[American Journal of Science, Vol. 261, October 1963, P. 741-755]

THE HYDROLOGY OF THE PERSIAN GULF AND ITS SIGNIFICANCE IN RESPECT TO EVAPORITE DEPOSITION

W. SUGDEN

Department of Geology, University of Oxford, England

ABSTRACT. Throughout the Persian Gulf there is net evaporation from the sea during the whole of the year, and despite some dilution by drainage from the Tigris-Euphrates valley, exceptionally high salinities are encountered in certain areas. Salinities in one minor embayment rise to as much as 70 percent above that of normal ocean water. Seasonal salinity variation, studied particularly in that same area, is not great and may be exceeded by erratic variations which result mainly from short term climatic accidents.

The hydrological regime of the Gulf is such that evaporating surface water passes toward the coasts, sinks, and escapes from the Gulf by counterflow at lower levels, the highest salinities, both of surface and bottom water, being in coastal areas. This regime, similar to that which must have existed in ancient evaporite basins, is used as a model by which to interpret probable circumstances of evaporite deposition. It is thence argued that in a marine basin in an arid region, introduction of a bar at the entry to the basin or simple overall shallowing without the introduction of a bar may produce similar results in respect to evaporite deposition and distribution. In either case higher grade evaporites will deposit in the more remote coastal areas of a basin contemporaneously with progressively lower grade evaporites toward the point of entry of "freshening" oceanic water.

Salinity evidently has some influence on the distribution of molluscs and other creatures in the Gulf, but at salinities of up to 70 percent above normal its effects are not easily distinguished among those of various environmental factors. In examining fossil faunas the influence of salinity within a similar range could very easily escape detection.

INTRODUCTION

The Persian Gulf is very shallow. Although its area is about 240.000 sq km, its mean depth is only 25 m, and the deepest water, where the narrow Straits of Hormuz form the exit to the ocean, is only about 100 m deep. The Gulf of Oman, with which the Persian Gulf connects, is by comparison very deep and can here be regarded as being part of the open ocean.

The Persian Gulf is the drainage center for almost the whole of Arabia, the whole of Iraq, and large parts of Syria, Turkey, and Iran. But most of this huge area is very arid, and little fresh water flows into the Gulf except at its northern end. There the Shatt al Arab, the confluence of the Tigris, Euphrates, and Karun, discharges. Elsewhere there is scarcely any runoff, virtually none from Arabia and only occasional local flood discharge along the Persian coast. Rainfall into the Gulf itself is not more than about three inches per year. Evaporation from the Gulf is, in fact, greatly in excess of fresh water ingress, and high salinities result. There are other large and nearly enclosed seas, the Red Sea and the Mediterranean, where similar net evaporation takes place (Sverdrup, Johnson, and Fleming, 1942), but unlike these the Persian Gulf has no constricting sill at its exit to the ocean.

The high rates of evaporation promote limestone deposition, and at the same time terrestrial, mainly eolian sediment reaches the Gulf. Sediments and sedimentation processes have been described elsewhere (Emery, 1956: Sugden, in press), and this article is concerned particularly with the hydrology of the Gulf and its implications in respect to evaporite deposition.

The hydrological regime of the Gulf is such as is characteristic of nearly landlocked seas with net evaporation (Sverdrup, Johnson, and Fleming, 1942).

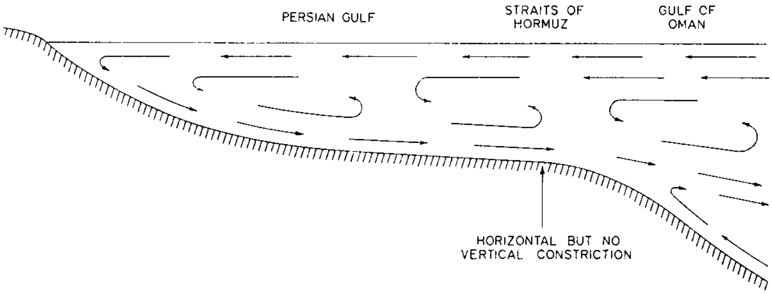

Fig. 1. Diagrammatic representation of water circulation in the Persian Gulf.

Evaporation is largely made up by the inflow of water from the open ocean. The inflowing water moves slowly over the surface of the Gulf toward its margins, becoming meanwhile more concentrated. Increasing density eventually causes it to sink to lower levels where it flows out again below the incoming water. Figure 1 is a very diagrammatic representation of the general circulation. Summer in the Gulf is far hotter than the winter, but the differences between summer and winter surface salinity are not great, and evaporation evidently continues at a high rate throughout the year. The control of density by salinity is, of course, modified by temperature changes, which vary in effect according to the seasons, but in the Gulf salinity, as opposed to temperature, is a much more important determinant of density than in the open ocean. Emery (1956) has demonstrated the kind of temperature and salinity distribution that exists in the Persian Gulf in midsummer when density stratification must be best developed. In autumn and winter, when surface water is being cooled, there must be greater vertical circulation and water turnover than in summer, but the overall circulation remains the same. As the Gulf as a whole is very shallow, winds also have significant effects on circulation, but their actual influence has not been investigated in detail.

THE HYDROLOGY OF THE PERSIAN GULF

Map of mean surface chlorinity.—Several authors have given data, maps, or diagrams of salinity in the Persian Gulf (Schott, 1908; Schulz, 1914; Blegvad, 1944; Emery, 1956). Emery prepared the first adequate surface salinity map and also valuable diagrams of vertical salinity distribution, from data obtained in August, 1948. But the highest salinities, to the west of the Qatar Peninsula and in the Trucial Coast embayment, remained undiscovered at that time, and it was in these areas that most of the writer's own sampling was later carried out.

