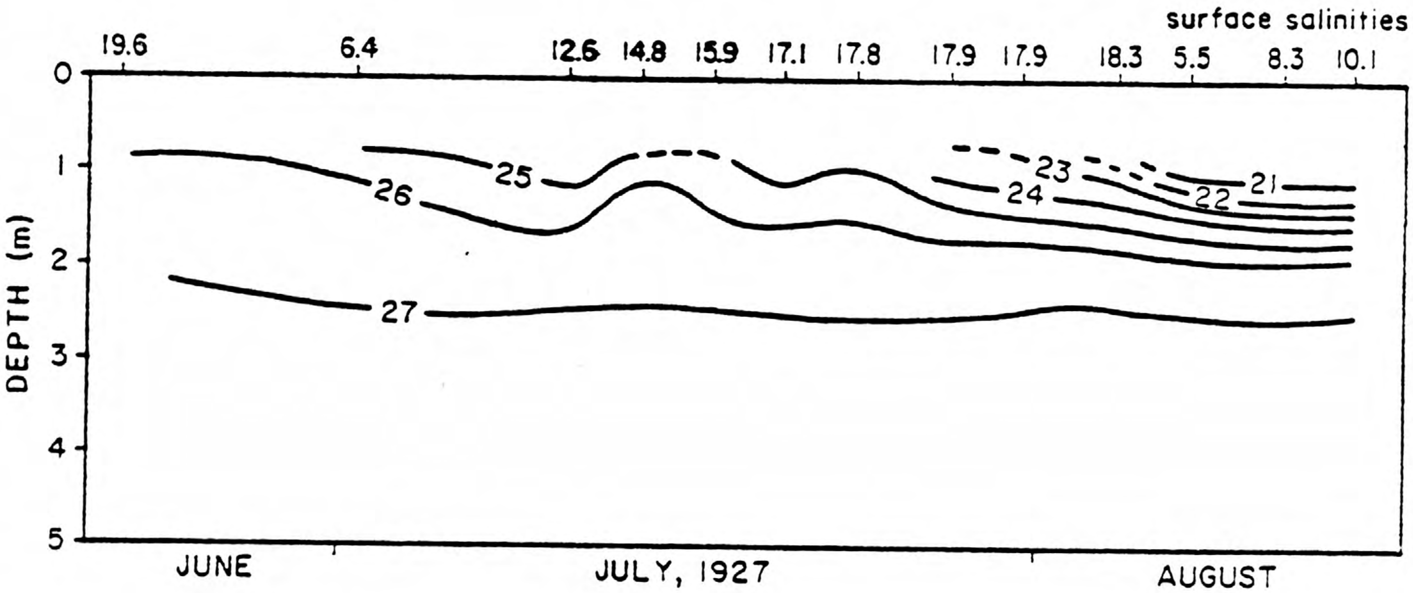



Figure I-34.--Variation of isosalinity lines with depth and time in Espevick Pond, Norway, summer of 1927; contour interval, 1°/oo; after Gaarder and Spärck (1932).

