# Nutrients and Ecology of the Western Salt and Exportadora de Sal Saltern Brines

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*ABSTRACT*

*In two case studies of the ecology and nutrient chemistry of solar saltern ponds, planktonic species composition and biomass were correlated with concentrations of dissolved phosphate, nitrate and ammonia. In comparison to the nutrient-rich Western Salt pond system, the relatively nutrient-poor Exportadora de Sal system maintained sparser phytoplanktonic and* Artemia salina *(brine shrimp) populations in the pre-crystallizer brines. The brine alga* Dunaliella *was absent in the Exportadora de Sal saltern. Halobacterial populations in the NaCl crystallizer ponds were dense. Strontium sulfate precipitated in these ponds. In both salterns, high purity NaCl precipitated.*

## INTRODUCTION

It is well accepted by solar salt companies that, by proper management of brine flow, the major chemical components of the brines can be controlled to produce high quality salt. Recent investigations have demonstrated that organisms thriving in solar salt pond systems may also influence the yield and quality of harvestable salt (Davis, 1974, 1978, 1980; Schneider and Herrmann, 1980; Jones et al., 1981). In order to optimize salt production, the biological parameters of a saltern should be carefully monitored.

The initial biological description of a solar saltern requires a biologist with expertise in this field. However, for routine analyses, several simple techniques are available to define chemically the "health" of a saltern, namely, the analyses of major nutrients and particulate organic matter. The major nutrients indicate how fertile the system may be. The particulate organic matter measured as total protein and chlorophyll *a* indicate the total standing crop and the relative abundance of photosynthetic organisms, respectively.

One purpose of this report is to describe how the major dissolved nutrients (reactive phosphate, reactive nitrate, and ammonia) and planktonic particulate matter (protein and chlorophyll *a*) can be used to describe the biological status of a saltern, and how these constituents may vary between nutrient-poor (oligotrophic) and nutrient-rich (eutrophic) systems. The two salterns studied are Exportadora de Sal., S.A. (ESSA), Guerrero Negro, Baja California Sur, Mexico and Western Salt Co. (WS), Chula Vista, California, U.S.A. Both salterns are located on the Pacific coast. The climate in Guerrero Negro is semi-tropical and arid (5 cm average annual rainfall). Mid-morning brine temperatures ranged from 11°C (winter) to 29°C (summer). The climate in Chula Vista is more temperate and wetter (25 cm average annual rainfall). Mid-morning brine temperatures ranged from 13°C (winter) to 30°C (summer).

The second purpose of this report is to describe the occurrence of celestite ($SrSO_4$) precipitation in NaCl crystallizer ponds. Although $SrSO_4$ precipitation has been demonstrated in evaporated marine brines (Braitsch, 1971; Butler, 1973; Holser, 1979), it has not been characterized in a saltern system. The preliminary evidence suggests that dissolved organic matter influences $Sr^{2+}$ activity in a manner similar to its influence on $Ca^{2+}$ activity with respect to $CaCO_3$ and $CaSO_4$ precipitation.

## METHODS

**Ionic Analyses.** Brine densities were measured with Bé scale hydrometers. All readings were corrected to 15.5°C. All analyses employed brines that had been first filtered (GF/C Whatman) or centrifuged ($\geq 27{,}000 \times g$ for 20 min at 15°–20°C). Potassium, calcium, and strontium were determined by flame atomic absorption spectroscopy (Perkin Elmer model 403). Magnesium was determined by the titration method of Gieskes (1974) and chlorinity was determined by $AgNO_3$ titration (Strickland and

Parsons, 1972). Sulfate was determined by $BaSO_4$ precipitation (Grasshoff, 1976). Sodium was determined by difference.

**Biological Analyses.** Methods for determining particulate protein, chlorophyll *a*, ammonia, and reactive phosphate have been described (Javor, 1983). Bacteriochlorophyll *a* was determined in the same extracts as chlorophyll *a* by employing an extinction coefficient of 73.5 liters·$g^{-1}$·$cm^{-1}$ at 750 nm (Cohen-Bazire and Sistrom, 1966). Analyses for nutrients employed filtered or centrifuged brines.

Reactive nitrate was determined by combining the methods of Mullin and Riley (1955) to reduce the nitrate to nitrite, and Strickland and Parsons (1972) to develop the color. In 25 or 70 ml-capacity stoppered bottles, 20 or 60 ml brine (diluted if necessary), respectively, was added. The phenol buffer and hydrazine sulfate-Cu solution were then added. The brine plus reagents filled the bottles nearly to capacity. The bottles were placed in the dark at least 16 h to reduce the nitrate. The contents of each bottle was then decanted into flasks containing acetone after which the sulfanilamide and naphthyl reagents were added according to Strickland and Parsons (1972). This method gave good reproducibility and was easier than nitrate reduction in a Cd-Cu column.

The following spectrophotometers were used: Bausch and Lomb Spectronic 20 (ESSA samples); Cary 14, Cary 17, or Beckman DU with a Gilford monochrometer (WS samples); Cary 14 or Beckman MVI (bacteriorhodopsin in both salterns).

**$SrSO_4$ Analysis.** Strontium sulfate in the brines was measured gravimetrically. Brines (usually 500 ml) were centrifuged as they were for ionic analyses. The pellets were rinsed once in deionized water and then were soaked in deionized water at ambient temperature at least 24 h in order to lyse bacterial cells. The precipitates were collected on pre-combusted GF/C filters and washed with deionized water to remove any remaining soluble salts. The precipitates were combusted 1 h at 400°–500°C to ash the remaining organic material. Filters were weighed on a Mettler HL 52 balance that was accurate to 0.01 mg.