In what follows, chlorinity rather than salinity is used as the term to express sea water concentration. In oceanographic work salinity is empirically determined from chlorinity (Sverdrup, Johnson, and Fleming, 1942) and, therefore, when referring to water concentration, the use of either term usually has the same significance.

All available information was used in the preparation of the accompanying map of mean chlorinity (fig. 2). Some 532 individual measurements of salinity

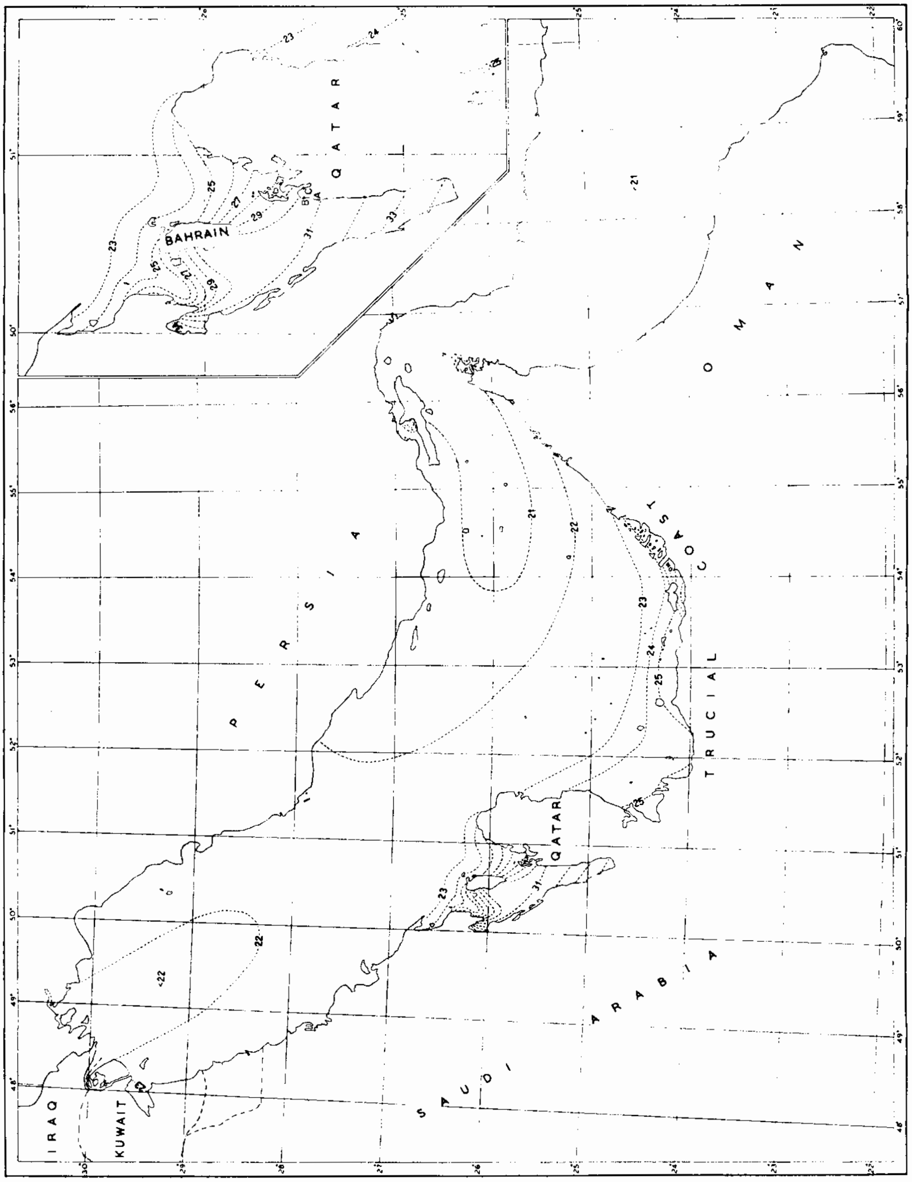

Fig. 2. Mean annual surface chlorinity of the Persian Gulf.

or chlorinity were available, more than 400 of these determined by the writer. The map was drawn from data that are in certain areas scant. Thus apart from a narrow strip bordering the coast, there is little data from the Trucial Coast embayment. and there is scarcely any information concerning the area adjoining the Saudi Arabian coast north of about Lat 26°45′N. Also the sampling has been for the most part erratic with respect to the seasons. This being so. there were difficulties, as will become apparent below, in making appropriate allowances for seasonal and other fluctuations of chlorinity which inevitably occur. The map, therefore, has its weaknesses, though representing considerable progress in several respects.

Open ocean water has a normal chlorinity of about 19 gm/kg (salinity 34.3 gm/kg), the highest chlorinities rarely exceeding 20.5 gm/kg. Chlorinities in the Persian Gulf are above these levels. and in limited areas they are unusually high. As is noted in a later section, there are few instances elsewhere of such high chlorinities existing over comparably large areas.

Diluting effect of the Shatt al Arab.—Circumstances result in the discharge from the Shatt al Arab being very variable during the year and from year to year. The levels of the Tigris and Euphrates, the principal rivers discharging by way of the Shatt. vary greatly with the seasons. During early spring the rivers reach high level in their upper valleys, and commonly flood. They are then impressive rivers indeed. But huge marshes in the lower river valleys act as dampers to river flow, and flooding of the Shatt al Arab is therefore several weeks later, and occurs far less often, than the flooding of the Tigris and Euphrates. A large fraction of the river water is lost by evaporation from the marshes. and flood control and irrigation schemes, which have come into operation during the last few years. have caused additional reduction of river discharge into the Gulf.

