Evaporite Deposits of Continental Margins

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ABSTRACT

Water budget constraints indicate that evaporite basin barriers must lie very close to or above world ocean level. These requirements are met most commonly by continental crustal areas or more rarely by oceanic islands. For these reasons evaporites are only formed within intracontinental basins or against continental margins, either in juvenile actively spreading areas such as the Miocene-Pliocene Red Sea and Albian South Atlantic, or in older oceans where continents are converging such as the Messinian Mediterranean. Continental margin evaporites may be deposited on continental and oceanic crust and may reach thicknesses in excess of 5 km. The geological significance of continental margin evaporites is briefly discussed.

INTRODUCTION

The water budget of a basin in which evaporite minerals are to be formed must be one of net evaporation, the total loss of water vapour across the brine-air interface being greater than the sum of all the opposing, diluting factors (precipitation, surface and sub-surface run-off into the basin, sea water influx and condensation of atmospheric water vapour under conditions of high relative humidity directly across the brine-air interface). The most advantageous combination of conditions favouring high evaporation rates (high absolute temperatures, thermal contrast of water and air masses, low relative humidity and high wind speed) produces a maximum annual water loss rarely exceeding two meters. This maximum places a severe constraint on the amount of dilution influx which can be tolerated. Most basins of restricted water circulation, in those climatic areas where one might expect evaporites to be forming today, do not in fact display net evaporation because of excessive sea water influx and reflux. The extreme restriction of sea water influx which is required, in order to generate standing bodies of brine in potential marine evaporite basins, is evidenced today by the Mediterranean and Red Sea, neither of which is a brine basin, despite almost complete isolation from the world ocean. Thus the barriers to restrict sea water influx must be very nearly complete and must extend either above world ocean level or lie at extremely shallow depths below this level. It would seem that effective sills to evaporate basins will lie within a few meters of world ocean level, or at their deepest, a few tens of meters.

Almost all large evaporite deposits are dominated by calcium sulphate or sodium chloride minerals and are dominantly of marine origin. They were formed from the evaporation of sea water, and the barrier across which influxing sea water reached the basin lay very close to world ocean level. During those periods when the brine basin and world ocean were connected the brine-air interface of the evaporite basin lay essentially at or marginally below world ocean level. However, during periods of complete isolation, the brine-air interface in the evaporite basin could have lain at any depth between world ocean level and the floor of the basin, which in some situations may have lain several kilometers below world ocean level.

Effective physical barriers and sills defining evaporite basins and lying close to or above world ocean level are almost entirely composed of continental lithosphere. It is for this fundamental reason that evaporites are almost wholly associated with continental areas, lying either in intracontinental basins or along continental margins. Yet the source of the evaporites, the sea water of the oceans, largely overlies oceanic lithosphere. The amount of oceanic lithosphere to be found close to or above world ocean level is confined to isolated oceanic islands; although very restricted in their occurrence, these oceanic islands, in certain temporal settings, play an important role in the formation of barriers or sills to evaporate basins.

GEOLOGICAL SETTING OF MAJOR EVAPORITE DEPOSITS

The major evaporite deposits of the world and their associated sediments may be described in plate tectonic terms as follows:

A. Those formed on a single lithospheric plate atop continental lithosphere; the evaporites of intracontinental, intracratonic or interior basins.

B. Those formed between two lithospheric plates, either

   1. Converging; possibly a not very important category.
   2. Diverging: the most important continental margin evaporite deposits.

A. Evaporites of the interior basin environment

The sediments, including evaporites, of interior basins are deposited atop continental lithosphere which has subsided slightly below world ocean level. Many of these interior basins contain evaporites (for example, the Williston, Delaware and Michigan basins of the U.S.; Marañon and Amazon basins of Brazil). These evaporite deposits are areally extensive but typically thin, being only tens or hundreds of meters and rarely more than one kilometer in thickness. Calcium sulphate minerals are commonly over represented relative to halite in interior basin evaporites. These basins are typically long lived, with active histories of several hundred million years and show evidence of irregular subsidence averaging about 10 mm per thousand years; a total sediment accumulation of 2–6 km is common at the basin depocenter. Our knowledge of the stratigraphy of several interior basins is fairly complete but our understanding of the factors controlling their rates and variations of subsidence, or even "why they are developed where they are," is poor or non-existent. The evaporites within interior basins are commonly of sabkha facies but those of standing body of brine facies give us evidence that at these times the rims of the basin extended close to or above world ocean level.

