A shallow-basin model for ‘saline giants’ based on isostasy-driven subsidence

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INTRODUCTION

The common assumption that ‘saline giants’ must have formed in deep basins and that their thickness reflects initial basin depth ignores the principle of isostasy. Due to the high density of anhydrite and high precipitation rates for evaporite minerals, isostatic compensation is much more important in evaporite than in non-evaporite settings. The main implication is that evaporite precipitation drives subsidence rather than the other way round, and that thick evaporite deposits require an initial basin depth much less than their final thickness. Once initiated, evaporite precipitation and consequent isostatic subsidence is a self-sustaining process that can result in kilometre-scale evaporite stratigraphy. Rapid isostatic compensation is facilitated by thin, fractured crust in extensional basins, which explains the typical occurrence of saline giants in such settings. It is shown that a shallow-basin origin in combination with rapid isostatic compensation can well explain the extreme thickness of saline giants as well as the commonly associated shallow-water sedimentary facies. Although there is no reason to exclude the possibility of a basin-wide dropdown of a few thousand metres as proposed for some saline giants, a desiccated deep basin is certainly not a requirement. An initially shallow basin that rapidly deepens by isostatic adjustment in response to the precipitation of evaporites eliminates the need for deep-basin desiccation, gigantic waterfalls, and repeated opening and closure of a connection to the world ocean, and makes the extreme thickness of saline giants less enigmatic.

Keywords Saline giants, isostasy, evaporites, halite, anhydrite, Zechstein, Messinian.

ABSTRACT

A number of evaporite successions are characterized by extraordinary thickness and are therefore commonly referred to as ‘saline giants’. They are up to 4 km thick and typically consist of a number of stacked, thinning-upward evaporite cycles (Table 1). For example, the carbonate-evaporite succession from the Permian Zechstein reaches a thickness of 2 km (Taylor, 1998); individual halite bodies are up to 600 m thick (Sannemann et al., 1978) and anhydrite bodies are up to 280 m (Van der Baan, 1990). The major Messinian evaporite succession in the western Mediterranean was estimated to be 2–3 km thick (Hsü et al., 1973) and is 2 km in the eastern Mediterranean (Jal et al., 2002). According to Krijgsman et al. (1999) these Mediterranean evaporites were deposited in no more than 0.6 Myr.

In the absence of recent analogues, developing models for saline giants has proven speculative. In the late 19th century Ochsenius (1877) developed a depositional model based on evaporite precipitation in a restricted lagoonal environment. Hsü et al. (1973, 1977) felt it could not explain the new data from the Mediterranean, which they interpreted as deposits formed by precipitation from shallow-water salt lakes that occupied the deepest parts of kilometres deep, desiccated basins (Fig. 1). The model is known as the deep-basin shallow-water model and is often used in explaining thick halite deposits (e.g. Sonnenfeld, 1984; Warren, 1999).

The formation of Zechstein halite bodies has also been attributed to deep-basin shallow-water
Table 1  Summary of stratigraphic, facies and thickness data for various Palaeozoic to Cenozoic saline giants

