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Ground-Water Flow Systems and the origin of Evaporite Deposits

Roy E. Williams

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ABSTRACT

Study of the literature on evaporite mineral deposits suggests a functional relationship between the origin of these deposits and ground-water flow systems. The theory on which the analysis of ground-water flow systems is based is reviewed in order to establish flow systems as a mechanism by which dissolved solids can be transported to sites of evaporite mineral accumulation. Comparison of observed spatial variations of ground-water quality with pertinent solutions to flow equations under specified boundary conditions reveals that quality of ground water is a function of flow path length, flow path route and flow velocity. Selected references provide evidence that sites of accumulation of non-marine evaporite minerals are discharge zones for poor quality water from regional ground-water flow systems.

A study of isotope ratios in oil field brines and standard mean ocean water indicates that water in some deep brines is of local meteoric origin; therefore, the brines are part of a ground-water flow system. Observed distribution of fluid potential in the saline portion of some ground-water flow systems on the Atlantic Coast of the United States reveals that saline ground water discharges toward the ocean floor. Therefore, ground water may also act as a transport medium for dissolved solids which are precipitated, under appropriate conditions, as marine evaporite deposits.

INTRODUCTION

The group of mineral deposits known as evaporites has in recent years been the subject of considerable discussion. The subject has in fact merited the publication of a complete text (Borchert and Muir, 1964) dedicated to an analysis of the distribution, mineralogy, sedimentology, physico-chemical characteristics and related tectonics of the deposits. It is probable that at least a portion of this interest is generated by a predictable increase in the exploitation of these deposits for useful elements such as lithium, boron and potassium.

The literature dealing with the origin of evaporite deposits treats in detail almost every aspect of the processes of their formation. One aspect which has not received sufficient study, however, is the role played by the flow of ground water. In most cases where the influence of ground water is considered, it is assumed that the effect took place after deposition (Shearman, 1966). The purpose of this paper is to examine the relation between ground-water flow systems and the formation of evaporite minerals.

LAGUNAL THEORY OF EVAPORITE ORIGIN

The classical mode of origin of marine evaporite deposits has probably been best summarized by Landes (1963a). Landes states, "Evaporite precipitation takes place when, under a proper climatic and physiographic environment, a sagging basin develops in an embayment so that a shallow sill or reef separates the basin from the main body of water. An inflow, across the sill, of sea water already enriched in sodium and chloride ions by the trip from the open ocean, is brought about by the greater evaporation within the nearly enclosed basin. The seaward return of the deeper, denser water is prevented by the sill." As the process of influx of sea water and rapid evaporation from the partially restricted inlet continues over long periods of time, the thickness of the evaporite deposits increases. Space for the thick deposits is created by a gradual, tectonic sagging of the embayment during precipitation from the saturated solution. Simultaneously, sediments and additional dissolved solids may be contributed to the embayment by fresh water streams. Variations in the suspended solids in the streams may give rise to cyclic depositional patterns within the deposits (Borchert and Muir, 1964, p. 37). A digital model to simulate evaporite sedimentation has been proposed by Briggs and Pollack (1967). Subsequent to deposition the evaporite minerals may be metamorphosed by one or more complicated reactions (Borchert and Muir, 1964, p. 93).

The role of ground water in the formation of non-marine evaporites is somewhat better defined. Although some authors feel that salts for inland deposits are derived from streams which cross evaporite outcrops (Landes, 1963b), ground water is credited with contributing dissolved solids to some closed basins. It is often assumed, however, that capillary forces pull the water toward the surface (Borchert and Muir, 1964, p. 180). In reality, ground water moves toward the ground surface in many locations under positive pressure and it may move at a relatively rapid rate. In addition to the dissolved solids contributed to non-marine basins by ground water and surface waters, suspended matter is also transported in. These suspended solids are deposited along with the salts in the evaporite deposits.

Before examining the detailed relation between ground-water flow systems and the formation of evaporite deposits a brief review of the theory of ground-water motion is in order.