The Permian evaporites of northwest Europe and the Devonian evaporites of western Canada do not readily fall into the simple interior basin category, but nevertheless were similarly deposited within a craton atop subsided continental lithosphere. It is these evaporite deposits of cratonic settings which are best known and which are generally thought of as the major evaporite deposits of the world. This conclusion is in need of modification in the light of more recent findings of extensive, thick continental margin evaporite deposits.

B. 1. Evaporites of the converging plate margin environment

In certain situations, when oceanic lithosphere is consumed between two converging plates, the continental lithosphere areas of the two plates will eventually come into contact. Irregularities of the two continental margins may enclose a relict area of ancient ocean floor and in this way a restricted evaporite basin may be formed. As a gross oversimplification we may consider the relict Tethyan Ocean, the present day Mediterranean Sea, to have had such an origin. During Messinian times evaporites were extensively deposited throughout the basin, on continental and oceanic lithosphere, at depths as much as three kilometers below present day world ocean level (Ryan et al., 1973). I have made a detailed study of several samples of these evaporitic sediments from cores collected at 2–3 km depth below sea level during Leg 13 of the Deep Sea Drilling Project; some of the anhydrite rocks have a nodular structure, with a felted lath texture, identical to anhydrites I have described from the sabkha environments of the Trucial Coast, Persian Gulf (Kinsman, 1966). Robert Park (personal communication) has also recognised filamentous organic structures, very similar to some present day blue green algal filaments, in layered sediments intercalated with the anhydrite and gypsum, which is again suggestive of very shallow water or intermittent exposure conditions. Somewhat similar conclusions have been reached by several authors reporting in the Leg 13 volume (Ryan et al., 1973). The most likely interpretation is that when isolation of the Mediterranean from the world ocean was complete, net evaporation brought about a lowering of the brine-air interface several kilometers below world ocean level (Ryan et al., 1973). The importance of the instability of the brine-air interface (in contrast to the brine-sediment interface) and the rapidity with which these drastic changes in level can occur are particularly noteworthy and place the problem of deep-water vs. shallow-water evaporites and associated tectonic problems in a new perspective.

The geological importance of the converging interplate evaporite basin is uncertain, such basins probably not forming very frequently. In addition the evaporite sediments are likely to be destroyed relatively soon after deposition as further plate consumption ensues. However, this is one geological setting where evaporites can definitely be deposited on oceanic lithosphere, at depths several kilometers below world ocean level. The evaporite basin, although deep, in terms of depth of the sediment-brine interface below world ocean level, need not necessarily accumulate all its evaporites in a deep-brine environment, because of the probability of the brine-air interface lying well below world ocean level for much of the time.

B. 2. Evaporites of the diverging plate margin environment

These are the evaporite deposits of continental rift valleys and those formed in juvenile actively spreading oceans, following rupture of a continental plate. Such deposits typically occur as linear belts along continental margins or within rift basins where an earlier phase of continental rifting subsequently aborted. These evaporite deposits are usually several kilometers in thickness (in excess of 5 km in some instances) and are dominantly halitic. This category is by far the most important type of continental margin evaporite and to understand the formation of these deposits we need to discuss the tectonic and sedimentary history of rifted continental margins. I have done this in some detail in an earlier publication (Kinsman, 1973) and much of the background justification for the following statements is to be found in this paper. Rifted continental margins of Triassic to Quaternary age border nearly the entire North and South Atlantic Ocean, much of the Indian Ocean, the Red Sea and possibly much of the Arctic Ocean and intracontinental rift valleys are well developed in East Africa; I have used the known geological history of these areas to synthesize the following model.

