Wind and Water Depth and Their Bearing on the Circulation in Evaporite Basins

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ABSTRACT

Different types of countercurrent systems may occur in subtropical basins. An anti-estuarine circulation develops if there is a horizontal salinity gradient and the wind effect is negligible (1). An estuarine-line circulation develops if the trade wind is blowing the surface water out of the basin, and salinity differences are negligible (2). Where both a horizontal salinity gradient and a counteracting wind are present, an anti-estuarine circulation dominates where the basin is deeper than a certain critical depth, whereas an estuarine-like circulation dominates in the shallow windward end. If the depth above the sill exceeds the critical depth, the subsurface water flows out (3), but if the depth is less than the critical depth an estuarine-like circulation develops above the sill preventing the subsurface water from leaving the basin (4). Type (2) leads to high fertility in the basin and to the development of bituminous deposits in the pre-evaporite phase. Types (1) and (3) lead to very low fertility. Type (4) leads to high salinities in deep basins, and eventually to the precipitation of thick salt deposits. This type (4) does not lead to high fertility in the basin itself, but an area of high fertility will develop above the sill.

In basins in the subtropics there are different types of countercurrent systems. Perhaps best known is the circulation pattern of the Mediterranean Sea with an inflow along the surface and outflow in deeper layers. The primary cause of this circulation is the dry climate involving an excess of evaporation over precipitation plus runoff. This leads to a horizontal increase in both salinity and density towards the head of the basin, the density gradient in turn effecting a downward slope of the sea surface. This slope causes an inward flow of ocean water due to hydrostatic pressure. The pressure field produced by the surface slope is exceeded at depth by the pressure field due to density, and this results in an outflow of deeper layers. In some basins the outflow is mainly restricted to layers above sill depth.

The inflowing water compensates in part for the outflow, and in part for the loss by excess evaporation, the amount required for compensation of loss by excess evaporation being many times smaller than the amount required for the compensation of the outflow (Sverdrup *et al.*, 1946, p. 147). This countercurrent system is called an anti-estuarine circulation since it is more or less the reverse of the circulation in river estuaries.

But one must realize that the anti-estuarine circulation is not the only possibility in the subtropics. In some subtropical basins an estuarine-like circulation is to be found with an outflow along the surface and an inflow in deeper layers. The driving force of this circulation is the wind. The wind effect is only important in the event of a wind of constant direction; the trade winds are such winds. When a semi-enclosed bay or marginal sea is lying with its long axis more or less parallel to the direction of the wind and the opening is

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downwind, the surface water is driven from the inner parts of the basin towards the open sea. This results in a shortage of water (so to say) at the inner end. To compensate for this, subsurface water flows in, and this water ascends towards the surface at the inner end. In this way an estuarine-like countercurrent system develops. An example of a basin with this type of circulation is the Gulf of Cariaco on the north coast of Venezuela. In this area the predominant wind direction is easterly (Gade, 1961a, p. 29); such winds carry the surface water out of the basin, and this outflow is compensated by an inflow of subsurface water over the sill (Richards, 1960; Gade, 1961a, b). Another example is the Gulf of California; during the winter and spring strong winds predominantly from the northwest drive the surface water out of the Gulf, the outflow being compensated below the thermocline by inflow of Pacific water (Van Andel, 1964, p. 263).

The trade winds blow between the subtropical highs (located at about lat. 30°N. and lat. 30°S.) and the equatorial low pressure belt. They are inclined to be dry in their near-subtropic parts, whereas they are more humid on their equatorial margins. In the dry parts of the trade wind belt there are two different forces that may bring about a countercurrent system: (1) the horizontal density (salinity) gradient as a result of the dry climate and (2) the stress of the trade wind. The wind will intensify the anti-estuarine circulation if the opening is upwind, but it will counteract this circulation if the opening is downwind. In the latter case it is a tug of war between the density gradient and the wind. With regard to this tug of war the question arises, when will one or the other predominate?

At the speaker's request the second author of this paper made calculations on the combined effect of these two factors. These calculations will be published elsewhere in detail (Groen, in press). In this paper we shall present only the results, and their bearing on the deposition of salt.