## RESULTS

**Standing Crop and Nutrients.** The ESSA and WS salterns are flow-through systems, meaning that seawater flows through a series of ponds of increasing brine density to separate NaCl spatially from other less soluble minerals in the evaporation sequence. The organisms and nutrient concentrations of the ESSA saltern have been documented (Javor, 1983). They are briefly described here. The saltern system encompasses nearly 22,500 hectares of evaporating and crystallizing ponds. Annual salt production is over 6 million tons. The WS saltern, located in San Diego Bay 800 km north of the ESSA saltern, is a comparatively small operation. Evaporating and crystallizing ponds encompass about 450 hectares and annual production is approximately 100,000 tons. The ESSA saltern produces NaCl of 99.8% purity, while the salt from the WS saltern averages about 98.8% to 99.5% purity. In spite of the difference in magnitude of operation of the two salterns, the major ionic composition of the brines in each system is similar. The major ions of the ESSA brines are presented in Figure 1A.

The concentrations of planktonic protein, chlorophyll *a*, and the major nutrients of the ESSA and WS brines are presented in Figure 2 and 3. The ESSA brines were monitored monthly and the WS brines were measured seasonally. The same vertical scale for each analysis is used to demonstrate the differences between these two salterns.

Table 1 lists the organisms present in both salterns. In the ESSA system, the pond floors near the seawater entrance were characterized by the occurrence of *Ruppia* sp. (ditchweed, a higher plant) and *Enteromorpha* sp. (a large green alga). The remaining sediments were covered with a film of four or more species of diatoms. The brine ciliate *Fabrea salina* sometimes reached high densities (casual observation). Phytoplanktonic standing crop was relatively low. The first pond in the WS saltern was characterized by a somewhat similar assemblage.

The middle density ponds (about 6°–13° Bé) in the ESSA system were characterized by thick bottom mats of cyanobacteria (largely members of the Oscillatoriaceae) covered with a film of diatoms (largely *Navicula* sp.). Chlorophyll *a* levels in these mats was high (up to about 10 μg·$cm^{-2}$ in the range of 8° to 10° Bé; May, 1979). The plankton was dominated by the coccoid cyanobacterium *Aphanothece halophytica* (termed *Coccochloris elabens* by some investigators). Between about 13° and 20° Bé, a gypsum cement formed a floor in the ponds and it was partially covered with a film of *A. halophytica*.

In contrast, only a thin (1–2 mm) and patchy bottom mat developed in the WS ponds in this density range. The organisms in these mats were similar to those in the ESSA mats. Planktonic chlorophyll *a* reached extremely high concentrations. The plankton was dominated by *A. halophytica*. *Dunaliella* sp. (green alga) was also present.

In the range of approximately 10° to 20° Bé, the ESSA brines were nearly devoid of algal and bacterial plankton, probably due to the grazing activities of brine shrimp (*Artemia salina*). *A. salina* populations were never more than about one animal per liter except on the leeward sides of ponds during winds. There is no commercial harvest of brine shrimp from these ponds.

In contrast, the WS ponds maintained high levels of planktonic particulate protein in all ponds downstream of the first concentrator (all brine shrimp except small larvae that passed through two layers of cheesecloth were excluded from these analyses). Chlorophyll *a* levels fluctuated with season and salinity. The plankton was dom-