In the proposed model of continental lithospheric rifting the initial uplift and post-rifting subsidence are considered to be directly related to sub-crustal lithospheric temperature and density distributions; the model is analogous to that proposed for sea floor rifting and subsidence. During all stages isostatic compensation is maintained. In Figure 1 are shown the basic structure, rock densities and surface elevations of isostatically compensated columns of continental and oceanic lithosphere, the subcrustal density being that typical for 100 m.y. old lithosphere. Early domal uplifts of the continent over deep mantle plumes are followed by interplume uplifts as a linear rupture zone is developed; the uplift is brought about by thermal piercement of the subcrustal lithosphere, with a resulting decrease in density, and continental elevations of 1–2 km. above ocean level typically result. Rift valleys are formed between the divergently rifting continental margins and the elevated areas are erosionally thinned. The eroded, elevated areas, several hundred kilometers in width, later subside below sea level to form the continental terrace (Fig. 2). Along transcurrently rifted continental margins (Fig. 3) little or no thermal piercement of the subcrustal lithosphere occurs during rifting, consequently there is little or no uplift and little or no associated erosional thinning. A zone of major intracrustal attenuation 30–40 km. wide along transcurrent margins and 60–80 km. wide along divergently rifted margins marks the outer edge of the continent. Morphologically this zone comprises the 3–4 km. high continental slope, which early in its history exists partly above sea level (Fig. 4); as the underlying lithosphere cools, the continental slope slowly subsides below sea level. The distribution of crustal thicknesses across these two continental margin zones (the zone of attenuation and the zone of erosional thinning), is reflected later in the thickness and horizontal extent of the sediments which accumulate.

Evaporites are commonly formed in two environments during the early evolutionary stages of a new ocean. The

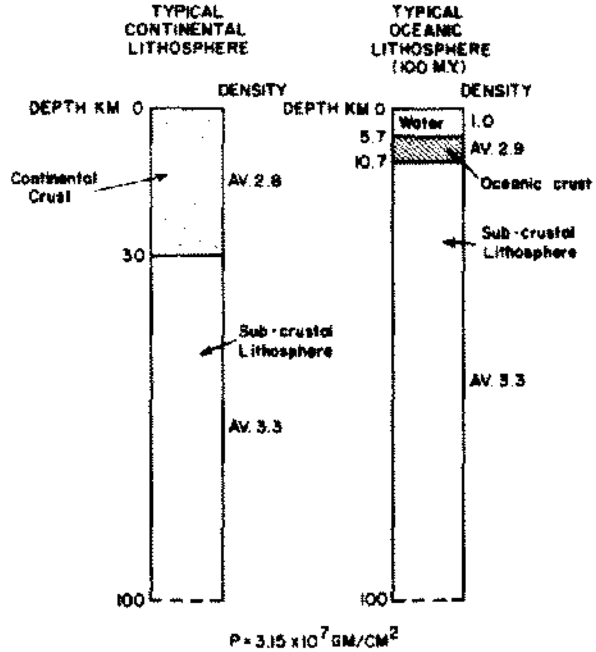

Figure 1. Lithospheric columns beneath typical continental and oceanic crust. The oceanic column is for ocean floor about 100 m.y. in age.