From the information available it would seem that from about August to December in a normal year the Shatt al Arab discharge is insufficient to have a readily appreciable influence on the salinity of the Gulf. At such times normal Gulf water salinities can be expected within a few miles of the river mouth. (see, for example, Emery, 1956). On the other hand, as indicated in figure 2. the effects of river dilution can at other times be expected at least as far from the mouth of the Shatt al Arab as 50°E 28°N, possibly occurring at that distance as semi-isolated rafts of water of low salinity. Much more needs to be known before the diluting effect of the river can be properly assessed.

The Gulfs of Bahrain and Salwa.—The Gulfs of Bahrain and Salwa lie between the Qatar Peninsula and Saudi Arabia (inset, fig. 2). The outer part of this area, surrounding the island of Bahrain, is the Gulf of Bahrain, and the comparatively narrow bay south of about Lat 25°30′N is the Gulf of Salwa. From extensive sampling, these two minor gulfs are now known to have far higher chlorinities than the remainder of the Persian Gulf.

The two minor gulfs contain many sandbanks and shoals. Figure 3 shows the distribution of shoals of less than three fathoms depth in the Gulf of Bahrain and the position of a number of very shallow reefs. The outer shoals have been accurately charted, but the inner parts of the Gulf of Bahrain have been only sketchily surveyed. The published information on this area has been sup-

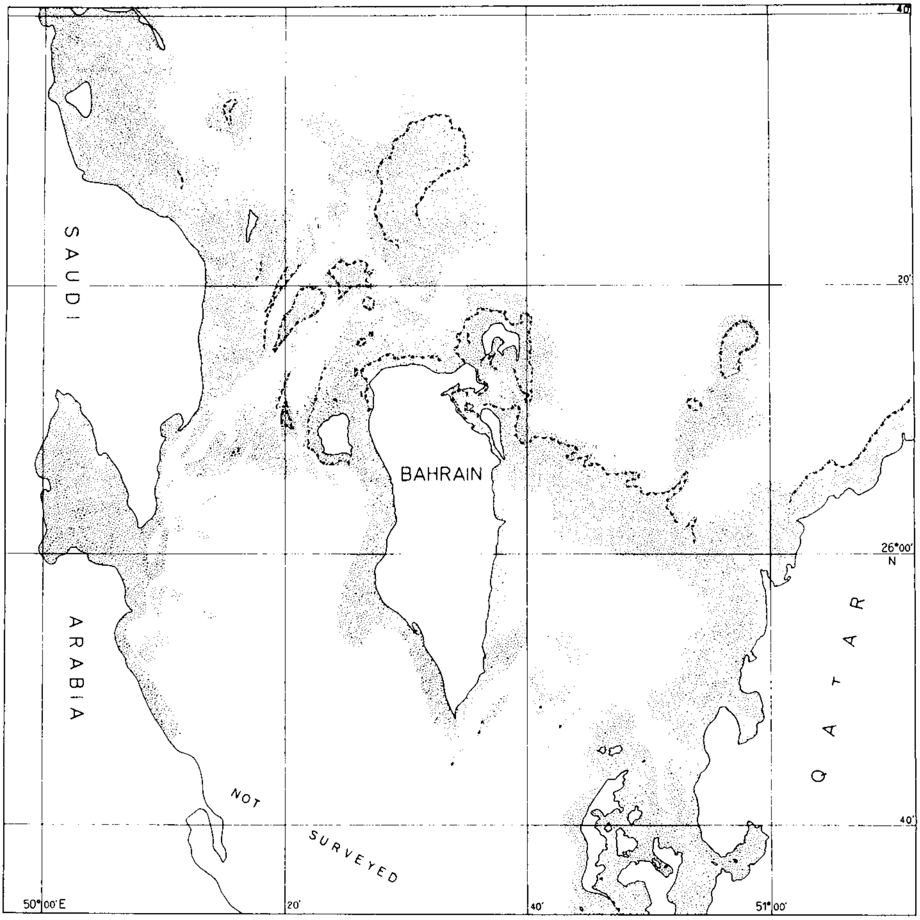

Fig. 3. Shoals of less than three fathoms depth (shaded) in the vicinity of Bahrain Island.

plemented in figure 3 from private sources, and most of the essentials of the bottom topography are shown. The Gulf of Salwa has not been surveyed at all. Toward its head the water is very shallow indeed, and it is probable that elsewhere it is mostly less than three fathoms deep.

Tidal ranges are small, even exceptional ranges in the Bahrain-Salwa area seldom exceeding about three feet, and the numerous banks and shoals restrict water movement. Nevertheless, a large interchange of water with the main part of the Persian Gulf is continuously taking place. From such meager evidence as is available it is suspected that the greater part of the water in the Gulf of Bahrain is changed every few weeks. There is north to south increase in chlorinity throughout the Gulf of Bahrain, but chlorinities to the east of Bahrain Island are lower than chlorinities to the west. This feature may have several contributory causes. Thus, for instance, there may be a more ready water exchange with the Persian Gulf to the east than to the west of Bahrain, but it is believed that the situation is dominated by wind-induced clockwise water circulation around Bahrain Island. The greater part of the exchange inflow is thus to the east of the Island, whereas the greater outflow is to the west. Under normal weather conditions there is also clockwise circulation in the Gulf of Salwa, and from chlorinity distribution it is apparent that this flow is to some extent independent of circulation in the Gulf of Bahrain.

Throughout the Persian Gulf there is quite a large climatic difference between winter and summer. The difference is reflected in seasonal variations of chlorinity. Also, local deviations from the seasonal mean chlorinity are the rule, such deviations being caused by ordinary irregularities of air temperature, relative humidity, rainfall, wind velocity, water turnover, and so forth. These deviations may be termed "random deviations". Seasonal fluctuation and random deviation have been investigated at three points in the Gulf of Salwa.