In order to determine the combined effect of the salinity gradient and the wind, a simple two-dimensional model, constructed parallel to the axis of an elongated basin, was evaluated. If no wind were blowing an anti-estuarine circulation would prevail everywhere in the basin, the deeper water layers flowing towards the opening, the upper layers towards the head of the basin (Fig. 1). If on the other hand, there were no salinity differences and with that no horizontal density differences, and a wind were blowing towards the opening of the basin, a pure wind-driven circulation would

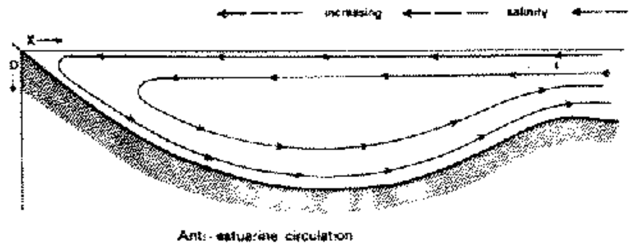

Figure 1. Circulation in basin with horizontal salinity gradient, wind effect negligible; X→ indicates axis and direction of opening of basin.

prevail everywhere in the basin; the upper layers would move with the wind, whereas the lower layers would flow as a compensation current in the opposite direction (Fig. 2). The stress of the wind on the surface of the water, i.e. the force per unit area, is proportional to the square of the wind velocity. Since this force is distributed over the whole water column beneath the surface on which it acts, the force *per unit volume* of the water is inversely proportional to the height of the water column, i.e. to the depth of the water.

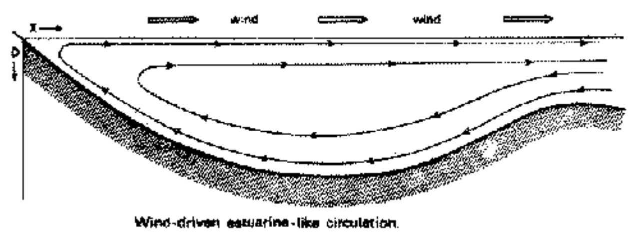

Figure 2. Circulation in basin without horizontal salinity gradient, wind blowing towards opening.

This conclusion is especially important if we now consider the case in which we are interested, namely the case where both a horizontal density gradient and a counteracting wind are present. It now appears that where the depth is small enough the wind-drift will dominate, whereas the anti-estuarine circulation dominates where the depth is great. In order to work this out quantitatively some computations have been made on the basis of the hydrodynamic equations which describe the interplay of forces. For these computations a somewhat simplified model of the hydrodynamic system is adopted, which will, however, give a fair approximation of reality.

It now turns out that, indeed, with a given wind stress and a given density distribution, there is found a critical depth, such that the surface current flows against the wind as long as the depth exceeds this critical depth *(D)*, whereas in places where the depth is less than *D* the wind drift dominates, the surface water flowing with the wind.

The value of the critical depth *(D)* is a function of the surface wind stress (To) and of the vertically averaged horizontal density gradient ($\partial\rho/\partial x$), in such a way that *D* increases with increasing To, but decreases with increasing $\partial\rho/\partial x$. Unfortunately, it is not possible to give a simple formula for *D* as a function of To and $\partial\rho/\partial x$. It can only be given implicitly, by means of an equation of which it is the root:

$$\frac{4\,T_o}{D^2}\,\text{log. nat.}\,\frac{D}{z_o} = -g\,\frac{\partial\rho}{\partial x} \quad , \qquad (1)$$

where z_o is the so-called "hydrodynamic roughness" parameter of the water surface and *g* the acceleration of gravity.

If the wind stress (To) and the density gradient ($\partial\rho/\partial x$) are given, one may find the critical depth *D* from equation (1). But one may also put things the other way round, in such a way that, for any given depth *D*, equation (1) gives a critical value of the (vertically averaged) horizontal density gradient, which must be exceeded in the water in order that at the surface it be able to flow against the wind, in an anti-estuarine sense.