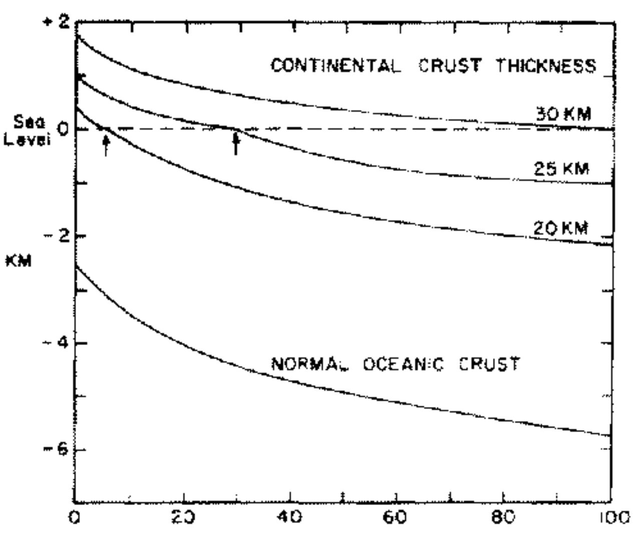

Figure 2. Subsidence profiles of continental and oceanic lithospheric columns. The normal oceanic crust curve is modified from Sclater and Francheteau (1970); the continental crustal subsidence curves were calculated assuming sub-crustal lithospheric densities at any time to be the same as those of sub oceanic crustal lithosphere of the same age. The arrows marking nick points on the 20 and 25 km. thick continental crust subsidence curves mark the post-rifting time at which these columns reach sea level and begin to be loaded with sea water.

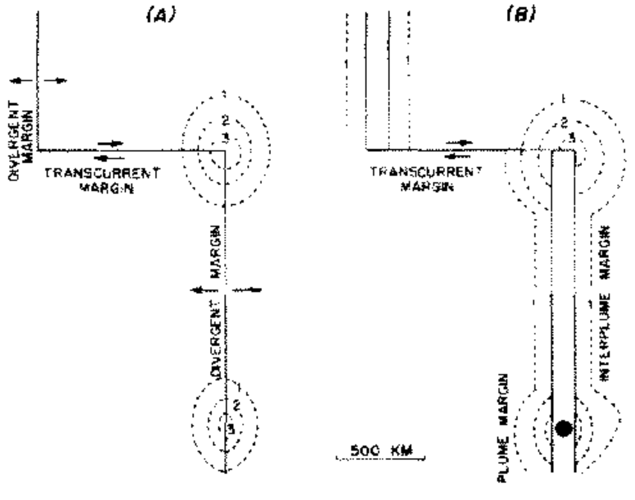

Figure 3A. Earliest continental rifting stage, with lengths of divergent and transcurrent margin indicated. Two plume sites are shown where continental crust has been updomed, elevations being marked in km. above sea level. Domes are cut by rift valleys.

Figure 3B. Later rifting period, interplume divergent margins now uplifted in addition to plume divergent margins. Transcurrent margins remain low. New ocean floor stippled; oceanic island over plume site in black, representing a potential "stopper" at the lower end of the juvenile ocean, in which evaporites may thus be deposited.

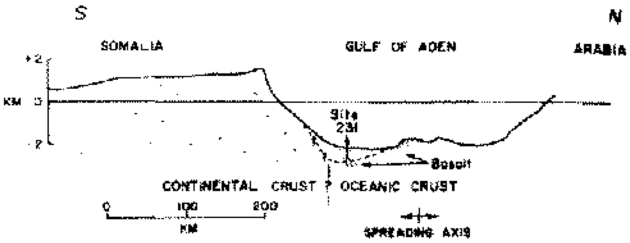

Figure 4. Topographic-bathymetric profile at 48° 10′ East extending from Somalia plate on the South across the Gulf of Aden, to the Arabian plate on the North. Note the updoming along the continental margin and the steep northward face of the Somalia continental margin, both above and below sea level (this 4 km. slope will be the submarine continental slope in 40-50 m.y.). No continental shelf is presently developed; in 40-50 m.y. the Somalia plateau will become the submerged continental shelf. The axis of sea floor spreading and the continental-oceanic crust boundary are taken from Laughton et al., (1970). Glomar Challenger, Leg 24, Deep Sea Drilling Project Site 231 is also marked; basalt was penetrated at this site beneath 570 m of hemi-pelagic sediments. Zone of attenuation/or drastic continental crustal thinning is shown to be 60-80 km. broad. Note the shape of the uplifted margin; a future basement ridge is already developed at the outer continental terrace—upper continental slope position. (Kinsman, in press).