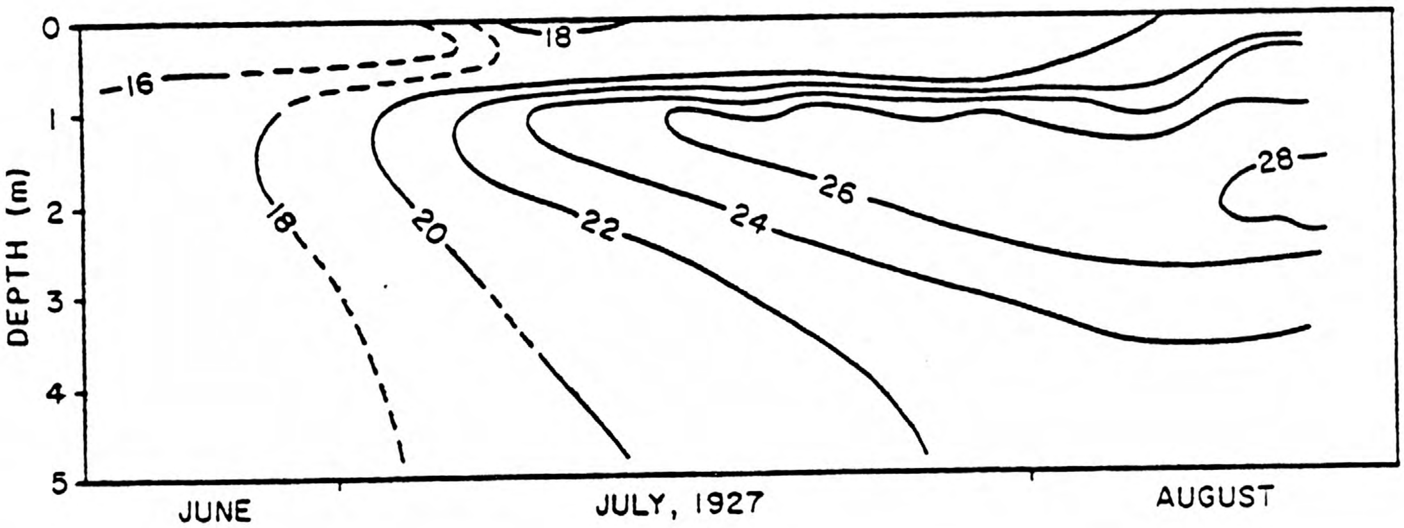



Figure I-35.—Variation of isotherms with depth and time in Espevick Pond, Norway, summer of 1927; contour interval, 2°C; after Gaarder and Spärck (1932).

Lakes Meggarine and Mardjadja, Algeria

Beadle (1943) observed that the bottom of Lake Meggarine, Algeria (33°12'N, 6°2'E), at a depth of 2 m, was composed entirely of salt crystals. On February 16, 1938, water near the bottom was nearly 10°C warmer than the water at the surface, which had a temperature of 15.5°C. Beadle also reported that unusually warm temperatures were observed on February 19, 1938, south of Biskra, Algeria in a shallow pan (0.3 m deep) receiving overflow from Lake Merdjadja. He reported that the temperature at the bottom of the pan was 31° C, 12° warmer than water at the surface. The bottom water was also five times denser than the surface water.

Solonowka Creek, Baraba Steppe, U.S.S.R.

Between the Irtysch and Ob Rivers in the south-central region of the U.S.S.R., about 350 km southwest of Novosibirsk, is a series of salt lakes on the Baraba Steppe. Unusually warm water was reported from a long (2 km), narrow (5-8 m) extension of Kutschuk Lake called Solonowka Creek (52°30'N., 80°E.) (Brecht-Bergen, 1908). The creek had a mean depth of about 1.5 m. Brecht-Bergen found that whereas the water at the surface of the inlet had a temperature of 22°C in summer, the temperature of the brine at a depth of one meter was 44°C. He attributed the temperature anomaly to accumulation of the "sun's warmth."

Devil's Kettle, Andros Island, Bahamas

A drowned sinkhole on the Bahama Banks in the vicinity of Andros Island, Bahamas, exhibits unusual thermal properties, and has been named the "Devil's Kettle." The bottom of the Devil's Kettle is about 5 m below average tide level (Kohout and others, 1968). A layer of water at the bottom of the hole is about 11 $^{o}/oo$ more saline and about 5°C warmer than the overlying clear, oxygen-rich waters (Figure I-36). The lower water layer, the monimolimnion, is anoxic, contains hydrogen sulfide and is red from the purple bacterium, *Lamprocystis rosea* Kutzing (Kohout and others, 1968).

The source of the warmer water was initially a mystery to Kohout and others. They considered and rejected "upward convection of geothermally heated seawater" and "chemical-reaction heat from bacterial metabolism" before recognizing that heat was derived from absorption of solar radiation.