<table>
<thead>
<tr>
<th>Basin</th>
<th>Age</th>
<th>Setting</th>
<th>Associated facies</th>
<th>Number of cycles</th>
<th>Total thickness (m)</th>
<th>Average cycle thickness (m)</th>
<th>Halite thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead Sea (Al-Zoubi et al., 2002; Neev &amp; Emery, 1967)</td>
<td>Pleistocene</td>
<td>Transtension</td>
<td>Lacustrine, alluvial</td>
<td>6</td>
<td>1500</td>
<td>250</td>
<td>375</td>
</tr>
<tr>
<td>Western Mediterranean Basin (Blanc, 2000; Dercourt et al., 1986; Hsü et al., 1973)</td>
<td>Miocene</td>
<td>Various</td>
<td>Various</td>
<td>nd</td>
<td>2000</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Eastern Mediterranean Basin (Blanc, 2000; Tay et al., 2002)</td>
<td>Miocene</td>
<td>Various</td>
<td>nd</td>
<td>nd</td>
<td>3500</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Red Sea (Sonnenfeld, 1984; Orszag-Sperber et al., 1998)</td>
<td>Miocene</td>
<td>Extension</td>
<td>nd</td>
<td>nd</td>
<td>3000–4000</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Khorat Basin (Anderson et al., 1972; El Tabakh et al., 1999)</td>
<td>Cretaceous</td>
<td>Extension</td>
<td>Red beds</td>
<td>3</td>
<td>1100</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>Cuanza Basin (Siesser, 1978)</td>
<td>Cretaceous</td>
<td>Extension</td>
<td>Shallow marine</td>
<td>nd</td>
<td>1500</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Gulf of Mexico Basin (Reed, 1994)</td>
<td>Jurassic</td>
<td>Extension, strike slip</td>
<td>Red beds, volcanics</td>
<td>nd</td>
<td>4000</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Southern Permian Basin (Zechstein) (Sannemann et al., 1978; Van der Baan, 1990; Ziegler, 1990)</td>
<td>Permian</td>
<td>Extension, strike slip</td>
<td>Aeolian, shallow marine, starved basin</td>
<td>4</td>
<td>2000</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td>East European Basin (Ural) (Northrup &amp; Snyder-Walter, 2000; Zharkov, 1984)</td>
<td>Permian</td>
<td>Transtension</td>
<td>Aeolian, shallow marine</td>
<td>6</td>
<td>2500</td>
<td>420</td>
<td>500</td>
</tr>
<tr>
<td>Precaspian Basin (Volozh et al., 2003)</td>
<td>Permian</td>
<td>Thin crust</td>
<td>Deep marine</td>
<td>nd</td>
<td>4000</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Delaware Basin (Anderson et al., 1972)</td>
<td>Permian</td>
<td>Transtension</td>
<td>Starved basin</td>
<td>2</td>
<td>1100</td>
<td>550</td>
<td>400</td>
</tr>
<tr>
<td>Paradox Basin (Catacosimos et al., 1990; Williams-Stroud, 1994; Zharkov, 1984)</td>
<td>Carboniferous</td>
<td>Transtension</td>
<td>Shallow marine</td>
<td>5–7</td>
<td>2000</td>
<td>300</td>
<td>270</td>
</tr>
<tr>
<td>Michigan Basin (Cercone, 1988; Stevenson &amp; Baars, 1986; Zharkov, 1984)</td>
<td>Silurian</td>
<td>Extension</td>
<td>Shallow marine</td>
<td>5</td>
<td>1000</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>East Siberian Basin (Zharkov, 1984)</td>
<td>Cambrian</td>
<td>Extension</td>
<td>Shallow marine</td>
<td>12</td>
<td>2500</td>
<td>210</td>
<td>nd</td>
</tr>
</tbody>
</table>

nd, no data available.
A shallow-basin model for 'saline giants'

Fig. 1 Deep-basin shallow-water model developed for saline giants. (After Kendall, 1992.) The model does not take into account any syn-depositional isostatic compensation due to evaporite loading.

deposition, although of different order (e.g. Tucker, 1991). Here the estimate of maximum basin depth equals the thickness of the thickest halite body (approximately 600 m) (Tucker, 1991; Warren, 1999). Estimated basin depth before evaporite deposition has been calculated in a similar way in, for example, the Delaware Basin and the Paradox Basin (Anderson et al., 1972; Williams-Stroud, 1994).

For the Zechstein (Southern Permian Basin) abundant drilling has shown that the thick evaporite succession consists of at least four major cycles, the thickest basal cycle being more than 600 m thick locally (Sannemann et al., 1978; Van der Baan, 1990; Tucker, 1991; Taylor, 1998). These cycles are composed of a marginal carbonate wedge, an anhydrite platform and an onlapping halite body (Fig. 2). It is widely accepted that at the termination of each cycle, halite had filled the basin approximately to sea level, and that after continued tectonic subsidence the deposition of a subsequent evaporite cycle started (Van der Baan, 1990; Tucker, 1991; Taylor, 1998; Warren, 1999). Such an internal architecture, with anhydrite pre-dating halite, is common in evaporite basins (Sonnenfeld, 1984; Warren, 2000).

Despite the wide acceptance of a deep-basin origin of halite bodies, a number of aspects of their formation have not been adequately explained. Following Nesteroff (1973), Sonnenfeld (1985) argued against a deep-basin shallow-water origin for the Messinian evaporites, giving a long list of arguments among which was the unexpected occurrence of tidal sediments. Recently, the deep-basin shallow-water origin of Messinian evaporites has been challenged by Hardy & Lowenstein (2004) and Manzi et al. (2005).