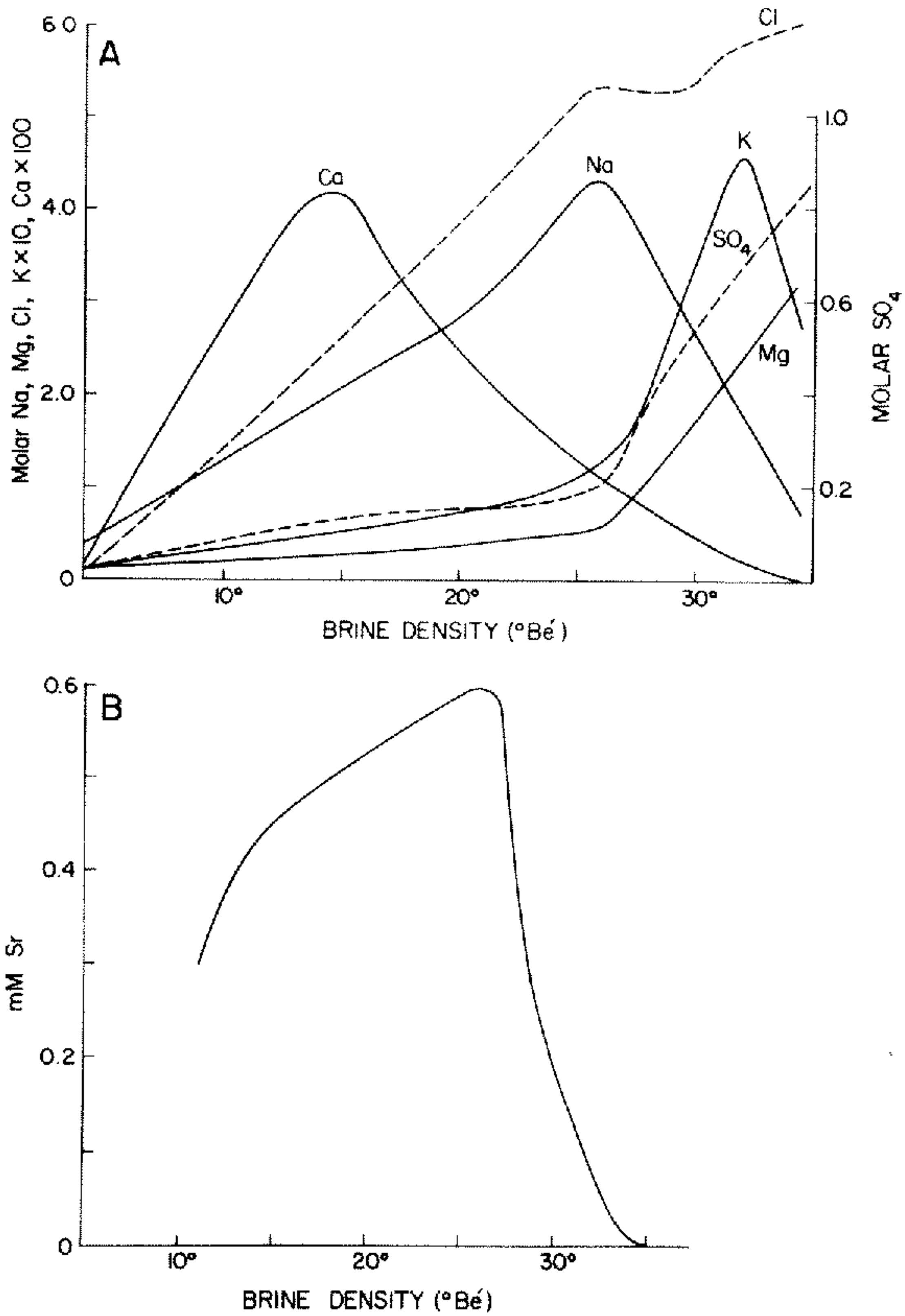


**Figure 1.** The major ions in the ESSA saltern, September 13, 1982. Each curve is defined by the analysis of 26 different brines in the range of 11.1° to 34.5° Bé. The curves were extrapolated to normal seawater concentration. A: $Na^+$, $Mg^{2+}$, $K^+$, $Ca^{2+}$, $Cl^-$, and $SO_4^{2-}$. B: $Sr^{2+}$.

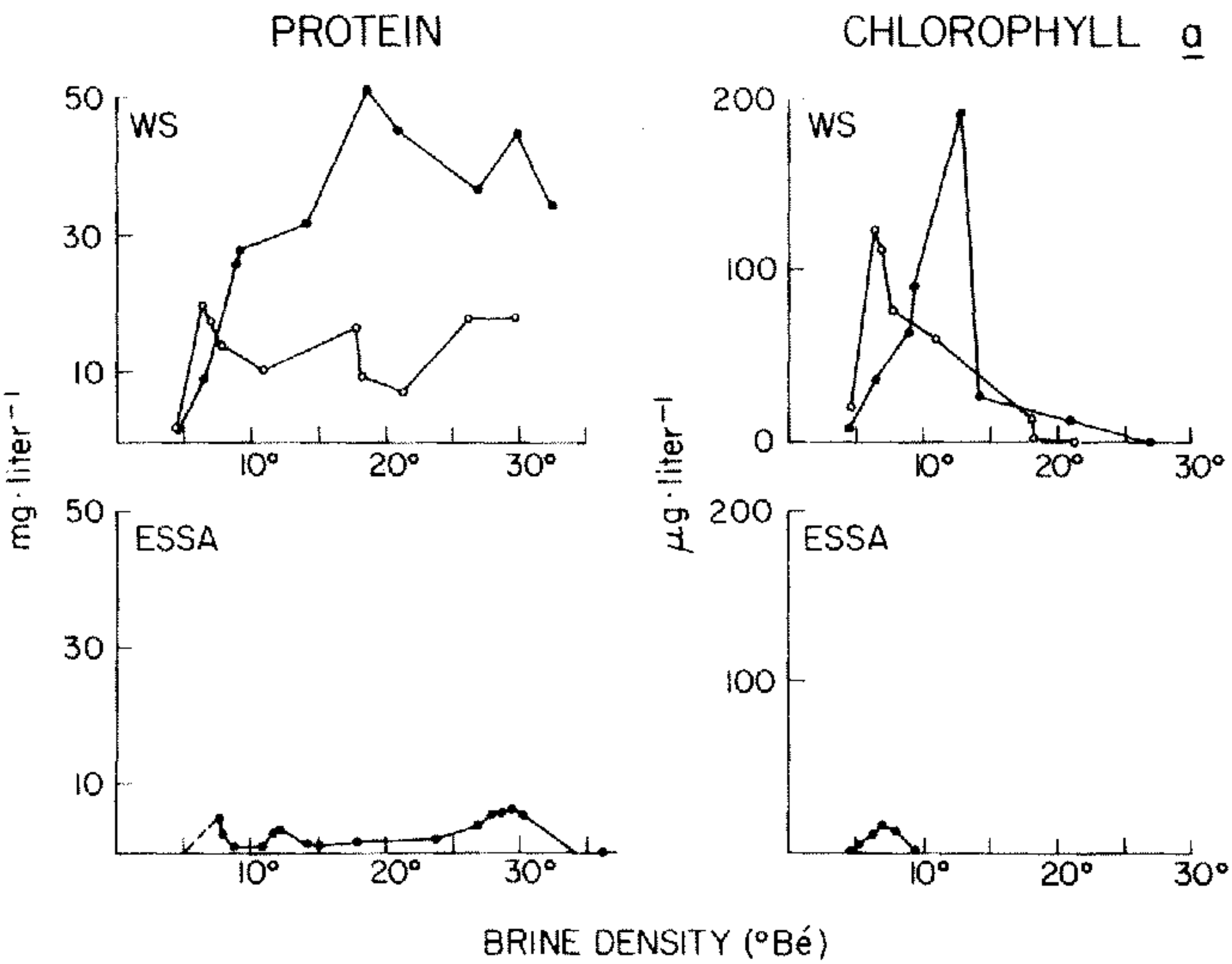


**Figure 2.** Particulate protein and chlorophyll *a* concentrations in the WS and ESSA salterns. Summer (closed circles; August 23, 1982) and winter (open circles; December 28, 1982) values are shown for the WS saltern. The ESSA data are adapted from Javor (1983). The points represented the maximum values measured at monthly intervals for one year during 1979–1980.

inated by *A. halophytica*, *Dunaliella* sp., and a rich bacterial flora. Planktonic bacteriochlorophyll *a* concentrations also fluctuated with season and brine density (data not shown). Significant bacteriochlorophyll *a* was found in brines in the range of about 10° to 18° Bé. It was measured as high as 46 $\mu g \cdot liter^{-1}$ (12.8° Bé, August, 1982). Brine shrimp occurred in dense populations, especially in the summer. They are commercially harvested from this saltern.