The transitions in temperature (from 26° to 34°C) and salinity (from about 24 $^{o}/oo$ to about 34 $^{o}/oo$) are remarkably abrupt (Fig. I-36). The data in figure I-36 by J. B. Rucker, U.S. Naval Oceanographic Office, show that the "warm temperature layer" is about 0.5 m higher than the "high salinity layer." This 0.5 m-thick layer of warm water with salinity characteristics of the upper water (23.8 $^{o}/oo$) should be unstable. Concentrations of sulfur bacteria were at a maximum in this zone and possibly the increase in specific gravity resulting from abundant sulfur-laden cells may have offset the decrease in specific gravity caused by the increase in temperature. An alternate explanation is that the chemocline and thermocline actually coincide at a depth of about 4 m. Either interpretation results in an extremely thin chemocline.

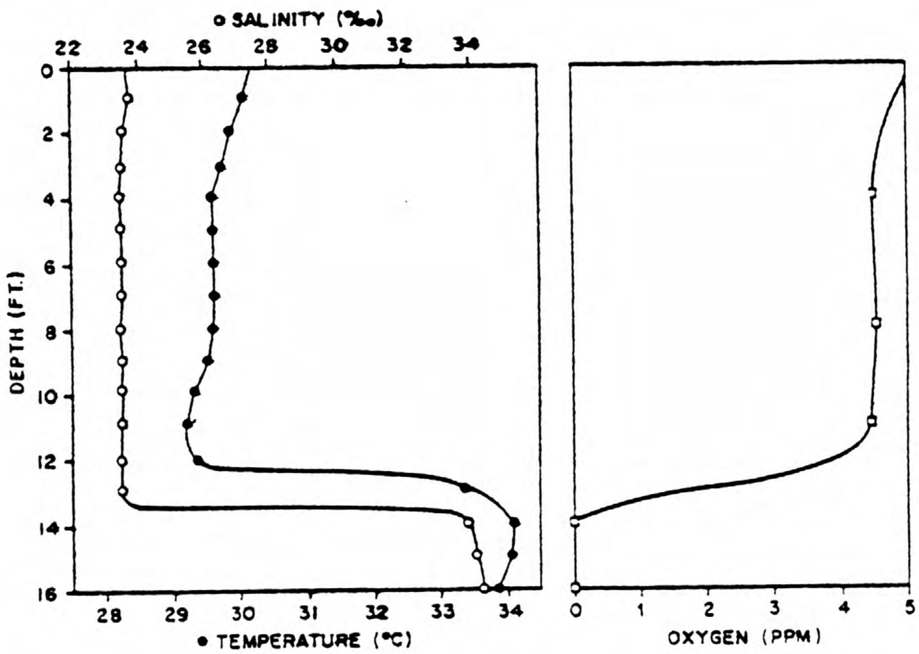



Figure I-36.--Variation of salinity, temperature, and content of oxygen with depth, Devil's Kettle, Bahama Banks (written commun., J. B. Rucker, U.S. Naval Oceanographic Office, 1967).

## Meade Salt Well, Kansas

The first report of a possible heliothermic lake in the United States was by Hollister (1903). He reported that the roof of a large subterranean cavern in southwestern Kansas collapsed sometime between the 3rd and 26th of March 1879 forming a gaping sinkhole. At the time of Hollister's visit, about 20 years later, the diameter of the depression at the level of the plains was 66 m. A pond in the depression, called the Meade Salt Well, was 38 m in diameter and about 2.7 m deep. The brine within the pond had a temperature, that, according to reports, at times was close to the boiling temperature. Hollister did not speculate on the source of the heat, but he did observe that the brine in the pond was chemically stratified. He states,

> "There were found to be two distinct layers of water, that on the top which was three feet in depth and one below six feet in depth and extending to the bottom. The top layer contained one-third less salt per unit volume than the under layer."

The Meade Salt Well was apparently accumulating solar energy.

