Evaporite basins with emphasis on the Permian Zechstein

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Abstract. This paper looks first at the distribution of modern evaporite-depositing areas and then at the much more extensive evaporite basins of the past, many of which have no modern analogue in size or depositional diversity. The inability to compare all aspects of evaporites past and present, reflects a failing of modern arid geological settings. Problems inherent in many of the correlation assumptions used in sequence stratigraphic interpretations of evaporite basins will discuss. For interpretations the Zechstein was chosen because there is no modern day equivalent to a seawater-fed drawdown basin such as the Zechstein.

Distribution of modern evaporites

Modern bedded evaporite deposits typically accumulate in saline lake and mudflat environments within groundwater discharge regions in the arid and semi-arid deserts of the world. Coastal deposits of evaporites occur in areas fed by marine seepage into isolated coastal depressions or mudflats. Continental playa deposits, typically contain much larger areas of salts than coastal deposits, but still do not approach the aerial extent or thicknesses of their ancient counterparts. Evaporite salts also form as lakes precipitates and efflorescences in the cold polar deserts of Antarctica, but the amount of salt in these regions pales to insignificance when compared with settings closer to the equator.

Salt-accumulating desert playas form as discharge areas within endoheic (internal drainage) basins; where more water is leaving the basin via evaporation than is entering it as rainfall, surface, or subsurface inflow. They are found at different locations such as tectonic basins, wind deflation hollows, and abandoned fluvial valleys. The greatest present-day volumes of salts are to be found accumulating within continental tectonic basins located in the world's desert belts.
Present day settings are not direct analogues for many environments where larger and thicker evaporites accumulated in the past.

For example, to produce and accumulate primary bittern salts, such as polyhalite, epsomite, carnallite and kieserite, in a modern system requires a degree of aridity. An aridity so extreme that it is difficult to envision any modern settings reaching the bittern stage for long enough periods, to accumulate substantial thicknesses of bittern salts. The only modern area of substantial potash salt deposition occurs in the Qaidam Basin of western China. Even there, the potash comes mostly from the dissolution of earlier subcropping Plio-Miocene potash originally deposited as bedded lake evaporites in continental transform depressions. To understand how substantial thicknesses of evaporite accumulate as widespread potash and salt beds with huge lateral extents, one must study pre-Quaternary deposits.

Distribution of ancient evaporites

There is no Holocene proof of a desiccated ocean basin. Yet in the Late Miocene (Messinian) salinity crisis the deep depression on the Mediterranean floor were filled with 2-km-thick sequences of halite and gypsum in less than 300,000 years (Balearic Basin; Fig. 1).These Messinian evaporites were laid down on the floors of a chain of shallow saline seas. Some of which were 2,000 meters below ambient sea level, and at times a seafloor desert extended from Spain to Israel and from northern Italy to Libya (Hsu et al. 1973).

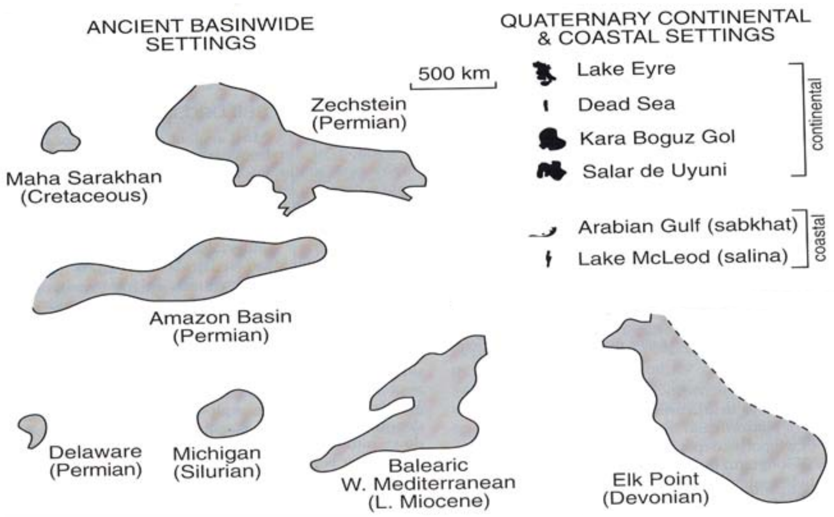

Fig.1. Comparison of aerial extent of Quaternary and ancient evaporite deposits (after James and Kendall 1992).