At locality A (inset, fig. 2) samples were collected twice weekly and at B and C once weekly for a year; figures 4 and 5 illustrate the three series of chlorinity measurements resulting. They show plots of actual chlorinity and seasonal means as drawn by visual estimate. Figure 4 also shows corresponding temperature records for locality A. The following conclusions are reached:

Temperature, even by the shore and in very shallow water, never varies by much more than about 4°C from the seasonal mean, and near shore temperatures never vary very greatly from the surface temperature of much deeper water in the same area. (Relevant temperature information is given by authors already cited and in the *Persian Gulf Pilot.*)

Chlorinity variation is not such a simple matter. Random deviations of chlorinity are comparable at the three sampling points, though in each case they are greater in winter than in summer. Also it may be seen that, despite the localities' being separated by only a few miles, the seasonal chlorinity curve for C is significantly different to those for A and B.

Because the water in the Gulfs of Bahrain and Salwa is so shallow, the wind exerts considerable control upon circulation. Thus in these gulfs, where there is great salinity variation over relatively short distances, a significant change in wind strength or direction can have a marked effect on chlorinity distribution. From about the latter part of May to the end of November the weather is settled. The wind is then nearly always light, and remains close to the northwest, the prevailing direction throughout the year. Chlorinity distribution during the summer and autumn therefore remains relatively stable. During the winter and spring however, the wind strength is very variable, and the wind frequently departs from the prevalent direction, sometimes to the extent of being reversed for two or three days together. This causes relatively large temporary changes in the prevailing water circulation, and hence greater local salinity fluctuation than during the summer months. Short-term weather variations also affect evaporation rates, and in this way additional random deviations of chlorinity result.

Localities A and B are about six miles apart, and on comparably open parts of the coast, and making due allowance for the nature of the data, the seasonal chlorinity curves of these two localities (figs. 4 and 5) are quite

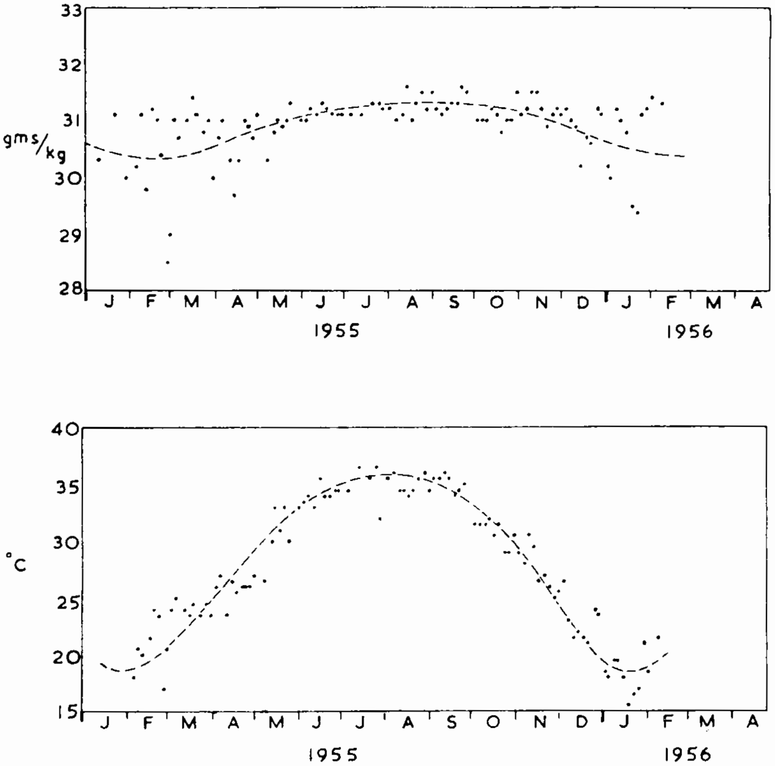

Fig. 4. Chlorinity and temperature at Locality A, Gulf of Salwa.

similar. Chlorinity range at C is, however, much greater than at A and B. C is in a long, narrow embayment with average water depths of only a few feet, even at high tide. Water exchange in the embayment is much slower than along the adjoining open coasts. In winter, when evaporation rates are lower, flushing of the embayment by the tide effectively keeps the chlorinity down. But in summer, when evaporation is more rapid, the equilibrium between evaporation and water exchange becomes such that chlorinities rise well above those along the more open coasts in the vicinity.

Random deviations of chlorinity in the Gulfs of Bahrain and Salwa are greater than seasonal variation. Random deviations are, therefore, such that for any point a large number of observations must be made before seasonal variation can be determined satisfactorily. From nowhere else in the Persian Gulf are there records of chlorinity such as exist for localities A, B, and C, but there are sufficient data from a number of points or limited areas to support general statements on chlorinity variation. Over most of the Persian Gulf seasonal variation and random deviation of chlorinity are less than in the Bahrain-Salwa area. At the same time, the magnitude of random deviation is everywhere very significant, and in many areas is greater than seasonal variation.