Although a shallow-basin shallow-water model well explains the occurrence of mainly shallow-water depositional structures, the model is qualified as 'unlikely in most tectonic environments' by Kendall (1992) because it requires subsidence and deposition to be in equilibrium during the deposition of kilometre-scale evaporite successions. In the discussion about the depth of such basins prior to the formation of saline giants, the role of isostasy on basin evolution and stratigraphic development is commonly not appraised. Here, the focus will be on isostatic compensation as a mechanism that can explain how thick evaporite sequences can form.

Fig. 2 Stratigraphy and cyclical character of the Zechstein evaporites. (Modified from Visser, 1956.) The Zechstein 1 halite from the original figure is not represented here, as it did not precipitate in the main basin (e.g. Van der Baan, 1990).
in shallow-water basins under long-term gradual subsidence.

**ISOSTASY**

Isostatic compensation is the response of the lithosphere to a change of overburden by flexure or elastic rebound to achieve regional equilibrium (e.g. Watts, 2001). Such corrections are accommodated by lateral displacement of more ductile, high-density asthenosphere beneath the flexing plate. That such corrections may be implemented rapidly is shown by the fast response to polar deglaciation, where unloading has been 90% compensated by glacial rebound during the 10 kyr of the Holocene (Watts, 2001).

It has been demonstrated that the deposition of a thick siliciclastic wedge at a basin edge causes a strong isostatic response (Watts, 2001), and this should be even more pronounced for an anhydrite wedge due to the higher density of anhydrite (Table 2). Hence, evaporite deposits such as from the Zechstein or the Miocene Mediterranean, which are 2–3 km thick and occupy basins many hundreds of kilometres across, must have created much of their own accommodation space by means of loading. It is therefore expected that the mechanism of isostatic subsidence during salt precipitation explains, at least partly, the great apparent basin depth of many evaporite basins (Fig. 3). A factor that is expected to facilitate isostatic correction during salt precipitation is the condition of the basement of many saline giants, which consist of thin, fragmented crust due to rifting or post-orogenic collapse (Table 1) (Burke, 1975; Stanley, 1986; Volozh et al., 2003).

Several authors have acknowledged the loading effect on the crust of thick salt deposits (Norman & Chase, 1986; Diegel et al., 1995; Van Wees et al., 2000), but they have not considered this to be a syn-depositional phenomenon. An advanced analysis of isostatic compensation in relation to evaporite basin evolution was published by Norman & Chase (1986). They applied the ‘Lake Bonneville’ principle of Gilbert (1890), who showed that the Late Pleistocene desiccation of the present Great Salt Lake caused a 40 m uplift of the lake-shore deposits. Norman & Chase (1986) demonstrated that desiccation of the Mediterranean must have resulted in large-scale uplift of the basin floor as well as its margins. Besides that they argued that the Messinian Mediterranean was much shallower than now due to isostatic compensation in response to salt loading. Fabbri & Curzi (1979) invoked an isostasy model to calculate the depth of deposition for the lower Messinian evaporites in the Tyrrenhian Sea, and concluded that they had been deposited in a shallow rather than a deep basin. On the other hand, Ryan (1976) performed a quantitative reconstruction incorporating the effect of loading, and concluded

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**Table 2** Rock, mineral and water densities relevant to this study (Vyalashko, 1972; Schumann, 1987; Watts, 2001)

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Density (g cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>2.65</td>
</tr>
<tr>
<td>Calcite</td>
<td>2.8–2.9</td>
</tr>
<tr>
<td>Sediment (30% water*)</td>
<td>~ 2.2</td>
</tr>
<tr>
<td>Halite</td>
<td>2.1–2.2</td>
</tr>
<tr>
<td>Gypsum</td>
<td>2.2–2.4</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>2.9–3.0</td>
</tr>
<tr>
<td>Water</td>
<td>1.0</td>
</tr>
<tr>
<td>Sea water</td>
<td>1.03</td>
</tr>
<tr>
<td>Asthenosphere</td>
<td>3.3</td>
</tr>
</tbody>
</table>

*Calculated value.
that the Mediterranean Sea was locally more than 2.5 km deep (Balearic Basin).