Compared with evaporite deposits of today, the wider extent, greater depositional and diagenetic diversity, and greater thickness of evaporites deposited on ancient platforms and across whole basins were due to three main factors:

- *Warmer worldwide climate* created wider latitudinal belts of evaporite deposition and preservation (Gordon 1975).
- *Huge shallow epeiric (epicontinental) seas* often formed large inland seaways in arid areas.
- *Set up of the correct tectonic and climatic conditions* for the formation of extensive evaporite deposits extending across whole depositional basins (e.g. saline giants such as the Zechstein strata of Northwest Europe) (Hsu et al. 1973).

Building blocks of ancient salt beds

Most ancient evaporite deposits have thicknesses and horizontal extents that are two to three orders of magnitude greater than those of Quaternary evaporites (Figure.2).

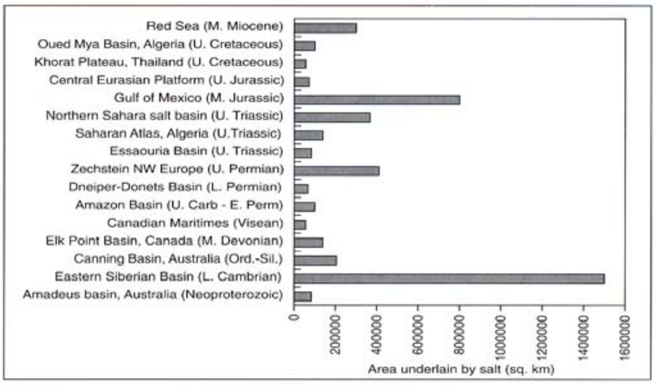

Fig.2. Plot of the areas underlain by salt in various significant ancient evaporite deposits (saline giants) (after Zharkov 1981)

Whatever the basin's regional or tectonic setting, the depositional signature of ancient evaporites can be broken down into three main blocks: mudflats, salterns and deepwater evaporites.

Evaporitic mudflat sediments form laterally extensive units (10-100m thick), composed of stacked, matrix-dominated cycles (1-5m thick). Salts were deposited as mosaics of dry and saline mudflats (sabkhas), which separated local brine-filled depressions (salinas) in both continental and marine settings. The vast extent of the mudflat and resulting high humidity in the overlying air greatly slowed the rate of evaporation.

Salterns were areas where widespread subaqueous shoalwater evaporite deposition took place in both, marine-fed and continental settings. Saltern describes extensive shallow-subaqueous evaporite beds that form continuous depositional units across hundreds of kilometers in the hypersaline parts of ancient evaporite lakes or seaways (Warren 1991). There are no modern counterparts in terms of scale or lo-

cation, although shallow-water evaporite textures can be observed in many salinas along the coasts of Australia and the Mediterranean.
Deepwater evaporites are usually only found in the deeper brine sections of basinwide evaporite successions and encompass slope and basin deposits (Fig. 3).

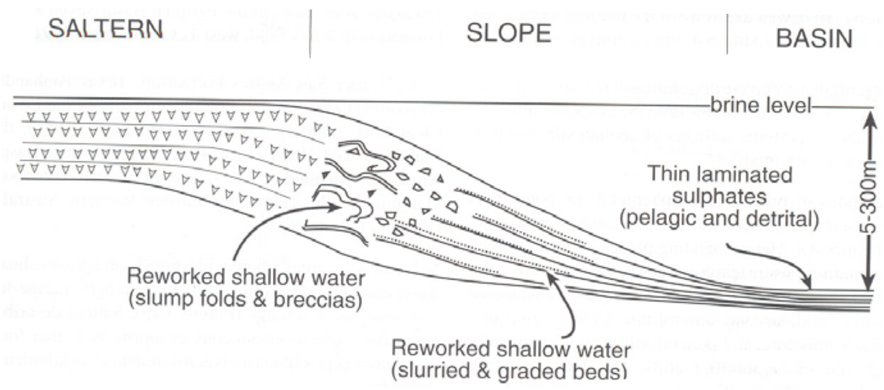

Fig.3. Depositional setting and characteristics of deep water evaporites (after Schlager and Bolz 1977)

Fine-grained laminites accumulated in the central deeper parts of the basin, separated and intercalated with less saline salts as well as carbonates or organic matter. These deepwater laminites accumulated in two main ways. Either as rainfall with crystallites forms in the brine column and then settling to the deep brine seafloor. Or they are the distal blasts of evaporite turbidites and debris flows that characterize the basin slope. Slope deposits are mechanically reworked from saltern or mudflat sediments and are characterized by textures typical of deeper water.
Studies of basin-centre and slope evaporites e.g. in the Permian of Delaware and Zechstein basins, and the Miocene of Red Sea rift indicate these ancient deepwater sequences can be interpreted in the same way that deposits are interpreted in carbonate and siliciclastic depositional systems (Richter-Bernburg 1986).
The best modern analogues for deep water evaporites are in the much smaller deepwater (30m) sodium-sulphate lakes of Canada and the finely-laminated bottom carbonates of the Northern basin in the Dead Sea (300m).