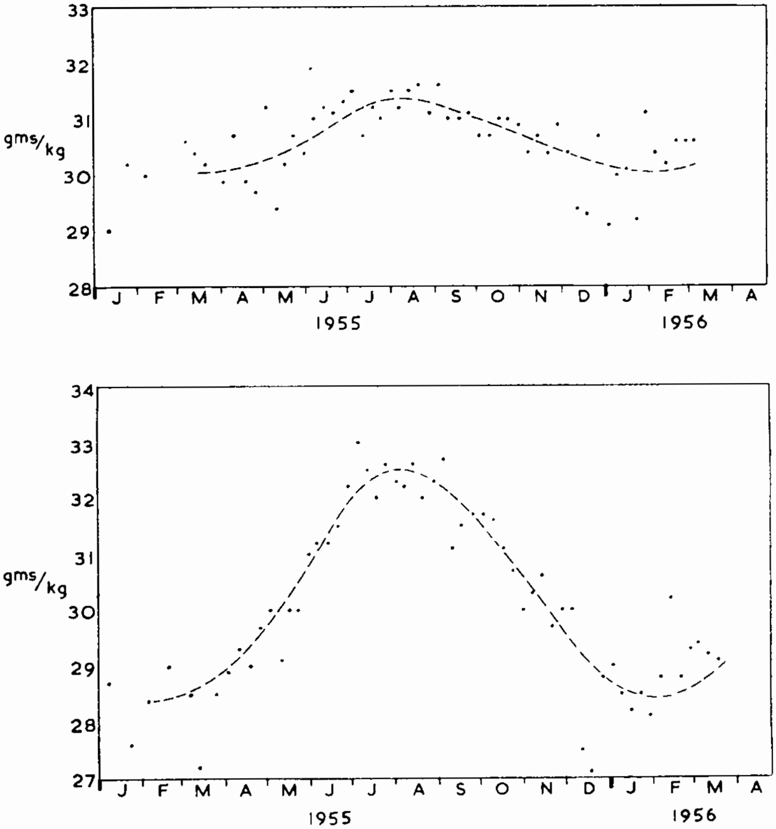

Fig. 5. Chlorinity at Localities B (upper) and C (lower), Gulf of Salwa.

In the Gulfs of Bahrain and Salwa there are a few coastal stations apart from those already mentioned at which mean annual chlorinity has been determined with fair accuracy. But in the preparation of the relevant part of figure 2, some interpretation was inevitable, and complete accuracy in placing the lines of equal chlorinity was not possible.

The Trucial Coast embayment.—About seventy surface water samples were obtained from a strip extending a few miles offshore along most of the Trucial Coast. The area sampled is shallow, and there are numerous banks and shoals and a few islands that must damp down water circulation. Nevertheless, the coast may be described as being, as a whole, open. This general area has the hottest climate of the Gulf, and despite the coast's being mainly open, near shore chlorinities are as much as 25 percent above the chlorinity of the sea water entering the Gulf.

It was, unfortunately, not possible to obtain a large number of samples from any particular point on the Trucial Coast, but enough were obtained from two shoreline localities to show that seasonal and random variations are comparable with those demonstrated in the Gulf of Salwa.

COMPARISON WITH OTHER EXAMPLES OF HIGH SALINITY

The Persian Gulf has very high salinities compared with any part of the open oceans, and the only large constricted sea having salinities of a similar range is the Red Sea (Schulz, 1914; Thompson, 1939a,b). There are, however, numerous lesser bodies of water connected with various seas or oceans that are subject to net evaporation and have unusually high salinities. A few of these are comparable in size with the combined Gulfs of Bahrain and Salwa. It is of interest here to give brief notes on their hydrologies. In all but two of the cases mentioned below, connection with the open sea is much more restricted than is the case in the Gulf of Bahrain. In these small basins the severity of evaporation is obviously closely linked to the control of water exchange by the constrictions existing at the entries to the water bodies.

The classic example of a small silled basin of high salinity is the Gulf of Kara-Bugaz, which connects with the Caspian. In this small gulf, Caspian Sea water of a salinity of about 12.8 gm/kg becomes concentrated to as much as 285 gm/kg (Zenkevich, 1957), but the composition of the dissolved salts is unlike that of ordinary sea water. In area the Gulf of Kara-Bogaz is comparable with the Gulfs of Bahrain and Salwa.

Also in Russia is the Sivash, a lagoon about 70 miles long separated by a sand spit, except for a small channel, from the Sea of Azov. The water in the Sea of Azov has a salinity of about 11 gm/kg, whereas salinities of well over 100 gm/kg are encountered over much of the Sivash (Hedgpeth, 1957).

In Western Australia two elongate bays, comprising parts of Shark Bay, have both dimensions and salinities comparable with those of the Gulf of Bahrain-Gulf of Salwa area (Logan, 1961). Compared with the latter area, bottom configuration and freedom of connection of both bays with the open sea appear to be similar.

In Lower California, Phleger and Ewing (1962) have investigated conditions in coastal lagoons, including the Ojo de Liebre. This particular lagoon is about 20 miles long and, though somewhat narrow, has depths of up to 60 feet. There is no definite bar at the entry to the lagoon, so that circulation is quite free, but salinities at the inner end of the lagoon are about one-third above those of the entering ocean water.

The Laguna Madre of Texas is about 140 miles long and up to 10 miles wide. Throughout its length it is separated from the sea by a narrow bar, there being a small inlet at either end. Salinities rise toward the center of the lagoon to as much as 80 gm/kg (Hedgpeth, 1957).

Morris and Dickey (1957) have described the hydrology of the Bocana de Virrila of coastal Peru. Though only about 20 km long and 2 km across, this relict shallow estuary is of special interest in that sea water of normal salinity becomes concentrated in its inner reaches to 355 gm/kg, or about ten times normal, so that both gypsum and halite are being precipitated.

As a final example, Day, Millard, and Brockhuysen (1954) give hydrological details concerning the St. Lucia estuarine lake of South Africa. Salinities in this lake rise above or fall below that of the adjoining sea with variations in annual rainfall and fresh water inflow.

The above examples of high salinity are all of interest in connection with the origins of evaporites, and in some cases attention has already been directed to their importance in this respect (see particularly Scruton, 1953: Morris and Dickey, 1957). The Persian Gulf is, however, certainly the best existing single model for the interpretation of the circumstances leading to evaporite deposition. It is far larger than most other available natural models, being more nearly on the same scale as many ancient evaporites. At the same time the principal conclusions arrived at by consideration of the Persian Gulf can usually be reinforced by reference to several of the smaller examples of similar hydrology mentioned above.