first environment is the intracontinental rift valley, where the rift valley intersects an older continental margin; sea water ingress is permitted when the axial block subsides below world ocean level. Barriers across the elongate rift basin may be of volcanic origin, as in the Pleistocene-Recent Danakil Basin of Ethiopia, or comprise transverse fault blocks across the rift. Examples of thick evaporite deposits in intracontinental rift valleys related to the rupture of continental plates are the Lower Cretaceous Sergipe-Alagoas Basin evaporites of Brazil and possibly analogous deposits of the Gabon; the Pliocene-Pleistocene Dead Sea evaporites (of enormous thickness, possibly in excess of 7 km.); and the Pleistocene-Recent Danakil Basin evaporites of Ethiopia.

The second major evaporite environment is the juvenile ocean itself and its enclosing rifted continental margins. The evaporites may be deposited on newly formed oceanic crust and on the attenuated continental margin crust in the lower continental slope position. The evaporite basin barriers are the elevated margins of the rifted continent along the length of the basin and transverse barriers may comprise continental fragments faulted off the main continental margin, continental segments where rifting is transcurrent, or volcanic islands over deep mantle plume sites.

For example during the opening of the South Atlantic rifting along the Guinea Coast was largely transcurrent and the juvenile ocean was blocked at its northern end. At its southern end the Tristan da Cunha plume site probably formed an oceanic island represented today by the landward ends of the Rio Grande Rise and Walvis Ridge. This oceanic island effectively restricted sea water circulation into the ocean to the north, net evaporation prevailed and evaporites were deposited, both against the attenuated continental margin itself and on the first formed ocean floor. The evaporites of the African margin immediately north of the Walvis Ridge are calcium sulphate deposits, whereas those farther north along the margin are dominated by halite; this is just the pattern to be expected if influx of sea water was over the Rio Grande–Walvis Barrier. The age of the evaporites is known to be Aptian in the marginal basins. The width of the zone of diapirs of possible halite along the South Atlantic margins (Leyden et al, 1971, 1972), which are located on the oldest ocean floor and seaward attenuated continental margin area, is about 200 km. which at a horizontal spreading rate of 2 cm/yr suggests a time period for salt deposition of around 10 m.y. The ability of an oceanic island at a plume site to act as an effective stopper to restrict sea water circulation into a juvenile ocean is obvioulsy limited because of time-dependent subsidence as cooling proceeds and the South Atlantic suggests 10 m.y. as the effective lifetime of the Tristan da Cunha barrier.

In the Red Sea the exact form of the Gulf of Suez region, which was the barrier over which sea water reached the evaporite basin, is unknown. However, the present Red Sea configuration at its southern end suggests another effective barrier to sea water entry into juvenile ocean basins, in the form of continental fragments, such as the Danakil Alps. The size of these fragments and the horizontal spreading rate will determine the life span of these evaporite basin barriers. In general the probability of evaporite formation in a juvenile rifted ocean decreases with time. Evaporite formation is most likely to occur during the initial 5–10 m.y. The widespread occurrence of rifted continental margin evaporites, many of them several kilometers in thickness, points to the frequency with which effective sea water circulation barriers are developed during the juvenile ocean stage of rifting. The thickness of some of these rift ocean evaporites is to be noted; in the western part of the southern Red Sea (Hutchinson and Engels, 1972) a profile at right angles to the axial rift shows 3–4 km of evaporites with intercalated basalts just west of the present axial rift and 7–8 km of evaporites near the present Red Sea shoreline. The landward thickening of sediment columns is the pattern predicted for ocean floor, the loading capacity of which increases with increasing age. These evaporite thicknesses are relatively close to those predicted for halite loading of oceanic crust (Fig. 5). To date, there is no definite evidence to support suggestions that the Red Sea evaporites are underlain by anything other than basaltic oceanic crust and certainly the evaporite thickness distributions would support this.