REVIEW OF THEORY OF GROUND-WATER MOTION

Of major significance in the study of the movement of ground water has been the demonstration of a scalar energy potential which has a value at every point in a saturated medium. The existence of such a potential was demonstrated in a precise manner by Hubbert (1940), (1956). If one postulates that Darcy's law is valid, the macroscopic bulk velocity vector for isothermal flow of fluid through a porous medium is defined by:

$$\vec{q} = \frac{-k\rho}{\mu} \left(-\vec{g} + \frac{1}{\rho} \text{grad } p \right) \quad (1)$$

where

- \vec{q} is the macroscopic bulk velocity vector
- k is the intrinsic permeability of the medium
- ρ is mass density which under isothermal conditions may be stated as $f(p)$
- $-\vec{g}$ is the gravitational vector
- p is fluid pressure
- grad is the gradient vector operator
- μ is the dynamic viscosity of the fluid.

Inspection of equation (1) reveals that the term $(-\vec{g} + \frac{1}{\rho} \text{grad } p)$ defines the force acting on each unit mass of fluid in the porous medium. If the ensemble of force vectors in a hydraulically continuous porous medium does in fact have a scalar potential field, ϕ , then

$$\text{grad } \phi = -\vec{g} + \frac{1}{\rho} \text{grad } p. \quad (2)$$

In order to show that the scalar potential field does exist it is necessary to show that grad ϕ is irrotational, that is, that $\text{curl}(\text{grad } \phi) = 0$. Proof that $\text{curl}(\text{grad } \phi) = 0$ also proves independence of path (Lass, 1950) and that (2) can be integrated to obtain ϕ at any point in the scalar field. If $\text{curl}(-\vec{g} + \frac{1}{\rho} \text{grad } p)$ can

be shown to equal zero, then $\text{curl}(\text{grad } \phi)$ must also equal 0.

$$\text{Curl} \left[-\vec{g} + \frac{1}{\rho} \text{grad } p \right] = -\nabla \times \vec{g} + \nabla \times \left[\left(\frac{1}{\rho} \right) \nabla p \right].$$

By considering \vec{g} to be constant in magnitude, $-\nabla \times \vec{g} = 0$, so

$$\text{curl} \left[-\vec{g} + \frac{1}{\rho} \text{grad } p \right] = \nabla \times \left[\left(\frac{1}{\rho} \right) \nabla p \right] = \nabla \left(\frac{1}{\rho} \right) \times \nabla p$$

Therefore, $\text{curl}(\text{grad } \phi) = 0$ when $\nabla \left(\frac{1}{\rho} \right) \times \nabla p = 0$. This condition is satisfied if

ρ is constant or if ρ is a function of pressure along, which is the case for a chemically homogeneous fluid under isothermal conditions.

When these two conditions are met a scalar potential field does exist and its value at any point (A) can be obtained by integrating equation (2) along any path from a reference state to that point, i.e.,

$$\phi(A) = gz + \int \frac{dp}{\rho} + C$$

where C is a constant of integration determined by conditions at the reference state. (For a modified derivation see Nelson, 1966.)

Flow of fluids in which potential varies with volume of dissolved solids can be treated in terms of equivalent fresh water potential. For an example of such a treatment see Cooper, et al., (1964).

In the study of flow of ground water, analyses have been directed along two major paths: unsteady and usually horizontal flow in aquifers and confining layers by employment of the Theis solution, or an extension of it, to the unsteady flow equation (Theis, 1935), (DeWeist, 1965, Chap. 6), and steady state flow through large cross sections of porous media by employment of one or more solutions of the LaPlace equation. In the former case a determination of the hydraulic characteristics of an aquifer has often been the major objective. In the latter case the objective has usually been an understanding of patterns of ground-water flow under varying conditions of topography, geology, and depth and width of flow systems. It is the latter case which is of interest with respect to the formation of evaporite deposits.

By examining the nature of the force potential under certain boundary conditions Hubbert (1940) first derived the idealized pattern of flow of ground water adjacent to a valley containing a stream, part of whose flow is contributed by ground water. This idealized flow system is portrayed in Figure 1. Although Hubbert assumed that water would leave the flow system via streams, it may be removed by evapotranspiration. Furthermore, empirical evidence has shown that local discharge areas may be broad and cover a large area (Domenico, et al., 1964, Feth, et al., 1962).