PERSIAN GULF HYDROLOGY AND EVAPORITE DEPOSITION

It has long been widely accepted that most ancient evaporite deposits were formed from ocean water in seas with continuing though restricted connection with the open ocean. The bulk of many ancient evaporites, their composition, and manner of distribution are generally considered to rule out any other possibility. Articles by Ochsenius (1888), Baker (1929), Lloyd (1929), Lang (1937), Roth (1942), King (1942), Hills (1942), King (1947), Scruton (1953), Sloss (1953), and many other authors argue or clearly accept this interpretation. The great volume of evidence supporting it cannot well be disputed, and it is here accepted without further comment.

However, though it is widely acknowledged that there must be severe restriction of circulation between an evaporite depositing sea and the open ocean, there is clearly still doubt in the minds of many authors as to what may have been the precise causes of such constraint in different instances. Ochsenius (1888), who developed the celebrated bar theory, evidently visualized that evaporite-depositing waters must be almost shut off from the open sea, and with respect to extreme evaporation, with the precipitation of potash and other minor constituent salts, it would doubtless be generally agreed that such an interpretation is in essence correct. But concerning the commoner exaporites, gypsum and halite, it is often open to debate as to how far and in what way evaporite-producing waters actually were partially isolated from the open ocean. A good example of the nature of this problem is provided by a series of articles by various authors on the Permian of Texas and adjoining areas (Baker, 1929; Lloyd, 1929; Lang, 1937; Roth, 1942; King, 1942; Hills, 1942; King, 1947). The Permian stratigraphy of that area has been closely studied, and it is known that a whole series of evaporite-depositing seas existed, that these were of very variable extent, and that circumstances controlling water circulation certainly must have altered considerably with time.

It is believed that consideration of the hydrology of the Persian Gulf can throw some light on problems of circulation control. Although its highest chlorinities are little more than half that at which sea water becomes saturated with calcium sulphate (Posnjak, 1940), the Gulf has a hydrological regime much like that which must have existed in many ancient evaporite basins. Thus it can serve as a model by which various interpretations concerning evaporite deposition can be derived or verified.

Using the Gulf as a model, there are two quite distinct possibilities by which we can suppose it might become converted to an evaporite-depositing basin. The first possibility is in keeping with what might be described as the popular bar concept. According to this concept, increasing constriction at the Straits of Hormuz would be suggested, and this could, without other changes, eventually limit circulation within the Gulf to the extent necessary to produce evaporite deposition. This is the kind of situation most commonly supposed to have controlled evaporite deposition in ancient basins.

The circumstances that would result from progressive reduction of circulation by a bar at the entry to the Gulf are such as have been deduced by King (1947) and Scruton (1953). Following the lines of Scruton's excellently developed interpretation, increasing sill constriction, by reducing the rate of escape of highly saline bottom waters, would eventually cause gypsum to be deposited in those areas that are now most saline. If the sill were maintained in that condition, gypsum could continue to be the only precipitated evaporite, other potential products of evaporation being returned, by counter-flow, to the ocean. But with continuing further constriction at the sill, gypsum precipitation would spread to a larger area, and eventually halite would be deposited, contemporaneously, in those coastal areas where gypsum was first precipitated. From all the various information available, there can be no doubt as to the soundness of Scruton's interpretation. It is, however, clear that, in the case of the Persian Gulf, connection through the Straits of Hormuz would have to be very greatly reduced, by reefs or other types of bar, before evaporite deposition would commence.

Conversion of the Gulf into an evaporite-depositing area could, however, conceivably come about in another way. According to this alternative concept a distribution of evaporites similar to that proposed above could be produced without the introduction of any new barriers merely by sufficient overall shallowing of the Gulf. Some authors, perhaps especially Hills (1942), have evidently been inclined to interpret the origin of certain ancient evaporites according to such a concept, though the analogy with circumstances in presently existing seas has not been as closely illustrated as has been the case with the bar concept. As the Persian Gulf is an unusually good illustrative model, there is some justification for considering this alternative possibility at some length.

Let it be supposed that the Persian Gulf, while remaining of the same horizontal extent as at present, was being silted up in such a way as to produce reductions of depth everywhere directly proportional to the depths now existing. Bottom relief would thus be reduced, but configuration would remain otherwise the same, with a general downward slope toward the deepest water at the Straits of Hormuz. Shallowing, together with reduction of bottom gradients, would slow down circulation, and the same rate of evaporation would therefore produce higher and higher salinities. Eventually the head waters of the Gulf of Salwa would become so concentrated that calcium sulphate would be precipitated. Further silting up would gradually extend the area of sulphate deposition to the Gulf of Bahrain. The shoals across the entry to the Gulf of Bahrain would play a part in raising the salinity of the area lying within them, but it would be the size of that area and its overall shallowness, rather than the existence of the shoals, that would give rise to the high salinities.

To extend the interpretation further it is necessary to consider a point concerning the present hydrology of the Persian Gulf. From data obtained on the one hand by Emery (1956) and on the other by the writer, it is known that in the deepest parts of the Gulf the outflowing bottom water has a chlorinity much lower than that of the surface waters near the shores of the Trucial Coast embayment or in the Gulfs of Bahrain and Salwa. Thus, though the high salinity coastal waters must eventually become part of the deep outflow, they become considerably mixed with less saline water before reaching the deepest parts of the Gulf.[1]

If we return now to the visualized silting up of the Gulf and its deduced consequences, beyond the results already inferred, continued silting up would cause gypsum precipitation in the coastal waters of the Trucial Coast embayment. Meanwhile the water in the main part of the Gulf would remain unsaturated with calicum sulphate, the surface water because it had not been sufficiently evaporated and the counterflowing deep water because the highly concentrated coastal water could not reach the greatest depths without becoming mixed with less concentrated water. Were silting up to continue indefinitely in the same manner, halite would also be deposited in the same areal sequence, starting at the head of the Gulf of Salwa, as was gypsum. But by this time sulphate deposition would have extended to large areas of the open part of the Persian Gulf.