Evaporites: general scale models

Saltern and mudflat evaporites, along with slope and basin deposits, construct three interrelated settings in either continental or marine-fed basins: ***continental evaporites, platform evaporites, and basinwide evaporites***.
In this contribution only basinwide evaporites which will find our interest.

Basinwide evaporites

Basinwide evaporites are thick, basin-filling units (often >50m thick) of deepwater/shallow water evaporite deposits containing textural evidence of many different depositional settings, including mudflat, saltern, slope and basin.

Basinwide evaporites have no modern in scale and diversity and are often described as "saline giants". They constitute the sedimentary fill in many ancient evaporite basins, such as the Delaware Basin of west Texas, the Zechstein Basin of Europe and the Late Miocene Messinian Subbasins in the Mediterranean (Figure 4).

Fig.4. Map showing location and age of some of major basinwide evaporite deposits (after Kendall 1992).

Basinwide evaporites were deposited in three main settings (Fig. 5; Kendall 1992):

- Deep water-deep basin
- Shallow water-shallow basin
- Shallow water-deep basin

For the further run away of this contribution some short remarks only to the deep water-deep basin.

Deep water-deep basin evaporites have basins centers dominated by "deepwater" evaporites composed mostly of finely laminated salts, where individual laminar grouping can be correlated over wide areas (Figure 5).

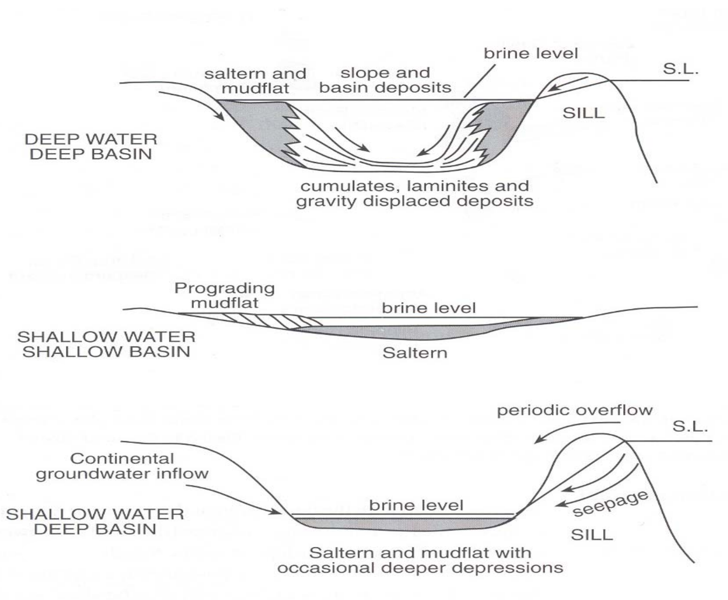

Fig.5. Basinwide evaporite settings (after Kendall 1992)

Basin slopes are dominated by reworked saltern evaporites deposited as slumps and turbidites. Seawater flows into the basin as a perennial seepage; if the basin remains isolated, the evaporite unit can fill the basin to a water level just below that of the supplying ocean. The basin fill starts off, dominated by deepwater laminated and resedimented salts that pass up section into shallow-water salterns, mudflats, or continental playas.
A good example of deeper water deposition, occur in the basin-centre deposits of the north and south Zechstein basins of NW Europe.

An example: the Permian Zechstein

One of the best documented areas, where high resolution sequence analysis has been attempted, is the basinwide anhydrite/halite evaporites of Permian Zechstein in NW-Europe.
The Zechstein Basin stretches from northern Britain, across the North Sea through the Netherlands, Denmark, Germany and Poland to the edge of the Hercynian massifs (Harz, Rhine and Bohemian mountains).
Zechstein sedimentation commenced when the sub sealevel Rotliegendes Basin was flooded through a combination of rifting and eustatic sea level rise. In the classic terminology, four main cycles (Z1-Werra Series, Z2-Stassfurt Series; Z3-Leine Series and Z4-Aller Series) and rudimentary fifth and sixth cycles then precipitated (Fig. 6). Each has a general sequence of clastics, carbonates, one or two

phases of sodium and potassium salts, regressive halite or anhydrite, and carbonate. An ideal classic Zechstein cycle starts with a transgressive nonevaporitic "shale", followed by carbonates and culminates in thick evaporites (mostly halite/anhydrite).