The NaCl crystallizer ponds of the ESSA ponds were populated only by bacteria, largely the extremely halophilic halobacteria (species identification is under current investigation). *Dunaliella* sp. was entirely absent from this saltern. In contrast, ponds up to about 26° Bé density in the WS saltern harbored *Dunaliella* sp. Halophilic bacteria also were abundant in the WS ponds in brine densities between 20° and 30° Bé. A photosynthetic pigment of the halobacteria (bacteriorhodopsin) was measured in the crystallizer plankton of the ESSA brines (Javor, 1983). This pigment could not be detected in the WS brines.

The major nutrients in the ESSA saltern were in low concentrations until the brines evaporated to the stage of NaCl crystallization. They increased to relatively high levels in the bitterns which are devoid of life. Little or no seasonal variation was detected. In contrast, the nutrients in the WS system fluctuated with brine density and season. In addition, nitrite was present at the seawater inlet and in the first concentrating pond both in summer and in winter. The summer value (4.6° Bé) was 2.2 $\mu M$ nitrite and the winter value (4.5° Bé) was 9.5 $\mu M$ nitrite (see Figure 3). Phosphate and ammonia tended to accumulate to relatively high levels when algal and bacterial productivity (measured as protein and chlorophyll *a*) were relatively low.

**$SrSO_4$ Precipitation.** Strontium concentration in the brines increases to nearly 0.6 mM (about 50 ppm) at 26°

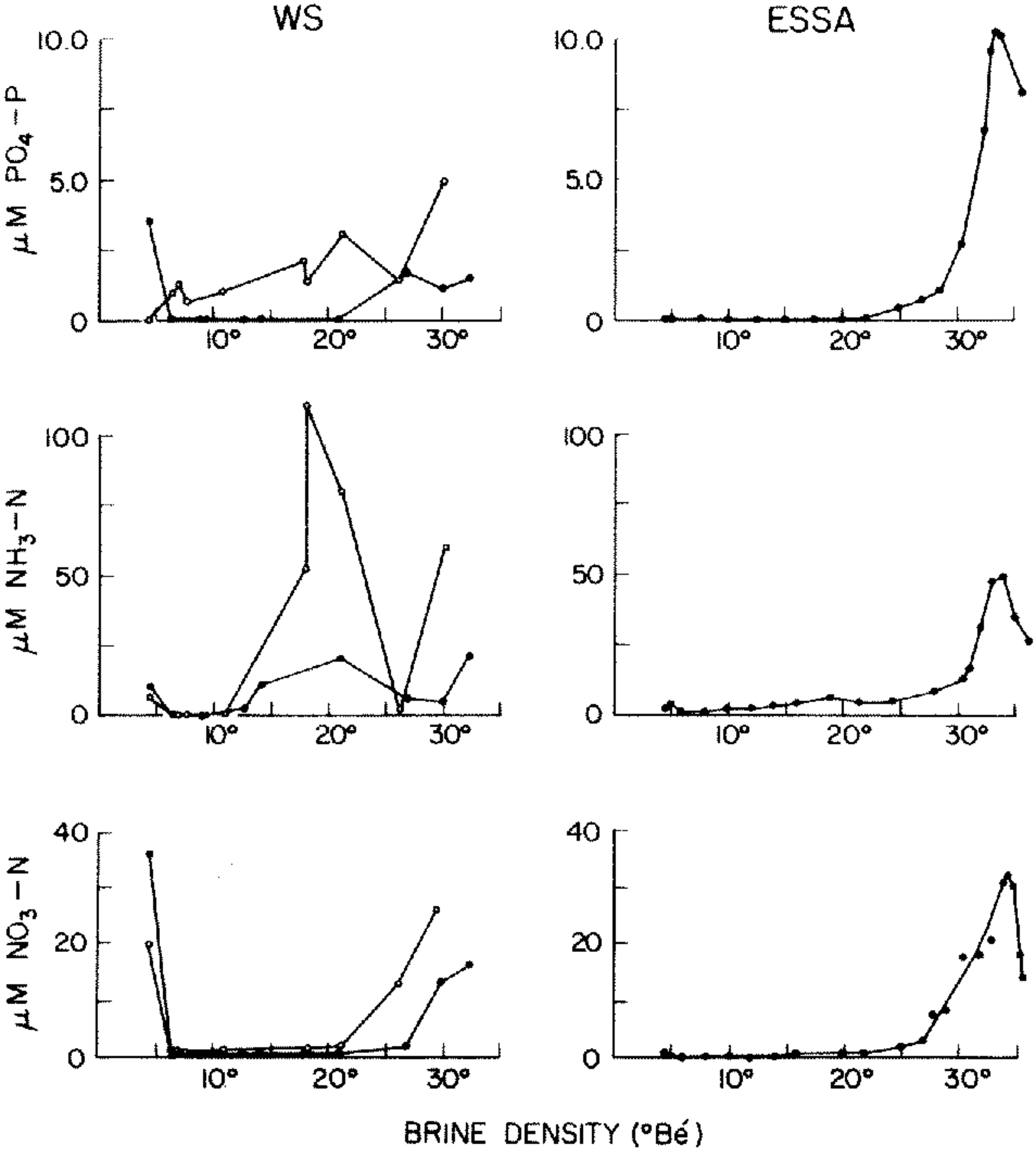


**Figure 3.** Reactive phosphate, ammonia, and reactive nitrate in the WS and ESSA salterns. Symbols are the same as those in Fig. 2. Nitrite values in the WS samples (4.5° and 4.6° Bé) are included.

Bé, above which density $Sr^{2+}$ completely precipitates from solution (Figure 1B). The change in slope of the $Sr^{2+}$ concentration near 13° Bé indicates that some strontium probably precipitates with gypsum. In 27° Bé and higher density brines, $SrSO_4$ (determined by x-ray diffraction analysis) precipitates as 10 μm-long, bilobate crystal bundles (Figure 4).