In order to theoretically analyze interbasin flow, Toth (1963) derived the two-dimensional fluid potential distribution within a drainage basin containing several smaller tributary drainage basins. Toth considered the homogeneous, isotropic case with impermeable boundaries beneath the recharge and discharge divides and along the bottom of the flow system. Figure 2 portrays the local, intermediate and regional flow systems indicated by the mathematical model.

Support for the existence of intermediate and regional flow systems containing water of low quality has been supplied by Clayton, et al., (1966) utilizing a line of evidence not incorporating distribution of potential. By comparing hydrogen isotope ratios and oxygen isotope ratios for samples of deep, oil field brines from the Illinois, Michigan, Alberta and Gulf Coast Basins with similar ratios for standard mean ocean water, the investigators concluded, among other things, that water in the brines is predominantly of local meteoric origin. This conclusion implies that the meteoric water in the brines must have entered some type of gravity ground-water flow system at a recharge point, then moved through the flow system to the sampling point. In route, by one process or another, the water became saline.

Freeze and Witherspoon (1967) have extended the study of potential distributions to several cases of anisotropy. They have determined the distribution of potential for several combinations of permeability and water table shape. Although variations in permeability within a porous medium do cause flow patterns to differ in detail from the patterns for the homogeneous, isotropic case, the general patterns of flow are similar. The major differences are in flow line deflections and in flow line spacing.