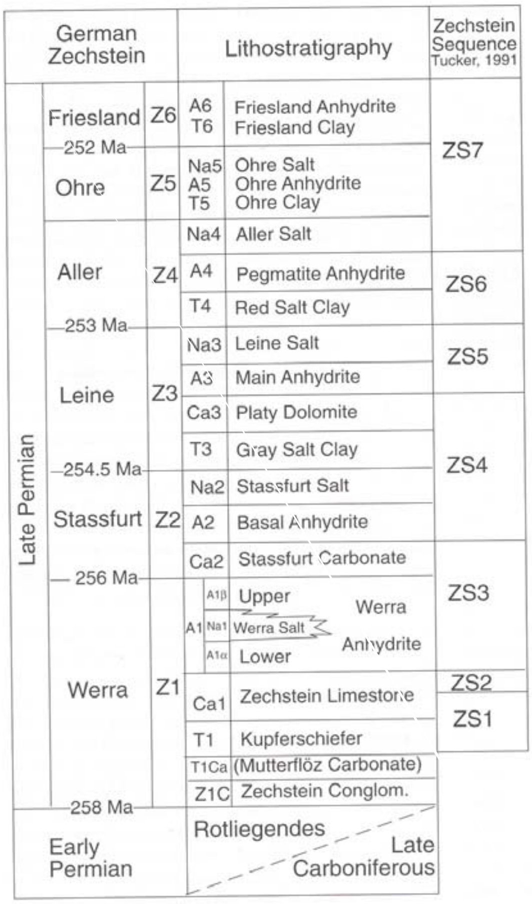

Fig.6. Lithostratigraphy of the Zechstein Series in Germany (after Strohmenger et al. 1996a, b). Shown are the classic Zechstein cycles (Z1-Z6) and the Zechstein sequences (ZS1-ZS7) as proposed by Tucker (1991)

Tucker (1991) published an alternative to the classic Zechstein stratigraphy based on what he interpreted as third order sequences (ZS1-ZS7). In it he correlates evaporites with sealevel lowstands (LSTs) and carbonates with sealevel highstands (TSTs and HSTs).

Tucker's approach, in tying evaporites to lowstands, is opposite to that of the classic approach. Strohmenger et al. (1996 a, b) went on to refine a sequence stratigraphic approach for the basal Zechstein (Z1 and Z2) (Fig. 7).

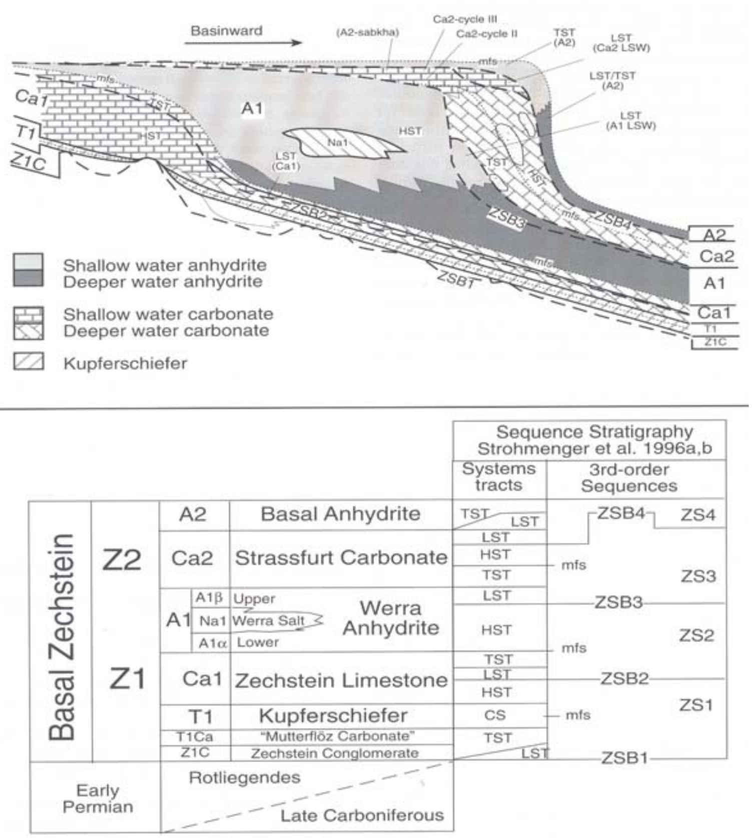

Fig.7. Zechstein evaporites of northwestern Germany (after Stromenger et al. 1996a, b). 1) Schematic of basal Zechstein relationships on the southern margin of the Zechstein Basin. 2) Lithostratigraphy of basal Zechstein showing classic subdivision (Z1-Z2) and Strohmenger et al. (1996a) subdivision (ZS1-ZS4).