Finally one might opine that when circumstances had become very extreme the highest grade evaporites, including potash salts, would be precipitated in the Gulfs of Salwa and Bahrain while gypsum and halite were being deposited in the main part of the Gulf.

It is quite obvious that river dilution at the northern end of the Gulf would limit the effects of evaporation in that area at all times during the process suggested.

As already mentioned, the distribution of different evaporites relative to one another and relative to other sediments would be similar whether there was bar control at the Straits of Hormuz or control entirely by overall shallowing. In either event circumstances would ultimately lead to a pattern of sedimentation such as has long been recognized to have existed in many ancient evaporite seas (Lloyd, 1929; Lang, 1937; Roth, 1942; Hills, 1942: King, 1942: Twenhofel, 1950: Scruton, 1953). At one and the same time limestones would be deposited near the entry to the Gulf while gypsum was deposited over much of the Gulf, and halite and possibly even higher grade salts, at some of its extremities. The important point to the present author's mind is that, at least as far as gypsum and halite are concerned, it need not necessarily be supposed that evaporite-producing waters are always confined within a very definite barrier. Considering the enormous area of some ancient evaporites, sufficient shallowing over a very large area is an alternative that frequently merits serious consideration.

---

[1] It is of interest that the deep bottom water in August, at the time of Emery's survey, was so cold that it must have formed mainly from the surface waters of the previous winter.

EFFECTS OF HIGH SALINITY ON FLORA AND FAUNA

Interbedded or closely associated with many ancient evaporites are limestones with what appear to be normal marine faunas. Some such faunas, though quite rich, are made up of a very limited number of species, whereas others may contain many species of diverse groups of animals. One is led to wonder how far such faunas signify truly normal marine conditions. There have been comparatively few investigations that provide very specific information relevant to this matter, as is clear from a summary by Hedgpeth (1957). The present author's observations in the Persian Gulf, though limited, may therefore be of some interest.

Circumstances in the Gulf favor prolific organic production (Emery, 1956), and plants and animals can migrate freely in waters of unusually high and variable salinity. But, as will be seen below, it would require very careful investigation to demonstrate clearly the effects of salinity on flora and fauna.

In the high salinity area of the Gulfs of Bahrain and Salwa, groups of organisms notable for their abundance and diversity are the algae, foraminifera, sponges, bryozoa, worms, molluscs, arthropods, and fishes. At the same time some limited groups of animals that are not uncommon elsewhere in the Persian Gulf are conspicuous by their absence in the Gulf of Salwa. Notable among these are the corals, but the Gulfs of Bahrain and Salwa are within the area where winter water temperatures fall below 18.5°C (*Persian Gulf Pilot*), and thus, according to Vaughan (1915) and Wells (1957), corals would not be expected to establish themselves, even were the salinity normal. Sharks and turtles, common in other parts of the Persian Gulf, do not occur in the Gulf of Salwa, and there is a multitude of less spectacular creatures absent in that area which could readily migrate into it. On the other hand, many species are abundant even at the highest observed salinities, and the difficulty of relating populations to salinity is well illustrated by a limited investigation carried out on mollusc faunas.

Sublittoral molluscs are extremely abundant in the Persian Gulf, both in numbers of species and numbers of individuals (Melville and Staden, 1901; Melville, 1928; Hass, 1952, 1954). On many beaches shell debris occurs in large banks around high water mark, and this is the case on many parts of the Gulf of Salwa coast. Mollusc faunas therefore appear to provide the most ready means of demonstrating any relationship between salinity and fauna. As complete a collection of molluscs as possible was made by the author between localities A and B, where the chlorinity averages about 30.3 gm/kg, and 35 species were identified (F. Haas, personal communication). This is to be compared with 64 species identified in a similar collection from Dubai (Haas, 1954), which is on the Arabian coast, not far from the mouth of the Persian Gulf. The chlorinity is there of the order of 22.2 gm/kg.

These appear to be the only two localities in the Gulf at which full collections have been made, and the results suggest a decrease in the number of species with increasing salinity. But further investigation emphasized the danger of drawing hasty conclusions. Shells were also collected near Jufair at the northern end of Bahrain Island, and at Umm Said on the southeast Qatar coast, at which two localities environmental circumstances appear to be similar.

The mean chlorinity is in both cases about 24.5 gm/kg. These two collections were not as complete as those previously mentioned but revealed the following: The two collections had many species in common, but numerous species were represented only in the one or the other; also, relative numbers of individuals of different species varied greatly between the two collections. It could in fact be said that these two faunas differ in composition from one another as much as either differs from the Gulf of Salwa fauna. Thus, whereas salinity differences such as are recorded in this article must certainly have a significant effect on fauna, other environmental variations, which are by no means obvious, evidently have as great or greater influence, so that the effects of salinity are well masked.

Hedgpeth (1957) gives information on the salinity tolerances of various species and groups of animals over a more extended range than exists in the Persian Gulf, and from the various information available the following picture can be built up:

In sea water that has normal salt composition a very diverse fauna can exist when the chlorinity is not more than about 33 gm/kg (about 75 percent above normal). Many marine species are unable to live at chlorinities as high as 33 gm/kg, but it would be very difficult to recognize, in fossil faunas, the effects of salinity control below that level. At chlorinities ranging upward from about 33 gm/kg there is a rapid reduction in the diversity of the species that can survive, and nearly all the major zoological groups are entirely eliminated when the chlorinity reaches about 44 gm/kg (2.3 × normal). The author believes that the effects of such drastic elimination can often be recognized in fossil faunas occurring in partly evaporitic sequences. At chlorinities above about 44 gm/kg hardly any animals can survive, though gypsum precipitation does not commence in modern sea water until a chlorinity of about 60 gm/kg is reached.