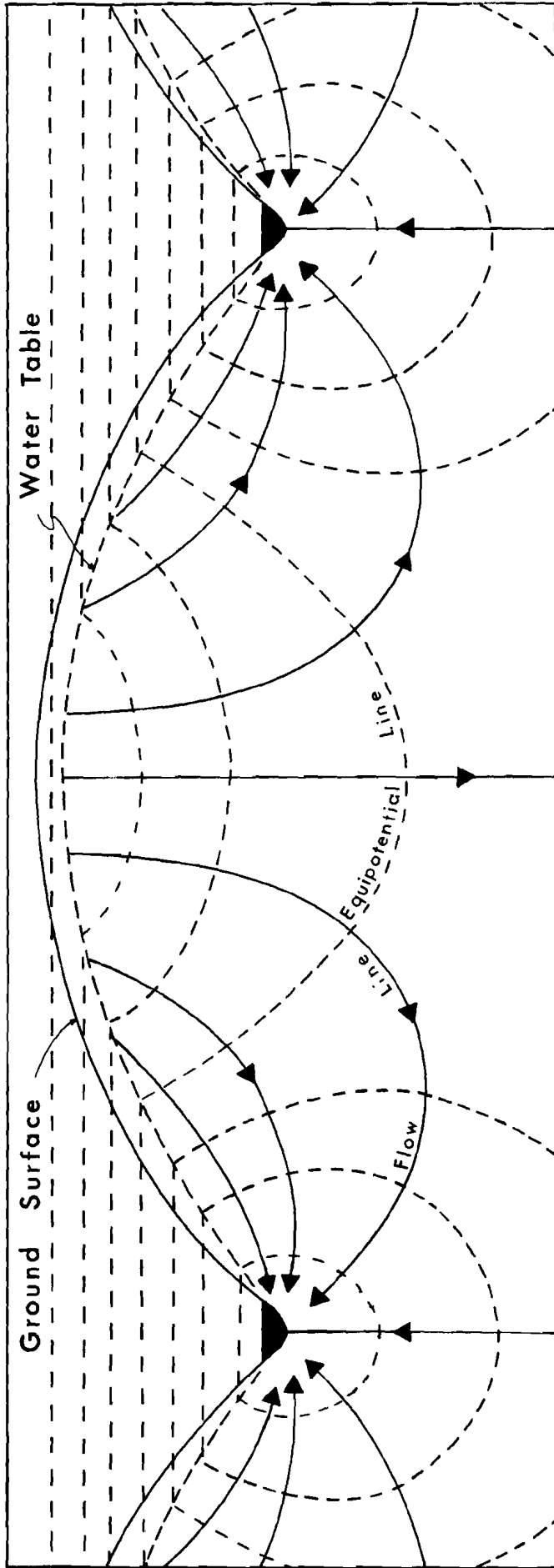
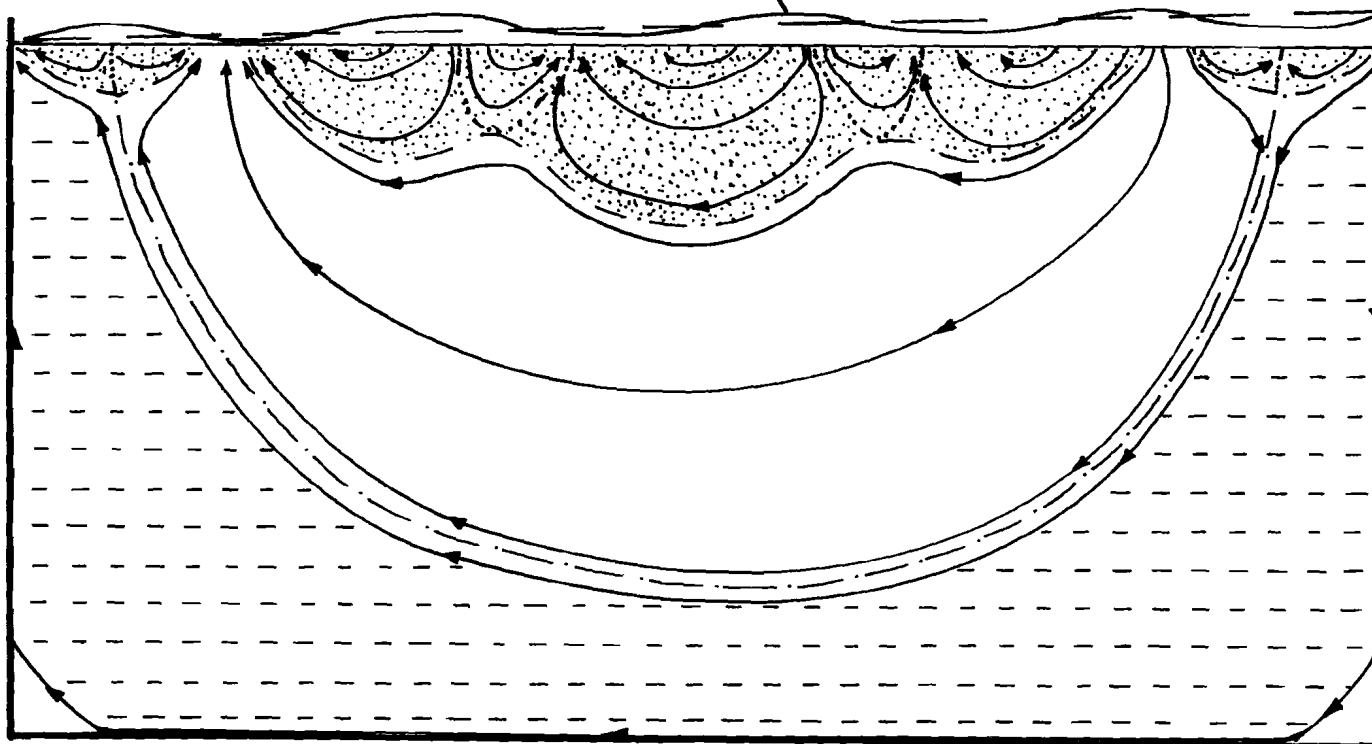



Fig. 1. Approximate flow pattern in uniformly permeable material between the sources distributed over the air-water interface and the valley sinks. (after Hubbert, 1940)


$s = 20000$ feet
 $z_0 = 10000$ feet
 $c' = 0.02$
 $a = 50$ feet

BOUNDARY BETWEEN FLOW SYSTEMS OF DIFFERENT ORDER — · — · —
 BOUNDARY BETWEEN FLOW SYSTEMS OF SIMILAR ORDER · · · · ·
 LINE OF FLOW —————>

POTENTIAL DISTRIBUTION ON THE SURFACE OF THE THEORETICAL FLOW REGION




 LOCAL SYSTEM OF
 GROUNDWATER FLOW


 INTERMEDIATE SYSTEM OF
 GROUNDWATER FLOW

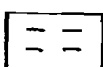

 REGIONAL SYSTEM OF
 GROUNDWATER FLOW

Figure 2. Theoretical flow patterns and boundaries between different flow systems. (After Toth, 1963)

These theoretical treatments have been checked by water level data from several localities (Williams, 1966; Toth, 1966; Domenico, et al., 1964; Meyboom, 1966, 1967).