**HALITE**

The deep-basin theory that was developed for saline giants requires that the unusually steep basin margins as they are observed now in the subsurface (Warren, 1999) were already in place before the onset of evaporite precipitation (Fig. 1). If the basin margins were indeed as steep prior to halite deposition as after, the marginal successions within such basins should be characterized by abundant clastic deposits. However, evaporite cycles are typified by an absence of clastic interbeds except for anhydrite breccias, while such deposits may be common in underlying or overlying formations (e.g. Sonnenfeld, 1984). It is assumed, therefore, that the tectonic component of total subsidence in evaporite basins is low.

The implications of isostatic compensation during the precipitation of evaporites may be assessed by making simple calculations based on the Airy isostasy model (Fig. 4). It was not the intention here to perform a state-of-the-art basin-scale modelling study. Instead, it has been explored how the incorporation of isostatic compensation may help to develop an alternative model that explains the large-scale subsidence history of salt basins, as well as their sedimentary development.

The calculations are based on two assumptions. First, it is assumed that isostatic adjustment of the lithosphere takes place **during** deposition. Note that the Late Permian, which was characterized by evaporite formation worldwide, lasted approximately 10 Myr. Kriegsman et al. (1999) have demonstrated that the Messinian salinity crisis lasted only 600 kyr: a short period for the precipitation of 2–3 km of evaporites. This should, however, be sufficient for isostatic compensation, as it operates on an even shorter time-scale of 10 kyr (Watts, 2001). Second, it is assumed that deposition occurs in a large basin (e.g. 300 x 1500 km for the Southern Permian 'Zechstein' Basin (Ziegler, 1990)), such that the flexural wavelength of the lithosphere is significantly smaller than the scale of the basin. For these conditions, the maximum thickness of the evaporite columns was determined, assuming that salt precipitation occurred under continuous isostatic compensation.

Rates of precipitation of halite are of the order of 10–150 mm yr\(^{-1}\) (Schreiber & Hsü, 1980; Sonnenfeld, 1984 and references therein), which is

**Fig. 4** An Airy isostasy model for basin drawdown and evaporite precipitation. (a) Water-filled basin (isostatic equilibrium). (b) Uplift due to basin desiccation. (c) Halite precipitation. (d) Subsidence due to halite precipitation. (e) Maximum halite-accumulation potential for a 'stage a' basin (isostatic equilibrium). *According to the deep-basin, shallow-water model, the basin desiccates causing isostatic rebound; according to the shallow-basin shallow-water model, the basin remains water-filled.
up to three orders of magnitude greater than subsidence for extensional basins with average rates up to a few millimetres per year (Einstein, 1992, and references therein). Precipitation rates for gypsum and anhydrite are of the order of 1–10 mm yr$^{-1}$ (Sonnenfeld, 1984), thus of the same order as subsidence rates of extensional basins. It is concluded that the tectonic component of overall subsidence during halite precipitation can be ignored, whereas it is important during gypsum/anhydrite precipitation. Hence subsidence of a halite-accumulating basin is likely to be entirely controlled by loading due to halite precipitation.

Balancing the columns in Fig. 4 for a case of a deep basin that dries out demonstrates that the amount of uplift due to desiccation is a function of the initial basin depth ($D_{\text{basin}}$):

$$\text{Uplift} = D_{\text{basin}} \times \left( \frac{\rho_{\text{water}}}{\rho_{\text{asterosphere}}} \right)$$

$$= D_{\text{basin}} \times \left( \frac{1.0}{3.3} \right) = 0.3 \times D_{\text{basin}}$$

The density values ($\rho$) used in the equations are presented in Table 2. As a density range applies to halite and anhydrite, the mean density has been used here. Hence the results vary slightly if lower or higher density values are used.