The crystals remain in suspension with the bacterial cells. An estimate of the concentration of celestite crystals suspended in the ESSA brines is shown in Figure 5. Above 29° Bé, the crystals apparently settle. These are maximum values due to the presence of the ash of cellular material on the filters with $SrSO_4$. Many extremely halophilic bacteria lyse in distilled water so that the weight of cells on the filters was partially reduced by soaking the precipitates in deionized water. Combusting the filters reduced

TABLE 1

Organisms represented in the Exportadora de Sal and Western Salt salterns

| Brine Density | Exportadora de Sal | Western Salt |
|---|---|---|
| 3.5°–ca. 6.0° Bé | *Navicula* sp. (diatom)<br>*Grammatophora* sp. (diatom)<br>*Striatella* sp. (diatom)<br>*Licmophora* sp. (diatom)<br>*Enteromorpha* sp. (green alga)<br>*Entophysalis deusta* (cyanobacterium)<br>*Ruppia* sp. (higher plant)<br>*Fabrea salina* (ciliate)<br>*Trichocorixa* sp. (insect)<br>unidentified fish | *Navicula* sp.<br>unidentified flagellates<br>unidentified boring algae<br><br><br><br><br>*Ruppia* sp.<br>*Fabrea salina*<br>*Trichocorixa* sp.<br>unidentified fish |
| ca. 6.0°–ca. 13° Bé | *Navicula* sp.<br>*Aphanothece halophytica* (cyanobacterium)<br>*Oscillatoria* spp. (cyanobacteria)<br>*Spirulina* spp. (cyanobacteria)<br>*Microcoleus chthonoplastes* (cyanobacterium)<br>*Phormidium* spp. (cyanobacteria)<br>unidentified photosynthetic bacteria<br>*Fabrea salina*<br>*Artemia salina* (brine shrimp)<br>*Ephydra* sp. (insect larvae) | *Navicula* spp.<br>*Nitschzia* sp. (diatom)<br>*Dunaliella* sp.<br>unidentified flagellates<br>*Aphanothece halophytica*<br>*Oscillatoria* spp.<br>*Spirulina* spp.<br>*Phormidium* spp.<br>unidentified photosynthetic bacteria<br>*Beggiatoa* sp. (bacterium)<br>*Fabrea salina*<br>*Artemia salina*<br>*Ephydra* sp. |
| ca. 13°–ca. 20° Bé | *Aphanothece halophytica*<br>*Artemia salina* | *Aphanothece halophytica*<br>*Dunaliella* sp.<br>unidentified bacteria<br>*Artemia salina* |
| ca. 20°–ca. 30° Bé | halophilic bacteria | *Dunaliella* sp.<br>halophilic bacteria |

organic matter to ash. A culture of halophilic bacteria (for culture methods see Javor, 1983) served as control. Cells (about 4 mg protein) were filtered and combusted. The ashed weight of washed cells was 0.5 mg and that of unwashed cells (after subtraction of the salts that remained on the filter) was 4.9 mg. Because of the high particulate organic content of the WS brines, they were not similarly analyzed. It was visually estimated that suspended $SrSO_4$ crystals were more abundant in ESSA brines than in WS brines of equivalent density.

Two experiments were performed to determine whether bacterial cells were directly involved in celestite precipitation in the brines. ESSA brine (28.8° Bé, 24.5 ppm $Sr^{2+}$) was centrifuged in order to remove cells and $SrSO_4$ crystals. In one set of capped vials, $Sr^{2+}$ (as $SrCl_2$ in a solution containing 2000 ppm $Sr^{2+}$) was added to give final added $Sr^{2+}$ concentrations of 0, 20, 50, 100, 150, and 200 ppm. In another similar set of vials, several drops of halobacterial cells suspended in 28.8° Bé brine were added to determine if they would promote $SrSO_4$ crystal nucleation. The vials were capped and agitated briefly to mix the contents.

There was no difference in the results between the two sets of vials. Within about 15 minutes, celestite crystals precipitated in the vials to which 200 ppm $Sr^{2+}$ had been added. These rod-shaped crystals were of similar dimensions as the bilobate crystal bundles, but they lacked the medial constriction. After 24 hours the following results were noted: in brines to which $\geq 100$ ppm $Sr^{2+}$ had been added, celestite rods precipitated; in brines to which 50 ppm $Sr^{2+}$ had been added, thin needles and slightly bilobate crystals precipitated; and in brines to which 20 ppm $Sr^{2+}$ had been added, no $SrSO_4$ precipitation occurred. All crystals were about 10 $\mu$m long. The thicker crystals resulted from rapid precipitation.

The second experiment was designed to determine whether celestite precipitation could be enhanced as a result of bacterial growth. The medium was centrifuged 28.8° Bé ESSA brine to which 1% peptone (Difco Technical) had been dissolved. To one set of flasks, cells (de-