WATER QUALITY AND THE FLOW OF GROUND WATER

As indicated earlier, one would expect total dissolved solids in ground water to increase with flow path length and decrease with increasing velocity. That this relation does hold has been documented by Toth (1966) near Olds, Alberta, and by Back (1966) in the Atlantic Coastal Plain. Seaber (1965) and Maderak (1964) have established that ground water decreases in quality with increased distance from a recharge area. Chebotarev (1955) has established a "cycle of concentration" which lists the ions to be anticipated in any given portion of a local flow system. It is also obvious that velocity and flow path length are not the only factors controlling ground-water quality; the solubility and composition of the material through which ground water moves must also play a significant role. In many cases it is impossible to separate the effect of long flow paths and slow flow from that of rock solubility. Also, in some flow systems, membrane effects by layers of low permeability may cause dissolved solids to become concentrated in ground waters (Bredehoeft, et al., 1962). Regardless of source of ions in solution, however, one would expect regional, and some local, flow system discharge zones to be the site of emergence of salts.

That ground-water flow systems do in fact discharge large volumes of salts to the surface can be documented in many localities. Baker, et al., (1964), for instance, concluded that the average daily chloride load of Salt Croton Creek (Texas) is 480 tons. Of the 480 tons, 330 tons is contributed by base flow from a ground-water flow system; base flow ranges from 0.5 to 2 cubic feet per second. The investigators note that salt springs and salt seeps discharge ground water in the Croton Creek basin and some salt flats occur. Similar saline discharge zones also occur in the Salt Croton Creek basin. West, et al., (1965) estimate that about 200 gpm (gallons per minute) of water discharging from a ground-water flow system into a 3-mile reach of the Pecos River contribute 420 tons of dissolved minerals to that reach of the river daily. Of the 420 tons of dissolved material about 370 tons is sodium chloride. In this case one would suspect that aquifers high in sodium chloride content are located in the flow system. Hood (1963) describes the relation between fresh and saline waters in the flow of ground water in the Roswell basin, New Mexico. Of particular interest is the effect of pumping on the saline portion of the flow system. Removal of water from the shallow, fresher flow zones causes the deeper, saline waters to assume an upward component of motion and salt water encroachment into the fresher flow system occurs. Hood and Kister (1962) list several other areas in New Mexico where saline water is discharged into streams or lakes. The nature of dissolved solids varies significantly from location to location. In addition they point out that salinity of streams is lowest during periods of high flow. During high flow much of the stream flow is surface runoff which contains significantly fewer dissolved solids than does water discharged from ground-water flow systems.

Pistrang and Kunkel (1964) have examined the hydrogeology of the Furnace Creek Wash area, located on the east flank of Death Valley. Two observations are of interest here. The spring waters vary in quality from less than 144 ppm (parts per million) in TDS (total dissolved solids) for one group to greater than 22,200 ppm for a second group. Because springs are emerging flow lines and different flow lines

emerge in different springs, this variation in TDS over a relatively small area (about 48 sq. miles) illustrates the influence of flow path length and (or) route on water quality. The investigators also note that an undetermined amount of underflow passes westward beneath the area investigated toward the center of Death Valley. This observation indicates that the springs at the Furnace Creek Wash area are local ground-water discharge zones and that the discharge zone for the larger flow systems lies nearer the center of Death Valley. Because discharge from Death Valley can occur only through evapotranspiration it follows that the salts transported by these flow systems are accumulating as evaporite minerals in the near-surface deposits of Death Valley.