An article on the extensive Riyadh (Upper Jurassic) and Lower Fars (Miocene) evaporitic sequences of the Persian Gulf region will be prepared shortly. Various of the ideas developed in this and the previous section will be applied in the interpretation of sedimentational circumstances existing during their deposition.

ACKNOWLEDGMENTS

The writer is indebted to numerous individuals, without whose help this paper would not have been possible, who assisted in the collection of water samples. Thanks are also due for a number of useful sea water analyses supplied from the records of several oil companies operating in the Persian Gulf area, and to the management of the Iraq Petroleum Co. for the use of laboratory facilities. Dr. H. G. Reading gave helpful criticism during preparation of the text.

REFERENCES

Admiralty, 1942, Persian Gulf Pilot.

Baker, C. L., 1929, Depositional history of the red beds and saline residues of the Texas Permian: Texas Univ. Bulletin 2901, p. 9-72.

Blegvad, H., 1944, Fishes of the Iranian Gulf: Danish Sci. Expeditions in Iran (1935-1938), pt. 3, 247 p.

Day, J. H., Millard, N. A. H., and Brockhuysen, G. J., 1954, The ecology of South African estuaries, Pt. IV, The St. Lucia system: Royal Soc. South Africa Trans., v. 34, p. 129-156.

Emery, K. O., 1956, Sediments and water of the Persian Gulf: Am. Assoc. Petroleum Geologists Bull., v. 40, p. 2354-2383.

Haas, F., 1952, Shells collected by the Peabody Museum Expedition to the Near East, 1950, I, Mollusks from the Persian Gulf: Nautilus, v. 65, p. 114-119.

——— 1954, Some marine shells from the Persian Gulf: Nautilus, v. 68, p. 46-49.

Hedgpeth, J. W., 1957, Estuaries and lagoons, II, Biological aspects: Geol. Soc. America Mem. 67, v. 1, p. 693-729.

Hills, J. M., 1942, Rhythm of Permian seas, a paleogeographic study: Am. Assoc. Petroleum Geologists Bull., v. 26, p. 217-255.

King, P. B., 1942, The Permian of west Texas and southeastern New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 26, p. 535-763.

King, R. H., 1947, Sedimentation in the Permian Castile sea: Am. Assoc. Petroleum Geologists Bull., v. 31, p. 470-477.

Lang, W. B., 1937, The Permian formations of the Pecos valley of New Mexico and Texas: Am. Assoc. Petroleum Geologists Bull., v. 21, p. 833-898.

Lloyd, E. R., 1929, Capitan Limestone and associated formations of New Mexico and Texas: Am. Assoc. Petroleum Geologists Bull., v. 13, p. 645-658.

Logan, B. W., 1961, *Cryptozoon* and associated stromatolites from the Recent, Shark Bay, Western Australia: Jour. Geology, v. 69, p. 517-533.

Melville, J. C., 1928, The marine Mollusca of the Persian Gulf, Gulf of Oman and north Arabian Sea; Addenda, corrigenda and emendanda: Malacol. Soc. London Proc., v. 15, p. 93-126.

Melville, J. C., and Staden, R., 1901, The Mollusca of the Persian Gulf, Gulf of Oman and Arabian Sea: Zool. Soc. Proc., v. 2, p. 327-460.

Morris, R. C., and Dickey, P. A., 1957, Modern evaporite deposition in Peru: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 2467-2474.

Ochsenius, C., 1888, On the formation of rock salt beds and mother liquor salts: Acad. Nat. Sci. Philadelphia Proc., v. 40, p. 181-187.

Phleger, F. B., and Ewing, G. C., 1962, Sedimentology and oceanography of coastal lagoons in Baja California: Geol. Soc. America Bull., v. 73, p. 145-182.

Posnjak, E., 1940, Deposition of calcium sulphate from sea water: Am. Jour. Sci., v. 238, p. 559-568.

Roth, R., 1942, West Texas barred basin: Geol. Soc. America Bull., v. 53, p. 1659-1674.

Schott, G., 1908, Der Salzgehalt des Persischen Golfes und der angrenzenden Gewässer: Annalen Hydrographie u. Maritimen Metiorologie, v. 36, p. 296-299.

Schulz, B., 1914, Beitrage zur Kenntnis der Oberfläschenverhältnisse der Ozeans: Annalea Hydrographie u. Maritimen Metiorologie, v. 42, p. 392-405.

Scruton, P. C., 1953, Deposition of evaporites: Am. Assoc. Petroleum Geologists Bull., v. 37, p. 2498-2512.

Sloss, L. L., 1953, The significance of evaporites: Jour. Sed. Petrology, v. 23, p. 143-161.

Sugden, W., in press, Some aspects of sedimentation in the Persian Gulf: Jour. Sed. Petrology.

Sverdrup, H. V., Johnson, M. W., and Fleming, R. H., 1942, The oceans: New York, Prentice-Hall, 1060 p.

Thompson, E. F., 1939a, The general hydrography of the Red Sea: John Murray Exped., 1934, Sci. Repts., v. 2, p. 83-103.

——— 1939b, Chemical and physical investigations; the exchange of water between the Red Sea and the Gulf of Aden over the sill: John Murray Exped., 1934, Sci. Repts., v. 2, p. 105-119.

Twenhofel, W. H., 1950, Principles of sedimentation: New York, McGraw-Hill, 673 p.

Vaughan, T. W., 1915, The geologic significance of the growth rate of the Floridian and Bahaman shoal water corals: Washington Acad. Sci. Jour., v. 5, p. 591-600.

Wells, J. W., 1957, Coral reefs: Geol. Soc. America Mem. 67, v. 1, p. 609-632.

Zenkevich, L. A., 1957, Caspian and Aral Seas: Geol. Soc. America Mem. 67, v. 1, p. 891-916.