From the above equation, it follows that the depth of a desiccated basin equates to 70% of the initial depth of a water-filled basin. For the desiccated deep-basin model of Hsü et al. (1973), it may be calculated that a 2.0 km deep desiccated basin would be up to 2.9 km deep before drawdown if isostasy were taken into account. If that basin were filled with halite under continuous isostatic compensation, the thickness of the ultimate halite column ($T_{\text{halite}}$) is a function of the depth of the desiccated basin:

$$T_{\text{halite}} = D_{\text{basin}} \times \left( \frac{\rho_{\text{asterosphere}} - \rho_{\text{air}}}{\rho_{\text{asterosphere}} - \rho_{\text{halite}}} \right)$$

$$= D_{\text{basin}} \times \left( \frac{3.3}{1.15} \right) = 2.9 \times D_{\text{basin}}$$

This equation predicts that a 2.0 km deep desiccated basin is filled with a maximum of 5.8 km of halite if precipitation takes place under a condition of rapid isostatic adjustment. On the other hand, a desiccated basin only 690 m deep would be sufficient to accommodate a 2.0 km thick halite sequence if halite precipitation occurred under rapid isostatic compensation.

The deep-basin shallow-water model of Hsü et al. (1973) implies that the filling with halite of a 2 km deep desiccated basin is followed by up to 2 km of subsidence to regain isostatic equilibrium. Note that a shallow basin and a deep basin both allow the formation of a 2 km thick evaporite succession (Fig. 5). However, it is felt that the shallow-basin model is more generally applicable and less restrictive where tectonic and geographical conditions are concerned. For example, it accounts for the occurrence of shallow-water sediments (early stage) as well as deeper-water sediments (late stage), without repetitive kilometre-scale marine desiccation and refilling.

The above calculations show that there is a simple alternative to the deep-basin shallow-water evaporite model, which explains the thickness of saline giants, as well as the occurrence of shallow-water sedimentary structures. The main implication of isostatic compensation in evaporite-basin evolution is that evaporite precipitation drives subsidence instead of the other way round, and that thick halite deposits as they are observed in the rock record require an initial basin depth much less than their eventual thickness.

A halite-deposition model, which explains the formation of saline giants under the condition of isostatic compensation, is shown in Fig. 6. First the connection of a shallow water-filled basin with the open ocean becomes restricted such that much of the oceanic inflow evaporates and that little outflow of dense brines occurs. This restricted outflow is attributed to a progressive narrowing of a straight that, for example, may be controlled by anhydrite precipitation along the margins of a graben.

The precipitation of halite is a rapid process allowing halite to rapidly fill a shallow basin. The rapid deposition of halite causes disturbance of the isostasy balance, thereby forcing a subsidence reaction of nearly 50% of the thickness of the halite column (Fig. 4). This newly created accommodation space may consequently be filled with halite, again causing a subsidence reaction. As long as the basin receives ocean water, which is to be expected if no tectonic events occur, the process can continue.
Fig. 5 Comparison of deep-basin and shallow-basin models. The deep-basin shallow-water model for saline giants is based on isostatic compensation after salt precipitation. The shallow-basin shallow-water model for saline giants is based on isostatic compensation during salt precipitation. Note that the latter model is characterized by an initially shallow basin, whereas the former model is characterized by an initially deep basin, which after filling with halite is subjected to a phase of isostatic subsidence.

Fig. 6 Model for halite precipitation under continuous isostatic compensation: rapid precipitation of halite in a shallow basin causes isostatic subsidence, thereby resulting in an apparent deep-basin structure. *Restricted outflow may be controlled by anhydrite-platform progradation into a narrow strait (e.g. rift), connecting the evaporite basin with the world ocean.

until subsidence approaches zero. By that time a halite column of up to three times the desiccated basin depth or twice the water-filled basin depth will have been accommodated. Note that this model requires continuous oceanic inflow and restricted outflow, whereas the deep-basin shallow-water model is based on repeated phases of complete isolation from the world’s oceans (Fig. 1).

For a water-filled basin the ultimate halite thickness is a function of the initial water depth ($D_{\text{basin}}$):

$$Th_{\text{halite}} = D_{\text{basin}} \times \frac{\rho_{\text{atmosphere}} - \rho_{\text{water}}}{\rho_{\text{atmosphere}} - \rho_{\text{halite}}}$$

$$= D_{\text{basin}} \times \frac{2.3}{1.2} = 2.1 \times D_{\text{basin}}$$

The above equation suggests that a halite body such as the thick Zechstein-2 halite (600 m) may form in a basin with an initial water depth of 285 m. A 2 km thick evaporite succession representing a single precipitation event may be accommodated within a 950 m deep water-filled basin. In the case of two evaporite units separated by a period with tectonic subsidence, an average basin depth of 425 m is sufficient to accommodate 2 km of halite in two phases. Note that many saline giants consist of four or more anhydrite–halite cycles (Table 1).
Hence, the average basin depth is then reduced to a few hundred metres or less.