Lago Pueblo, Grand Roque Island, Venezuelan Antilles

A shallow (generally less than 1 m) inland lagoon on Grand Roque Island, the principal island in a group of islands in the Venezuelan Antilles known as Los Roques (I-37), contains a 5.25-m hole that accumulates dense brines as a result of evaporation of seawater. The island is in the Caribbean sea 150 km north of Caracus, Venezuela and about the same distance east of the island of Bonaire. After the winter rainy season of 1973, density stratification resulted when the dense brines became covered by a mixture of normal seawater and freshwater from an inflowing stream. Solar heating to temperatures between 44° and 47°C resulted (Hudec and Sonnenfeld, 1974)(Fig. I-38). The high temperatures of the dense brine were throught to persist to the bottom of the 5-m hole, although precise measurements of temperature were not made below a depth of 1.3 m. The increased density of the water was accompanied by an increase in its refractive index (Fig. I-38) which was important in trapping and absorbing that light reflected from the bottom of the lagoon at angles of less than about 10° (Hudec and Sonnenfeld).

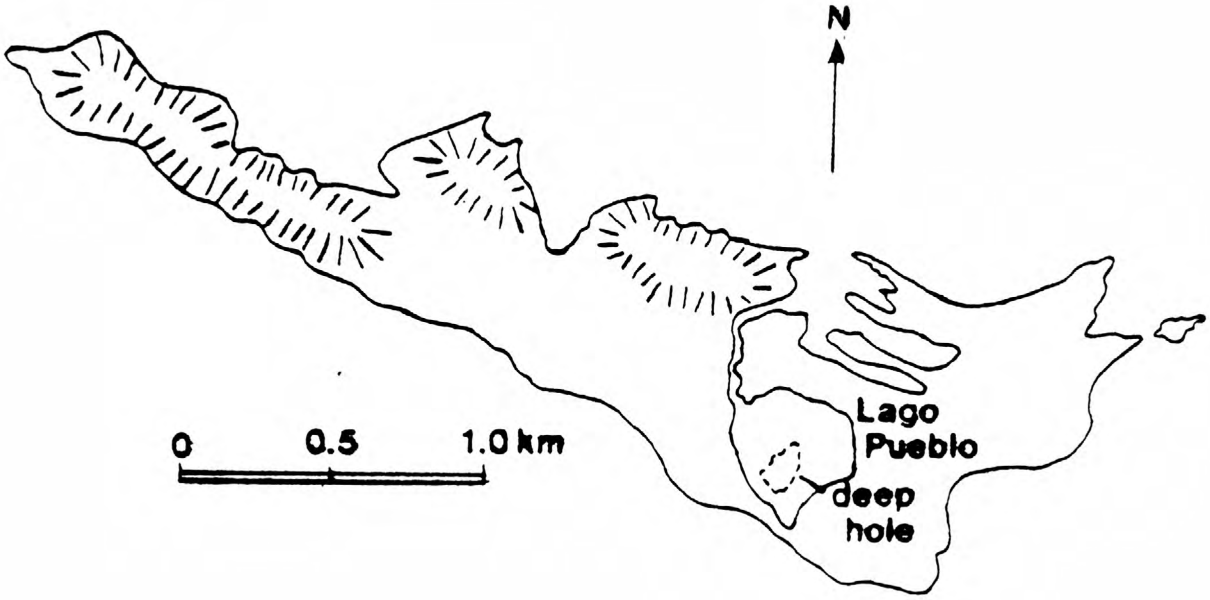



Figure I-37.--Location of Lago Pueblo, Isla Gran Roque, Venezuelan Antilles.