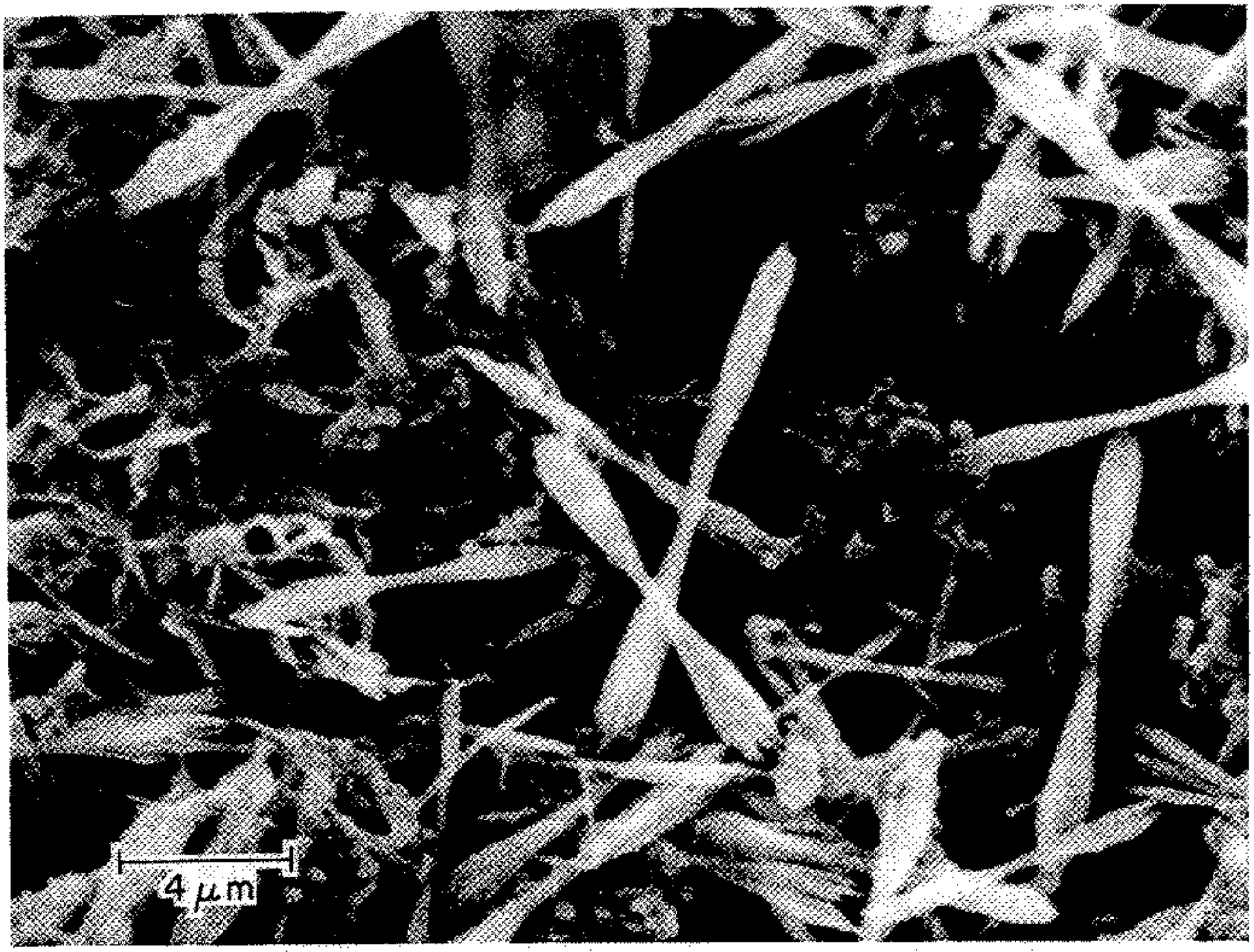


**Figure 4.** Scanning electron micrograph of $SrSO_4$ crystals in ESSA NaCl crystallizer brines.

scribed above) were added. A second set of flasks without cells served as controls. $Sr^{2-}$ (from a $SrCl_2$ solution containing 2000 ppm $Sr^{2+}$) was added to final added concentrations of 0, 5, 20, and 40 ppm. The flasks were plugged (but not sealed) and agitated at ca. 125 rpm at ambient temperature for two weeks.

After two weeks, $SrSO_4$ precipitates were found in all brines to which $\geq 20$ ppm $Sr^{2+}$ had been added, even the control brines. Crystals were thin needles and slightly bilobate rods. The occurrence of $SrSO_4$ precipitation in brines to which 20 ppm $Sr^{2+}$ had been added in this experiment in contrast to its absence in the experiment in the capped vials was probably due to evaporation and/or longer incubation time.

The peculiar morphology of the celestite crystals in saltern brines (Figure 4) is partially a result of slow precipitation rates in solutions only slightly supersaturated with respect to $SrSO_4$. It is also apparently influenced by the dissolved organic constituents in the brines. When solutions of $Na_2SO_4$ and $SrCl_2$ were mixed, only thin needles precipitated. When peptone (a crude pepsin digest of slaughterhouse waste products) was first dissolved in one of the solutions before they were mixed, the $SrSO_4$ crystals resembled those seen in the above experiments with ESSA brines. The same general phenomenon was observed when $SrCO_3$ was precipitated by mixing solutions of $SrCl_2$ and $Na_2CO_3$: thin needles precipitated when no organic material was present, and thicker, rod-shaped crystals precipitated in the presence of dissolved peptone.

## DISCUSSION

**Nutrients and Standing Crop: General Considerations.** The levels of phosphate, nitrate and ammonia in the WS saltern were similar to those reported for other saltern systems (Carpelan, 1957; Jones et al., 1981) as well as for the Great Salt Lake (Post, 1977). In contrast, each of these nutrients was found in low or negligible concentrations in the ESSA saltern until brines evaporated to the stage of NaCl saturation.