The derived depths are within the depth range of current desiccated continental depressions such as Death Valley, California (−85 m), the Dead Sea rift, Jordan (−411 m), the Qattara Depression, Egypt (−134 m) and the Danakil Depression in the Afar Triangle, Ethiopia (−116 m). The flooded evaporite-precipitating Gulf of Karabokhaz, Turkmenistan is currently 35 m below global sea level. Hence, these depressions which are characterized by thinned and fractured crust may well host future saline giants if connected to the marine domain.

ANHYDRITE

Evaporation of marine-sourced brines causes calcium sulphate (CaSO₄) to precipitate well before the halite saturation point is reached (Hardy, 1967). Consequently major halite bodies are found in association with CaSO₄ precipitates. Major anhydrite bodies have been shown to be basin-margin wedges, and the bulk of these bodies have precipitated in shallow coastal sabkha environments (Sonnenfeld, 1984). Evaporation has the greatest net effect in shallow water and thus coastal platforms act as evaporite traps. Primary formation of anhydrite is inhibited by chemical boundary conditions, but primary gypsum may be directly converted into anhydrite under high temperature and/or high brine salinity, conditions commonly observed in coastal sabkha environments (Hardy, 1967).

The stability of either of the two CaSO₄ minerals is important with respect to isostasy, since their density values are markedly different (Table 2). The density of anhydrite is much higher than that of porous sediment, thus a change from non-evaporite to anhydrite deposition has a major effect on isostatic balance and subsidence. The density of gypsum is approximately equal to the density of porous sediment, so that both have a similar effect on the isostasy balance in terms of density. Gypsum precipitation also may result in accelerated isostatic subsidence because of the common high precipitation rate. Based on constraints of brine concentration and temperature, it is assumed (cf. Tucker, 1991; Warren, 1999) that anhydrite generally precipitates on the platform (high net evaporation) while gypsum (selenite) precipitates on the platform slope (low net evaporation).

In an aggradational-platform situation where tectonic subsidence, sedimentation and isostatic subsidence are in equilibrium, a change from non-evaporite to anhydrite precipitation would approximately cause tripling of total subsidence according to the equation:

\[
T_{h,\text{anhydrite}} = T_{h,\text{sediment}} \times \left( \frac{\rho_{\text{atmosphere}} - \rho_{\text{sediment}}}{\rho_{\text{atmosphere}} - \rho_{\text{anhydrite}}} \right)
\]

\[
= T_{h,\text{sediment}} \times \left( \frac{1.10}{0.35} \right) = 3.1 \times T_{h,\text{sediment}}
\]

The long-term laterally equivalent deposition of coastal-sabkha anhydrite and inland sabkha clay under continuous isostatic compensation therefore would result in a rapid basinward thickening rock column, where the anhydrite column is up to three times thicker (Fig. 7). Locally such differential subsidence may be facilitated by passive (non-tectonic) fault movement, as has been observed on seismic cross-sections for Zechstein anhydrite bodies (Van der Baan, 1999).

The proposed model for anhydrite deposition is illustrated in Fig. 7. As long as some tectonic subsidence occurs and fresh seawater is supplied, aggradational anhydrite precipitation along the basin margin can continue. The rate of anhydrite precipitation is expected to be higher on the platform than on the platform slope, so a progressive steepening of platform clinoforms is predicted. This may result in mass movement, as observed in the Zechstein and other basins where slumpd anhydrite and anhydrite turbidites occur (Van der Baan, 1990; Tucker, 1991; Warren, 1999).

The thickest anhydrite body in the Zechstein is the up to 280 m thick Werra anhydrite (Van der Baan, 1990). Most of its relief is filled with the 600 m of halite belonging to the Zechstein-2 cycle (Fig. 2). The precipitation of a thick anhydrite wedge results in the formation of an equally deep adjacent basin, which may be characterized by the precipitation of pelagic gypsum (varves) as observed in the Zechstein (Van der Baan, 1990) or in the Delaware Basin, Texas (Sonnenfeld, 1984; Van der Baan, 1990), and is the later site of halite precipitation. Hence, the prolonged basin-margin precipitation of anhydrite initiated under shallow-water, lagoonal conditions may contribute to the formation of very thick halite bodies (Fig. 7).
that were transgressed by the sea during the break-up of Pangea (Burke, 1975).