In a detailed study of the Weber Delta District, which covers an area of about 400 square miles between the Wasatch Range and the east shore of Great Salt Lake, Feth, et al., (1966) note that artesian conditions, some flowing wells and springs occur in the area. These conditions indicate that ground water at some depths beneath some portions of the area has an upward directed, vertical component of velocity. The authors also note that recharge occurs in portions of the area, therefore, a complicated combination of local and regional flow systems is apparently operative. Nevertheless, because the basin of Great Salt Lake is closed and because it is the lowest point in the immediate vicinity, any ground water entering the Weber area and not discharged locally must enter a flow system which eventually discharges into Great Salt Lake or a stream leading to it. Although the superimposed piezometric surface maps presented by Feth, et al., (1966, plate 9) are not of sufficient detail to delineate all the local flow systems (a ground-water mound indicating recharge from the Weber River is shown) they do indicate what one would expect on the basis of Toth's model; the fluid potential gradient between the Wasatch Range and the east side of Great Salt Lake is in general directed toward the lake. In other words, Great Salt Lake is a discharge zone for at least an intermediate flow system and probably a regional flow system for which the Wasatch Range is the major recharge area. Further evidence for this conclusion is presented by the existence of flowing wells in the Weber district which indicate an increase of fluid potential with depth. With respect to volume of ground water discharging into Great Salt Lake, Peck (1954) has estimated that 360,000 acre feet of ground water is contributed to the lake annually. Feth, et al., (1966) also present data which show that ground water varies considerably in quality within the basin. Ground water of the calcium or magnesium chloride, sodium bicarbonate, sodium chloride, and calcium magnesium bicarbonate types occur at different localities. These variations can logically be attributed to variations in flow path length and route.

In an earlier study Feth and Brown (1962) attempted to estimate the rate of upward discharge from the ground-water flow system to the mudflats of Great Salt Lake by using the rate of salt crust accumulation supplied by the discharging brines. The discharging brines contained 93,000 ppm or about 126.5 tons per acre foot of total dissolved solids. The investigators calculated an evaporation discharge of 2500 acre feet of water from 60,000 acres of barren land during the frost free season. For a salt content of 126.5 tons per acre foot these figures indicate a minimum annual upwelling of 316,250 tons of salt through the 60,000 acres of barren land, or about 5.3 tons per acre. That the actual figure for the annual quantity of salts brought to the surface is greater than 5.3 tons per acre is ascertained by the fact that during

the cold season discharging brines gradually flow lakeward without the formation of a salt crust.

For additional studies illustrating the discharge of saline waters from ground-water flow systems into surface water bodies the reader may wish to refer to articles by Kister and Mundorf (1963) and Jordan, et al., (1964). The articles mentioned here by no means represent a complete list.