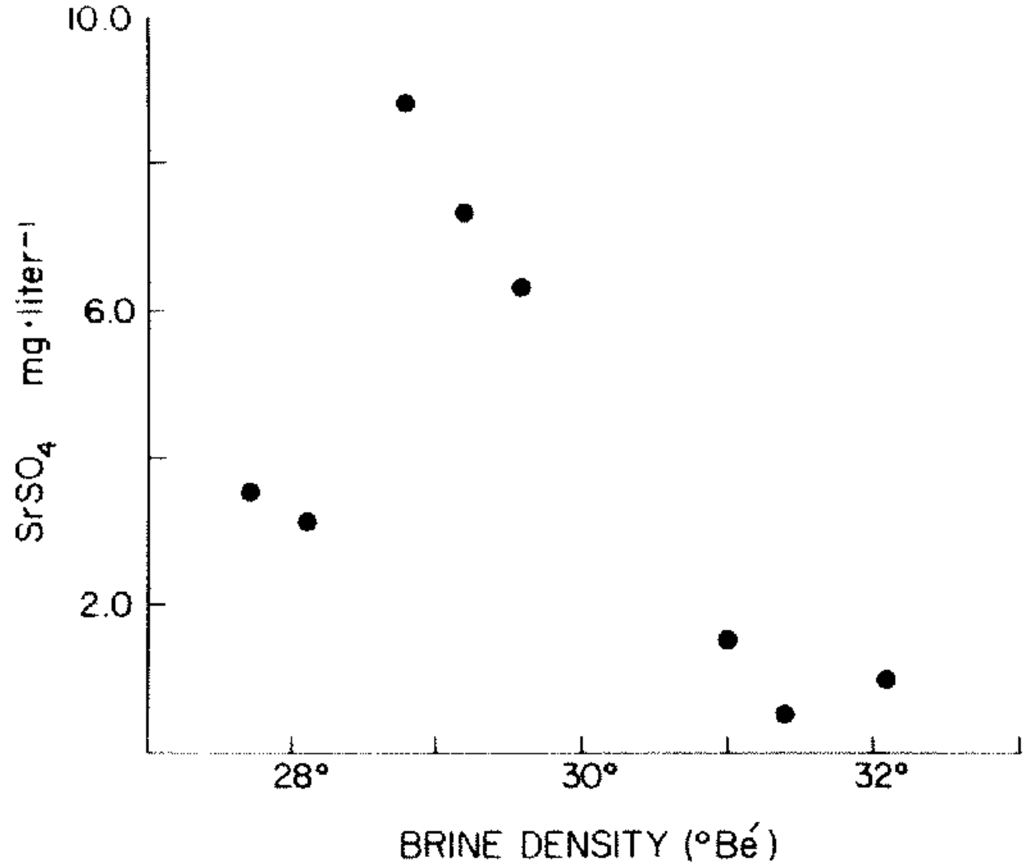


**Figure 5.** Maximum concentrations of $SrSO_4$ suspended in ESSA brines, September 13, 1982.

The reasons for these differences are climate and geography. Guerrero Negro is located at the edge of a large desert plain (a continental sabkha environment), free from the influence of rivers and major urban centers. The WS saltern is in San Diego Bay, which is influenced by several small rivers, a large urban center, and intensive maritime activity. Until strict pollution laws were put into effect in the 1970s brine shrimp harvests were significantly higher in the WS saltern than they are currently (personal communication, Bill Soderberg, February 7, 1980). Such great secondary productivity was probably attributable to higher primary productivity, which in turn was a result of greater phosphate and/or combined nitrogen levels permitted in waste effluents.

One consequence of the difference in nutrient chemistry of the two salterns is the dominance of mat organisms in the ESSA system as opposed to planktonic dominance in the WS system. In freshwater systems, this phenomenon also occurs. Eutrophic lakes are often characterized by great blooms of phytoplankton that shade the benthos and thus prevent mat development. Oligotrophic lakes such as Lake Tahoe, U.S.A. (Goldman and de Amezaga, 1975) and Waldo Lake, U.S.A. (Malueg et al., 1972) are nearly free of phytoplankton, but they support bottom mats, felts, or macrophytes. Mat organisms benefit by cohesion to one another in order to sequester nutrients as they are released by cells in the community. There is no systematic study of nutrients vs. mat or planktonic dominance in saline lakes and salterns, but biological principles would suggest that this phenomenon should hold true in any aquatic system. The other saltern systems cited in this report probably are characterized by intermediate nutrient conditions that allow development of both mat and planktonic communities.

Planktonic standing crop and chlorophyll *a* concentrations in the WS saltern were much higher than these parameters in the ESSA system as a direct consequence of the nutrient conditions. Unfortunately, none of the studies of the other salterns included measurements of the plankton in terms of protein and chlorophyll *a*. A summer value of nearly 200 $\mu g \cdot liter^{-1}$ chlorophyll *a* in 12.8° Bé brines in the WS saltern was recorded. However, even higher phytoplanktonic densities have been measured in saline lakes, including a value of 2170 $\mu g \cdot liter^{-1}$ chlorophyll *a* in a lake in Ethiopia (Talling et al., 1973).

The occurrence of significant concentrations of bacteriochlorophyll *a* in the range of 10° to 18° Bé brines of the WS saltern demonstrates that blooms of algae and photosynthetic bacteria can coexist in this system. Although photosynthetic bacteria in the brine column have not been studied in salterns, they have been studied in hypersaline lakes. (Borowitzka, 1981). The photosynthetic bacterial species composition and the sulfur chemistry of the WS saltern are currently under investigation. Further investigations of the primary productivity in this saltern will provide a basis for comparisons of both algal and photosynthetic bacterial ecology in saline lake systems.

In temperate climates, nutrients and standing crops show seasonal fluctuations. An assessment of the "health" of salterns in such environments (i.e. WS) must take this phenomenon into consideration, since a one-time measurement will not describe the ecology of the system. The taxonomic description of the saltern is preliminary, since changes in species composition during the course of a year have not been thoroughly monitored. In contrast, salterns in tropical or semi-tropical climates, especially in arid locales, show less seasonal variation. The ESSA saltern is such a system. Seasonal variations in that saltern were even less conspicuous due to consistently low nutrient concentrations.

The great difference in ammonia concentrations between seasons in the WS ponds is noteworthy. The peak in ammonia concentrations between about 15° and 20° Bé was probably due to excretion by brine shrimp. The lower concentrations in the summer reflect the harvest of ammonia by phytoplankton when cell densities were relatively high.

The presence of nitrite at the seawater inlet is indicative of intensive activity by nitrate-reducing bacteria under anaerobic conditions. The relatively higher nitrate concentrations in the WS NaCl crystallizer ponds in the winter may be significant. The depletion of nitrate in the crystallizers in the summer may be a consequence of dissimilatory nitrate reduction by halobacteria (Elazari-Volcani, 1957; Werber and Mevarech, 1978; Colwell et al., 1979). These observations on nutrient fluctuations should provide a basis for investigations of the biological processes responsible for combined nitrogen transformations in hypersaline systems.