If evaporite deposits are so commonly formed against attenuated continental margins and on the adjacent oldest ocean floor, then they should be deeply buried during the later history of a trailing margin, as sediment eroded from the continent accumulates above them. The evaporites are likely to be buried at the base of a pile of sediment which may be up to 16–17 km in thickness. The occurrence of such evaporites, flooring eugeosynclinal sediment piles, may have possible structural importance during the later compressive history of the margin. A probable example of a continental margin evaporite deposit, deeply buried beneath a very thick sediment pile, is the Jurassic Louan Salt which underlies the Mississippi Delta.

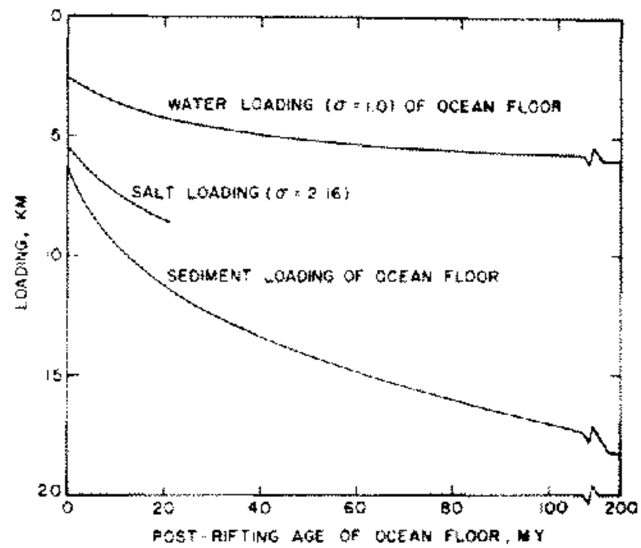

Figure 5. Showing increase in maximum sediment loading of ocean floor with post rifting time elapse, based on ocean floor profile of Figure 2 and sediment density date of Kinsman (in press.). The water loaded profile from Figure 2 is included for comparison. The maximum thickness of halite deposited on ocean floor during the first 20 m.y. of post rifting history is also shown.

REFERENCES

Hutchinson, R. W., Engels, G. G., 1972. Tectonic evolution in the southern Red Sea and its possible significance to older rifted continental margins. *Geol. Soc. Amer. Bull.* 83:2989–3002.

Kinsman, D. J. J., 1966. Gypsum and Anhydrite of Recent age, Trucial Coast, Persian Gulf, p. 302–326. *In: Proceedings Second Salt Symposium,* Ed. J. L. Rau, Northern Ohio Geol. Soc.

Kinsman, D. J. J., 1973. Rift valley basins and sedimentary history of trailing continental margins. In: *Petroleum and Global Tectonics; Hedberg Volume.* Ed. A. G. Fischer, S. Judson, Princeton University Press.

Kinsman, D. J. J. (1974, in press). Gulf of Aden; summary of Leg 24 drilling results. *In:* R. L. Fisher, E. Bunce, D. J. J. Kinsman (and others), *Leg 24, Initial Reports of the Deep Sea Drilling Project,* National Science Foundation.

Laughton, A. S., Whitmarsh, R. B., Jones, M. T., 1970, The evolution of the Gulf of Aden. *Phil. Trans. Royal Soc. London.* 267:227–266.

Leyden, R., Ludwig, W. J., Ewing, M., 1971, Structure of continental margin off Punta del Este, Uruguay and Rio de Janeiro, Brazil. *Amer. Assoc. Petrol. Geol. Bull.* 55:2161–2173.

Leyden, R., Bryan, G., Ewing, M., 1972. Geophysical reconnaissance on African shelf: 2. Margin sediments from Gulf of Guinea to Walvis Ridge. *Amer. Assoc. Petrol. Geol. Bull.*, 56:682–693.

Ryan, W. B. F., (and others), 1973. *Initial Cruise Reports of the Deep Sea Drilling Project, Leg 13, Mediterranean.* 2 vols. National Science Foundation.

Sclater, J. G., Francheteau, J., 1970. The implication of terrestrial heat flow observations on current tectonic and geochemical models of the crust and upper mantle of the earth. *Geophys. Jour. Royal Astronom. Soc.*, 20:509–542.