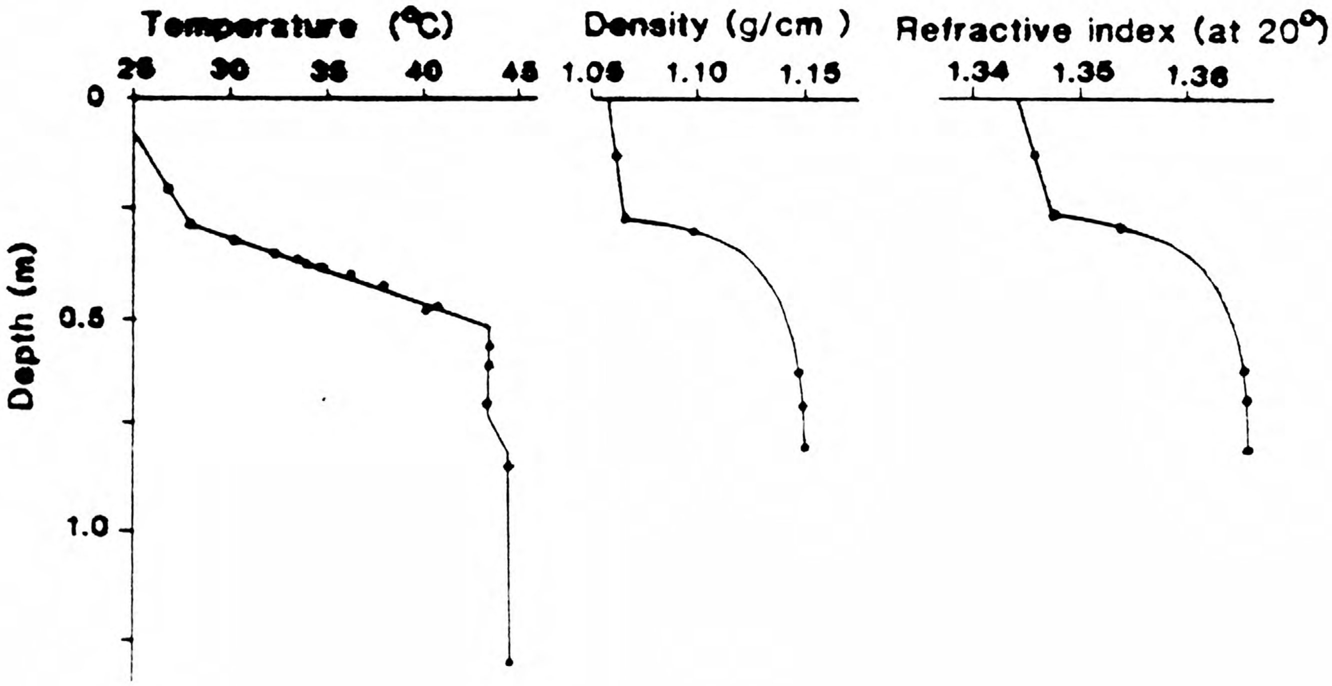



Figure I-38.—Variation of temperature, density, and refractive index with depth, Lago Pueblo, December, 1973 (after Hudec and Sonnenfeld, 1974).

APPENDIX II

Descriptions of Manmade Heliothermic Lakes

Basancon, France

The first manmade heliothermic lake was constructed by accident. In 1872, a large salt water pond with a depth of about 5 m was constructed for the salt-works at Basancon in eastern France (47°15'N., 6°E.). In Ocotber 1872, the basin was filled with brine and the pond remained undisturbed and uncovered for six months until April 1873, when it was drained. Inexplicably, the outlfow of bottom water had a temperature of 44°C (Ziegler, 1888).

The pond was refilled with brine and was again left uncovered so that rainwater could dilute the upper waters. On August 14, 1873, a maximum temperature of 62°C was recorded. Ziegler reported that under different conditions of weather this temperature might have been higher "because at this time it was neither particularly continuously bright nor was the air unusually warm." By December 1873, the maximum temperature had dropped to 25°C at a depth of 2.5 m. The following differences were observed between the temperature of the water at the surface and the water in the hot zone:

| Date | Surface | Hot Zone | Difference |
|---|---|---|---|
| July 30, 1873 | 16°C | 59°C | 43°C |
| August 14, 1873 | 22°C | 62°C | 40°C |
| September 9, 1873 | 23.5°C | 57.5°C | 34°C |
| October 14, 1873 | 10°C | 42°C | 32°C |
| November 14, 1873 | 8.5°C | 33°C | 24.5°C |
| December 14, 1873 | 2.5°C | 25°C | 22.5°C |

Ziegler recognized that a nonconvecting zone of water was responsible for the unusually high temperatures. He stated, "The layers of successively less saturated water that the rain laid over the brine make upward movement or rise of the brine completely impossible and protect its diffusing warmth from loss toward above like a blanket."