Davis (1978) demonstrated that the poorly developed biota in a saltern was responsible for poor harvests of NaCl. The inadequate development of the biota was attributed to low concentrations of phosphate, ammonia, and nitrate. Fertilization of that saltern increased biological productivity and NaCl production. In contrast, the ESSA saltern is an example of a successful oligotrophic saltern. In spite of low concentrations of nutrients, it maintains adequate biological productivity to promote the large scale production of high quality NaCl.

**Species Distribution.** Another consequence of the difference in nutrient levels in the two salterns is differences in species composition. One noticeable difference is the reported presence of *Dunaliella* in salterns worldwide with the exception of ESSA. Its absence may reflect its inability to compete under poor nutrient conditions. Unfortunately, no data concerning the effect of nutrients on *Dunaliella* distribution are currently available. A more complete taxonomic study of the two salterns may reveal other "oligotrophic" and "eutrophic" species.

Another observation may indicate the physiological state of the halobacterial flora in the crystallizing ponds. Bacteriorhodopsin, a photosynthetic pigment unique to halobacteria, is preferentially synthesized under conditions of low oxygen when it provides an additional source of energy to the cells (Oesterhelt and Stoeckenius, 1973). Growth medium with halobacteria has little or no dissolved $O_2$ unless it is vigorously aerated (standard laboratory growth conditions). In order to enhance bacteriorhodopsin production in the laboratory, the aeration must be turned off.

These observations are in agreement with the finding of bacteriorhodopsin in the halobacterial flora in the ESSA crystallizing ponds (Javor, 1983) and in the Dead Sea (Oren and Shilo, 1981), but inconsistent with its absence in the WS saltern. One reason is that halobacteria incapable of bacteriorhodopsin synthesis or non-halobacterial species may predominate in the WS ponds (currently under investigation). Another explanation is that the native halobacterial flora may be able to grow well using specific dissolved organic substances that accumulate in the eutrophic saltern in the absence of significant $O_2$. Centrifuged WS brines are pale yellow (presumably due to dissolved organic material) whereas ESSA brines are clear. The physiological ecology of the native bacterial flora and the organic chemical nature of the crystallizer brines are currently under investigation.

**$SrSO_4$.** The occurrence of celestite precipitation in marine brines saturated with NaCl is expected, because it has been documented to occur in less concentrated marine brines (Butler, 1973; Holser, 1979). Butler's (1973) study of sabkha porewaters demonstrated that $SrSO_4$ first began to precipitate in 3.8 × seawater concentration, and that mass precipitation occurred above 6 × seawater concentration. In the ESSA saltern, mass $SrSO_4$ precipitation did not appear until about 12 × seawater concentration (beginning of halite precipitation). The ESSA data are in agreement with the calculations of Braitsch (1971) who determined that celestite precipitates from normal seawater at the beginning of the stage of halite precipitation.

The unusual bilobate morphology of the crystal bundles deserves further investigation. No direct bacterial influence was noted as it was earlier suggested (Javor, 1983). The observation that dissolved organic matter influenced the crystal morphology of $SrSO_4$ and $SrCO_3$ precipitated in the laboratory suggests that the types of organic chemical interactions are similar to those described for $CaSO_4$ (Barcelona et al., 1976, 1978, 1979) and $CaCO_3$ (Chave and Suess, 1970; Jackson and Bischoff, 1971; Suess, 1970, 1973). These investigations demonstrated specific interactions of $Ca^{2+}$ with both lipids and non-lipids.

It was observed that suspended celestite crystals appeared to be more abundant in ESSA brines than in equivalent density WS brines. In 28.7° Bé brines from the La Salina saltern (a small saltern in Baja California, Mexico, 100 km south of the WS saltern), no $SrSO_4$ was observed although the dissolved $Sr^{2+}$ concentration in these brines was similar to that in equivalent density ESSA brines (Javor, unpublished data). These brines were even richer in bacterial plankton than the WS brines and the supernatant of centrifuged brines was very yellow. $SrSO_4$ may be absent from these brines due to settlement. However, the apparently rich organic nature of these brines suggests that dissolved $Sr^{2+}$-organic complexes and/or $Sr^{2+}$ adhesion to particulate organic material may effectively lower $Sr^{2+}$ activity and prevent celestite precipitation. Alternatively, an organic film on $SrSO_4$ crystal nuclei would prevent further crystal growth. The WS brines would represent a less extreme example of the same phenomena. These observations may have a direct bearing on the disagreement in the literature concerning the earliest stage of brine evaporation in which $SrSO_4$ precipitates from solution. An investigation of the activity of $Sr^{2+}$ and the particular organic compounds that bind to $Sr^{2+}$ may clarify the problem.

The observations on celestite and strontianite crystal morphology may be of practical value to geologists. The very low solubilities of both $SrSO_4$ and $SrCO_3$ are conductive to their preservation in evaporite deposits. A study of the crystal morphologies of these strontium minerals in such deposits may indicate the organic nature of the brines from which they precipitated. Such an investigation could be corroborated with a study of the interstitial brines or brine inclusions in associated halite deposits. Coastal lagoons are often characterized by high organic productivity, and they may have been the sources of the organic matter of many ancient petroleum deposits (Kirkland and Evans, 1981). Because many such petroleum deposits are associated with evaporites, the presence or absence of celestite, as well as its crystal morphology, may be good diagnostic tools for petroleum exploration in sediments associated with halite. In addition, an investigation of strontium mineral crystal morphology in Precambrian evaporites would be indicative of the organic nature of the ancient ocean if no major diagenesis could be demonstrated.

## CONCLUSIONS

Salterns characterized by either low nutrients and low organic productivity or high nutrients and high organic productivity can produce high quality NaCl as long as good management practices are followed. A baseline study of the nutrients and organisms in the saltern indicates the "health" of the system. A trained saltern biologist can use these data to determine if and how changes can be made in the saltern to improve NaCl production.

$SrSO_4$ precipitates in NaCl crystallizer brines. It is most evident in brines characterized by low organic productivity. The commercial harvest of celestite from such brines deserves consideration. A thorough study of its precipitation would be valuable to geochemists, petroleum geologists, and paleontologists, as well as to saltern managers.

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