Their analysis (Fig. 7) shows that reworked sandstones of the Weissliegendes and/or the Zechstein conglomerate (Z1C) record the initial transgression of the Zechstein Sea and overlie the Zechstein sequence boundary (ZSB1). Transgressive systems tract (TST) deposits of the first Zechstein sequence (ZS1) are also represented by deeper marine carbonates of the Mutterflöz (T1Ca). The overlying Kupferschiefer is interpreted as a condensed section (CS) indicating maximum flooding (mfs) of the first Zechstein sequence.

The bulk of the shallow water Zechstein limestone is interpreted as a highstand systems tract (HST). It is separated from the thin uppermost part of the Zechstein limestone by a karst horizon corresponding to an erosive sequence boundary (ZSB2). The uppermost part of the Zechstein Limestone represents the transgressive systems tract of the second Zechstein sequence (ZS2). According to Strohmenger et al. (1996a, b) there is no indication of a sequence boundary at the top of the Ca-1 platform carbonates. They place the maximum flooding surface (mfs) of the second Zechstein sequence at the top of the Ca1 platform carbonates. The overlying anhydrites of the A-1 sulphate platform are interpreted as predominantly highstand systems tract deposits displaying an erosive sequence boundary (ZSB3) at its top. This is in direct contradiction with Tucker (1991).

This contradiction underlies the difficulties in sequence stratigraphic analysis of evaporite deposits using models derived from geometries of marine systems. The terms highstand systems tract and lowstand systems tract are largely defined by whether the shelf of the basin is covered by water. In the marine sector we are talking about eustatic sea level amplitudes of no more than a hundred or so meters in icehouse periods and less than decameters in greenhouse periods. In an evaporite basin that is undergoing drawdown we are discussing isolation rapidly followed by a water level fall of more than 500-1,000 meters before widespread evaporite formation. During complete drawdown the whole highstand shelf and slope as well as part of the basin floor is exposed and water levels are mostly less than a few tens of meters and no more than 100 or 200 meters.

The Zechstein 2 Carbonate (Ca2) overlies the A1-Sulphate and according to Strohmenger et al. (1996a, b) encompasses transgressive systems tract as well as highstand systems tract deposits of Zechstein sequence ZS3. The maximum flooding of the Ca2 is correlated with the flooding of the A1-sulphate platform. Therefore, Ca2-platform carbonates (Main Dolomite) are dominated by shallow-water highstand deposits of the third Zechstein sequence (ZS3).

The transition of shallow-water Ca2 carbonates into the overlaying anhydrites of the A1 is often gradational (Strohmenger et al. 1996a, b). Carbonates, showing typical Ca2 facies, are often intercalated with the anhydrites of the A2. The lower part of the A2 is interpreted as sabkha deposits (A2-sabkha) indicating the emergence of the Ca2 platform at the end of Ca2 time. According to Strohmenger et al (1996a, b) the fourth sequence boundary of the Basal Zechstein (ZSB4) occurs not on top of the Ca2 shallow-water-carbonates, but somewhere within the A2-platform deposits. The lower part of the A2 is interpreted as the time equivalent of shallow-water Ca2 carbonates. The uppermost part of the A2 is thought to represent the transgressive systems tract of the fourth Zechstein sequence (ZS4). The relatively thick anhydrite accumulations of the A2 (approx. 100 m) are thought to represent both, lowstand systems tract as well as transgressive systems tract deposits of the fourth Zechstein sequence (ZS4).

Whatever approach Tucker or Strohmenger is more correct, discussions about-stratigraphic analysis of the Zechstein are not yet complete.

In summary, work in modern and ancient successions shown that kilometer-thick sequences will be deposited in less than 300,000 years and that infill only happens at times of complete basin isolation when there is no surface connection of the world’s oceans.

Quo vadis high-resolution sequence stratigraphic analysis in saline giants?

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