## Sedom and Atlith, Israel

The National Physical Laboratory of Israel has constructed several artificial heliothermic lakes, which they call "solar ponds". This term is also used to designate a freshwater pond covered by one or more sheets of transparent plastic for the purpose of collecting solar energy.

A heliothermic pond constructed in Jerusalem in 1958 had an area of only 1 $m^2$; the bottom temperature reached 60°C (Tabor, 1963, 1964). In 1959 an evaporation pond at Sedom (Sdom) (31°2'N., 35°22'E.), on the shore of the Dead Sea, was converted into a heliothermic lake. This pond is about 370 m below sea level and was built about 25 years previously as an evaporation pond. The pond had an area of 625 $m^2$ and a depth of 0.8 m. Concentrated brine containing mainly magnesium, potassium, and chloride ions was mixed with progressively greater and greater amounts of relatively fresh water to create a linear density gradient (Fig. 2). To make up for that lost by evaporation, water was added about once a week. In early June of 1960, about 1.5 months after solar heating was initiated, a peak temperature of 96°C was reached just above the bottom of the pond (Weinberger, 1964; Tabor and Matz, 1965); water at the surface at this time had a temperature of 28 to 32°C (Tabor, 1963). That the temperature did not get higher was attributed in part to "the fact that the solution became dirty due to the disintegration of the old wooden walls of the pond" (Tabor, 1963). At the end of the experiment, almost no sunlight was reaching the bottom.

A second pond similar in size to the first was prepared at the Sedom site and was in operation from June to December 1962. Temperature data for this pond have not been published. The waters of this second pond, unlike the first, remained clear. Tabor and Matz (1965) report that on June 27, 1963, about one year after initiation of the pond, the following amounts of radiation were reaching various depths:

| Depth | Percent of radiation that impinged on the surface | Time |
|---|---|---|
| 0.1m | 59.7 | 12:00 |
| 0.2 | 58.4 | 12:20 |
| 0.3 | 53.4 | 12:30 |
| 0.4 | 49.9 | 12:40 |
| 0.5 | 46.7 | 12:50 |
| 0.6 | 40.6 | 13:00 |
| 0.7 | 35.3 | 13:30 |
| 0.8 | 27.6 | 13:40 |

In order to avoid the problems associated with the old ponds at Sedom and in order to obtain climatic conditions that were more typical of Israel, a new pond was constructed at Atlith (32°49'N., 35°00'E.), near Haifa. Its dimensions were 25 m by 55 m by 1.5 m deep. Unfortunately, end-brines from a local salt-works that were to be used in creating the density gradient were dirty. Neither sand filtration nor attempts to coagulate and precipitate the dirt were entirely successful. The pond was filled with brine of progressively decreasing salinity in April 1964. The bottom of the pond had been constructed of a compacted earth fill over an old salt marsh. At a bottom temperature of 65°C bubbles began to appear, and at a bottom temperature of 74°C bubbles were abundant (Tabor and Matz, 1965). The bubbles resulted from bacterial decomposition of organic matter in the marshy sediments underlying the floor of the pond; fermentation was apparently accelerated by the increase in soil temperature. Because of this difficulty and because the process added more dirt to the brine, no attempt was made to extract energy from the pond.

For 17 days prior to the onset of bubbling, the temperature at the bottom of the pond at Atlith increased at a rate of 1.3°C per day despite the unclear brine (Tabor and Matz, 1965). During this period, about 12.5 percent of the solar radiation that impinged on the surface was reaching the bottom; this was about one-half of the expected value (Tabor and Matz, 1965).