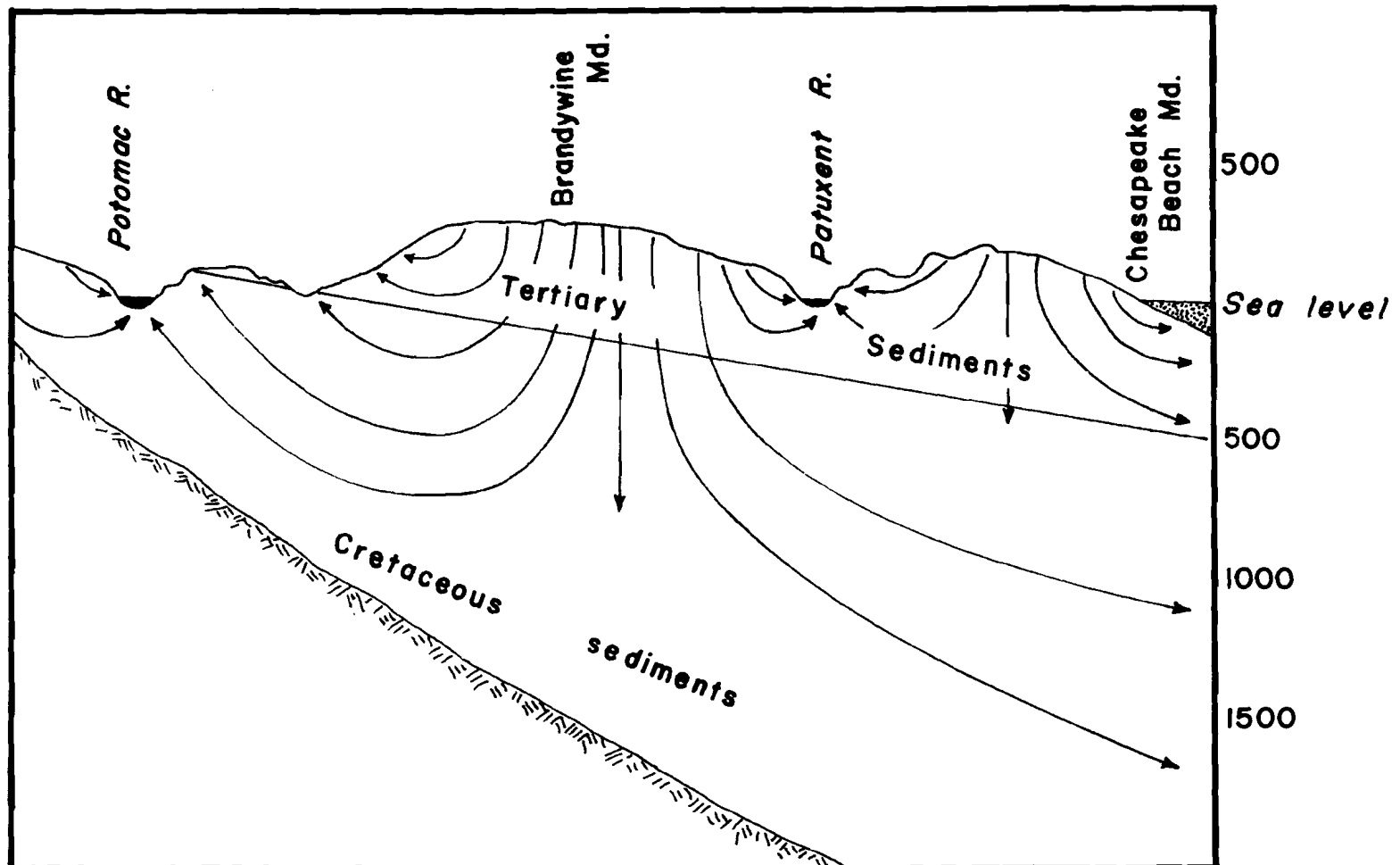
Discussion to this point has illustrated that ground-water flow systems may discharge sufficient quantities of salts to form evaporite deposits, that the ground-water flow lines emerging in saline discharge zones need not have intersected rocks with a high salt content, that the identity of the ions constituting the total dissolved solids in ground water can vary over a wide range, and that not all saline discharge zones of ground-water flow systems are the site of accumulation of extensive evaporites. To accomplish the latter end we need the existence of appropriate climatic and physiographic conditions, i. e., an arid closed basin, such as Great Salt Lake Basin, wherein discharge from the ground-water flow system can be evaporated leaving salts behind to accumulate. Whether the salts are contributed to such a basin directly by ground-water flow systems or indirectly by discharge of ground water into streams which flow into such a basin is immaterial. Both mechanisms are probably operative in many cases. These observations serve as explanations for the accumulations for most non-marine evaporites.

We now come to marine evaporites and their relation to ground-water flow systems. The literature on this subject is, however, much less extensive. The previously mentioned work of Toth (1963) and of Clayton, et al., (1966) indicates that ground waters with high total dissolved solids, even brines, must be viewed as dynamic systems wherein water moves along an energy gradient from recharge area to discharge area. Because few wells are finished in the saline portion of a flow system, little information on potential distribution is available and all too often such waters are viewed as static.

Given the assumption of brines in motion it follows that some discharge area must exist for any given system. It is not difficult to move from this notion to the notion of discharge of ground waters with high total dissolved solids into shallow seas. Near a coastline where one would expect shallow and regional flow systems to meet, flow is often complicated by the existence of a near-surface density interface between the shallower, fresher, ground-water flow system and the deeper, more saline, intermediate or regional flow systems. On the basis of previous comments it seems important that this zone should be considered as a boundary between different scale flow systems as well as a water quality boundary. The location in space of this interface often migrates with changes in potential in the shallower, fresher flow system relative to the level of the adjacent sea. Because of the concentration gradient within the zone of diffusion a local, near shore, flow cell, for which the sea acts both as a recharge area and a discharge area, may even be superimposed on the regional flow system. Such a case has been empirically demonstrated by Kohout (1960) and treated theoretically by Cooper, et al., (1964) for the assumption of horizontal flow in an aquifer cropping out at the sea coast. The circulation within the shallow cell is caused by the concentration gradient across the zone of diffusion between the fresh