As for the deeper layers, it appears from the basic equations of motion that the boundary between the two circulation regimes is tilting down towards the shallower parts of the basin, reaching the bottom in a place where the depth is about one-third times the critical depth.

For a numerical evaluation of equation (1), an empirical relationship is used between the wind stress To and the wind velocity *W* (To being proportional to W^2), and for z_o a value 0.5 cm is adopted (valid for moderate and strong winds). In this way one may calculate from (1) for any given wind velocity, pairs of corresponding values of *D* and the horizontal density gradient $\partial\rho/\partial x$, or of *D* and the (vertically averaged) horizontal salinity gradient (the latter follows from $\partial\rho/\partial x$, at least within certain ranges of the salinity, if the temperature is given). A few examples are given in Figure 3 where a water temperature of 25° C is adopted. If the salinity gradients that go with a certain water depth are exceeded, the surface water will flow towards the head of the basin despite the counteracting wind. Lower water temperatures would give smaller values of the salinity gradients with the same *D* and *W*.

Wind, m/sec → / D, m ↓	6	8	10	12
20	1,2	2,15	3,4	4,85
50	0,21	0,38	0,59	0,86
80	0,09	0,16	0,24	0,35

Salinity gradients in ‰ per km

Figure 3. Critical values of (vertically averaged) horizontal salinity gradients in % per km. Water temperature 25°C.

It should once more be stressed that the above results are based on a simplified model of the processes involved and therefore should be considered only as reasonable approximations. Nevertheless, they give a picture which is thought to be quantitatively correct.

Now what is the importance of this approach for a better understanding of the geology of evaporites? Assume a deep basin in the subtropics with a horizontal salinity gradient, and a steady counteracting wind. In such a basin either a circulation as shown in Figure 4 or a circulation as shown in Figure 5 will develop depending on whether the

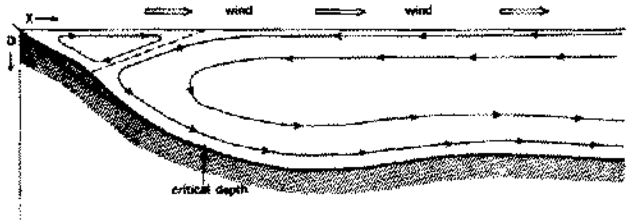

Figure 4. Circulation in basin with horizontal salinity gradient and counteracting wind. Water depth above sill larger than critical depth.

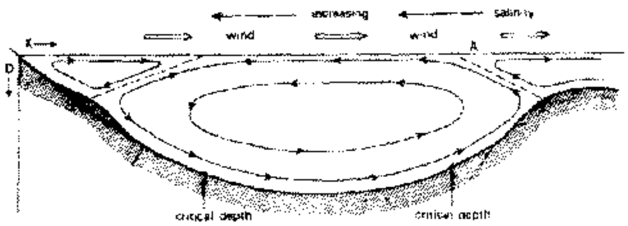

Figure 5. Circulation in basin with horizontal salinity gradient and counteracting wind. Water depth above sill smaller than critical depth. Upwelling at A.

water depth above the sill is larger or smaller than the critical depth corresponding to the locally prevailing density gradients and wind. In the latter case an anti-estuarine circulation dominates in the deeper parts, whereas above the shallow sill the wind is the winning party. This wind-driven estuarine-like circulation is then lying as a watchdog above the shallow sill, preventing the outflow of the deeper saline layers of the basin, for above the sill a subsurface current is flowing in. By far the greater part of this inflowing subsurface water returns to the ocean before entering into the basin. Only a small percentage (an amount about sufficient to compensate for the loss by evaporation) will enter and mix with the highly saline basin water. The composition of the basin water will hardly be changed by this inflow, even if the latter has the salinity and the composition of normal sea water.