A relatively weak and thin crust, dissected by faults, thus seems to characterize sites of major evaporite formation. Such conditions would have allowed rapid isostatic adjustment that favoured thick evaporite accumulations. The location of major evaporite bodies at the downthrown sides of major faults (Van der Baan, 1990) suggests that reactivation of existing faults may have allowed a quick isostatic response locally.

The application of the isostasy principle predicts that kilometres-deep continental depressions are not a prerequisite for the formation of saline giants, but that relatively shallow basins located on a weak crust, such as the Dead Sea or the Danakil and Qattara depressions in the northernmost East African rift, offer favourable conditions. Brine and influx modelling by Tucker & Cann (1986) has shown that deep-brine basins are not required for the formation of thick evaporite series, and that ‘for most geological examples it is possible to postulate a shallow-basin origin in which the basin is continuously replenished by new influx’, i.e. that many saline giants could have formed in basins of only a few hundred metres deep that were replenished by normal sea water. Their model requires that evaporite deposition is balanced by constant basin subsidence, a condition that is met in a shallow-basin model by the isostatic effect of salt loading.

The shallow basin concept requires a shallow depth of deposition of sediments underlying saline giants. The evaporites from the Zechstein conformably overlie aeolian sands, playa shales and evaporites from the Rotliegend Group, the basal Zechstein Coppershale and a thin unit of basal Zechstein ramp carbonates (Taylor, 1998). The Rotliegend itself developed on thin crust after orogenic decay. Similarly, other saline giants appear to be associated with shallow-marine deposits as well as arid terrestrial siliciclastics (Table 1).

Due to rapid precipitation during phases of strong evaporation, isostatic subsidence (loading) outpaced tectonic subsidence. Most evaporite successions are characterized by a number of anhydrite–halite cycles separated by relatively thin carbonate sequences. To allow such repetitive phases of evaporation, it is necessary that halite precipitation phases of short duration are followed by

**DISCUSSION**

Isostatic compensation during evaporite deposition is expected to have a major influence on evaporite-basin evolution, due to the high density values of the minerals involved and the high deposition rates of evaporite minerals. Saline giants typically formed in (post-orogenic) rifting-dominated areas (Table 1). Late-Carboniferous to Permian evaporites formed on thin, fragmented crust that developed during the collapse of Hercynian mountain chains (Stanley, 1986; Volozh et al., 2003). Triassic to earliest Cretaceous evaporites formed in rift-basins

![Diagram of evaporite deposition](image-url)
longer periods of carbonate or anhydrite deposition to allow the (tectonic) formation of accommodation space for a new phase of halite precipitation.

Considering the similarity in thickness and extent of the Mediterranean Messinian halite bodies and other saline giants (Table 1), the obvious question is whether their genesis was similar. A deep-basin model has been advocated for the Messinian evaporites based on assumed evidence of pre- and post-Messinian deep-marine deposition (Hsü et al., 1973; Cita, 2001) and on the assumption that the Mediterranean Sea was already deep before the Messinian period. It has been demonstrated here that isostatic compensation of salt precipitating from continuously inflowing marine water in arid climate zones may allow relatively shallow basins to develop into saline giants. Hence this model could provide a simple alternative for the deep-basin theory. Note that the model eliminates the need for repeated opening and closure of the oceanic connection, deep-basin desiccation and gigantic waterfalls.

Future saline giants may form in present-day arid-region continental depressions such as the Dead Sea and the Qattara and Danakil depressions of the East African rift. Once such depressions tens to some few hundred metres deep are connected to the world ocean by a relatively shallow strait, the formation of evaporites is expected to cause gradual isostatic subsidence and thus allow the deposition of evaporites much thicker than the present-day depth of these depressions. The size of many of these areas is comparatively small, however continued rifting and subsequent flooding with sea water may result in a rapid increase of surface area. For example, continued widening and collapse of the main East African rift, now only below sea level in the northernmost Afar Triangle, could result in an evaporite basin as large as the Southern Permian Basin (Zechstein).

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