and saline ground waters. Such flow cells may allow saline waters to move from the sea at one location and back into the sea at a nearer shore location. In locations where no zone of diffusion occurs, or at some distance from this zone if it does exist, the work of Toth (1963) and of Clayton, et al., (1966) suggests that saline ground water should move upward toward the sea floor. Some empirical data support this concept. In the Savannah, Georgia, area, Counts and Donsky (1963) note that according to water levels in the only well deep enough to penetrate the material beneath the principal artesian aquifer, saline water is slowly leaking upward into the principal aquifer from the underlying sediments. Nearer the coast the aquifer itself becomes saline. Because upward leakage implies an increase of potential with depth it follows that the poor quality water beneath the principal artesian aquifer is probably near the discharge zone for a more regional flow system. Further evidence that this discharge zone is near the mouth of the Savannah River is supplied by the seaward existence of saline water in the principal aquifer. Referral to Figure 2 indicates that the regional, intermediate and local flow systems meet at the major discharge zone for the entire flow system which in this case would be the sea. Kohout (1960) notes at least one well in the saline portion of the Biscayne aquifer near Miami, Florida, in which the potential is always greater than the potential at sea level. Here also then ground water moves toward the sea floor from the deeper zones of higher potential in the regional flow system. As an illustration of this concept, a generalized sketch of the seaward flow of ground water for the northern part of the Atlantic Coastal Plain as interpreted by Back (1960) is presented in Figure 3.

Regardless of whether a zone of diffusion exists, given the proper climatic and physiographic conditions, these observations support the conclusion that evaporites may form as a result of precipitation of dissolved solids contributed to a restricted embayment by ground-water flow systems. It is interesting that essentially the same climatic and physiographic conditions required by the classical theory of evaporite formation are also required for the formation of evaporites by discharging ground-water flow systems. In the latter case, however, the sill or reef at the mouth of the restricted embayment prevents the seaward escape of saline, discharging ground waters. As the discharging ground water evaporates, the salts are left behind. In the classical theory the sill or reef acts as a trap for marine waters brought into an embayment at high tide or during high waves or as the result of low water level caused by a high evaporation rate in the embayment. The writer does not wish to say that the classical theory is nowhere operative. It is undoubtedly operative today at Kara Bogaz, for example. On the other hand it does seem advisable to consider ground water as a source for many marine as well as non-marine evaporites. Discharge of poor quality water from regional ground-water flow systems into the Black Sea and the Baltic Sea may well be a partial source for the brackish water currents which Borchert and Muir (1964, p. 15) note to be flowing into the Sea of Marmara and the North Sea, respectively. A similar situation may partially explain the saline currents from the Mediterranean into the Atlantic. Ground water discharge may also be the cause of high salinity in some of the salt marshes described by Chapman (1960). Data collected by the writer indicate that weathering of apatite in basalts adjacent to Lake Coeur d'Alene, Idaho, is contributing significant quantities of phosphate to the ground-water flow system discharging into that lake. Therefore, under appropriate climatic and physiographic conditions ground-water flow may act as a transport medium for phosphates to sites of accumulation.



(11)

Figure 3. Diagrammatic cross-section through southern Maryland showing the lines of ground-water flow. (After Back, 1960)

Differences in composition of waters discharging from different ground-water flow systems may serve as an explanation for differences in evaporite minerals found in different deposits. If, for instance, discharging ground water is predominantly of the sodium chloride type, one might expect deposits of halite to form. Because the composition of ground water can differ significantly from that of sea water an explanation is provided for the occurrence in evaporite deposits of compounds not common to sea water. Cyclic variations within a given deposit may be explained by the cyclic addition of dissolved and suspended solids from surface water sources to the more consistent quality of discharge from ground-water flow systems.

In this paper no attempt has been made to distinguish between the mineralogy of evaporite deposits produced by ground-water flow systems and the mineralogy of deposits formed via the classical lagunal process. Without considerable field work it would indeed be difficult to determine which process was operative during the formation of a given deposit. Nevertheless, a comparison of the mineralogies of the two types of deposits is the next logical step and the writer is in the process of initiating such an investigation.

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