The watch-dog system above the shallow sill combined with strong evaporation and with an anti-estuarine circulation in the deeper parts provides a mechanism that will lead to high salinities in deep basins. In this respect it is noteworthy that in recent years various authors have argued for a deep water origin of thick rock salt deposits. At many times during the geologic past, evaporites, in thin layers, mostly consisting of gypsum, probably have been formed in the shallow environment. It is unlikely, however, that this also applies to the thick halite accumulations which developed from time to time in the geologic past. Richter Bernburg (1960), Yanshin (1961), Pannekoek (1965), and others provided convincing arguments that the basins of sedimentation were deep when the precipitation of halite started, at least as deep as the total thickness of the rock salt deposits. Their arguments for deposition in the deep environment are convincing, but the conditions under which the salinity in deep basins can increase to very high values were not clear. We may suggest that the trade wind played an important part in deposition in such basins. If the opening of the basin was downwind, as long as the sill depth exceeded the critical depth, the highly saline subsurface water could leave the basin; but as soon as it became smaller an estuarine-like circulation would have developed over the sill (at least in the months of strong winds) preventing the outflow of saline water. This must have led to a sharp increase of salinity in the basin.

Another conspicuous problem in the geology of salt is the frequent association of evaporites with bituminous sediments, the bituminosity being particularly characteristic in deposits of the pre-evaporite phase. This problem has already been discussed by the first author at the "Symposium on the geology of saline deposits" in Hannover 1968 (Brongersma in press, further literature in Brongersma, 1968), but an addition must be given in the light of Groen's calculations.

The inorganic nutrients required for the growth of phytoplankton are extracted from the sea in the surface layers by living organisms, and returned to the sea in deeper layers by decaying organisms; this may lead to an increase of the nutrient content with depth. Under certain circumstances the biological process also leads to a shifting of nutrients in a horizontal direction. This occurs if the surface and the subsurface layers flow in opposite directions.

Figure 6 diagrammatically illustrates the process. In the surface water the nutrient content decreases in the direction of flow by the removal of nutrients, whereas in the subsurface water the content increases in the direction of flow by the input of nutrients. If the surface and subsurface layers flow in opposite directions the sum increases in the direction in which the subsurface water is flowing. In basins with an estuarine-like circulation where the subsurface water ascends and overturns in the inner parts (Fig. 2), the sum becomes higher and higher in the course of time until a steady state is

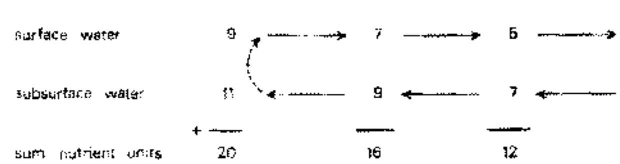

Figure 6. Shifting of nutrients in countercurrents (simplified model, influence of turbulence neglected).
Figures denote content of nutrient units in water, arrows indicate direction of flow.

reached. This produces high productivity in large parts of the basin. On the contrary, an anti-estuarine circulation (Fig. 1) leads to impoverishment, the nutrients being carried out of the basin towards the ocean (cf. Redfield, Ketchum & Richards, 1963, p. 64, Fig. 13 on the nutrient content of the Mediterranean Sea).

High productivity in the surface water leads to high oxygen consumption in the waters below, where large amounts of dead plankton sink down and decay. If high consumption is combined with low oxygen supply anoxic conditions develop. In this way bituminous sediments can be formed in basins with an estuarine-like circulation; this circulation predominates in the pre-evaporite phase when the salinity differences are low.

When speaking in Hannover the first author assumed that with increasing salinity the estuarine-like circulation (Fig. 2) would turn into the anti-estuarine circulation (Fig. 1) involving impoverishment of the basin and disappearance of the bituminous layer. The calculations by Groen have shown, however, that the situation is more complicated, as the circulation of Figure 2 turns either into that of Figure 4 or into that of Figure 5. The circulation of Figure 4 leads to an impoverishment of the basin indeed. In the case of Figure 5 there is hardly any gain from or any loss to the ocean, but there is upwelling above the shallow sill (A in Fig. 5), and this means a region of high fertility at the entrance of the basin. With an occasional change in the force or the direction of the wind, some of the plankton-rich water may enter into the basin leading to the development of a thin bituminous layer between the evaporites. All the same the most appropriate conditions for development of bituminous sediments occur with the estuarine-like circulation of Figure 2 predominating in the pre-evaporite phase.

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