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A Quantitative Model for Salt Deposition in Actively Spreading Basins*

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Search and Discovery Article #30117 (2010)
Posted June 30, 2010

*Adapted from extended abstract prepared for presentation at AAPG International Conference and Exhibition, Rio de Janeiro, Brazil, November 15-18, 2009

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Introduction

The processes that sometimes lead to extensive deposition (several 100,000 km^2) of massive, thick evaporites (several km), with multiple, stacked-up, recurrent sequences of gypsum/anhydrite, halite, and complex salts including carnallite and tachyhydrite along passive margins are not fully understood.

In most evaporite basin models it is often assumed that salt deposition occurs in shallow water, within sags of fixed geometry. Here we explore the possibility of salt deposition in deep marine environments with rapidly changing depths and widths, and the impact this might have on subsequent halokinesis or on the existence of potential plays above oceanic crust. We present a quantitative salt deposition model that takes into account the mass balance for fresh water, seawater, evaporation, and salt precipitation, combined with continuous plate motion and the resulting increase of accommodation space. The set of differential equations obtained is solved numerically. The model is applied backward in time to calibrate parameters, based on seismic measurements of evaporite layer thicknesses, basin geometry and plate separation rate. We discuss results concerning the main salt deposits in the Campos and Santos basins, offshore Brazil, and in basins offshore Angola and Congo.

Rifting, Spreading, and Tectonics of Brazilian and Congo-Angola Basins

The salt basins that face one-another between the Rio Grande rise and the Gulf of Benin are among the largest along Phanerozoic passive ocean margins. They formed during the Aptian (125-110 Ma), in the early, though not initial, stages of the opening of the northern South Atlantic (Figure 1). The geometric, kinematic, and temporal environment of this Early Cretaceous episode of salt deposition (Figure 2) appears to have been strikingly similar to that of the mid-late Miocene Red Sea (15-5 Ma). While a wealth of geophysical and geological data has been acquired in the last 30 years, both in Brazil and Africa, there is still much debate on fundamental questions concerning the structure and origin of the sag basins in which the salt accumulated. Where known, for instance, the ages of salt deposition are somewhat different from sub-basin to sub-basin. The nature of the crust under the salt or pre-salt sediments is also an open issue, the only consensus being that salt deposition generally postdated rifting. We further explore here the possibility, previously suggested or rejected by various authors (e.g., Jackson et al., 2000; Davison, 2007; or Karner and Gamboa, 2007, respectively) that much of the thickest salt was deposited during sea-floor spreading, largely on oceanic crust, but in a complex and very dynamic environment of overlapping, dueling, and ultimately connecting rifts/ridges, as observed in the southern Red Sea and Afar (e.g., Barberi et al., 1971; Manighetti et al., 1997, 2001).

The time frame and tectonic scenario we favor, based on data summarized by Karner and Gamboa (2007) and others, is outlined below. Subsequent to the impact of the Tristan da Cunha hot spot on the African-South American lithosphere, about 143 million years ago, the South American plate started to separate from the African plate at an average rate of several mm/yr. Narrow rifts (50-80 km-wide), with broadly overlapping segments, formed along the newborn plate boundary and were filled with sediments brought by rivers flowing from either continent. Hundreds of meters-deep lakes, some of them anoxic, and basaltic volcanism punctuated the geology of such rifts in the Neocomian-early Barremian (133-128 Ma).

Breakup occurred between the late Barremian and the early Aptian (128-125 Ma). As full seafloor-spreading started, the plate separation rate increased 4- or 5- fold, to a few cm/yr, and the accommodation space between Africa and Brazil rapidly widened and deepened. However, the now 1700 km-long, still complex marine basin remained isolated between two large “dams”: the large topographic swell built by hot spot volcanism in the South (Walvis Ridge-Rio Grande Rise), and the Vema–Saint Paul transform/fracture zones in the nascent Gulf of Benin to the North. These two volcanic/tectonic flood-gates let only limited amounts of seawater flow into the basin, mostly through tectonic fissures across basalts to the south. Such a restricted depositional environment persisted for about 9 myr. During that period, the rapid evaporation of sea-water created most of the thick-layered evaporite deposits, capping both oceanic and attenuated continental crust topped with rift and pre-rift sediments, in the broad (300-500 km) and deep (1-2 km) basin, still complexly compartmentalized by steps and overlaps. Perennial open-marine conditions were re-established at the beginning of the Albian (112-110 Ma), due to major reorganization (simplification) of the Mid-Atlantic ridge north of the hot spot.

Evaporite Deposition Model

The generic model proposed for evaporite deposition (Figure 3) is a restricted basin initially filled with seawater. The initial water depth in the basin must be on the order of the final total thickness of evaporites. A limited flow rate Q_{sw} of seawater flowing across the Walvis-Rio Grande volcanic ridge through tectonic extensional fissures brings the salt required to create thick evaporites. Q_{fw} is the fresh water flow rate from rivers. The total water evaporation rate for the basin is the product of the evaporation rate per unit area E_{bw} by the surface area A occupied by the water. Q_{sw}, Q_{fw}, and E_{bw} are defined as 100-year averages. The time step used to solve equations is an integer number of years to smooth out seasonal effects. The geometry of the basin is captured in the function relating the surface area of water $A(z)$ to the water level z. This function has an important property: it is always increasing. Before salt precipitates the differential equations describing the system are

$$A(z)\ dz/dt = -E_{bw}A(z) + Q_{sw} + Q_{fw} \quad (1) \qquad V_{bw}(z) = \int_0^z A(x)dx - V_{salt}(t) \quad (2)$$

$$\rho_{bw}(t)S(t)V_{bw}(z) = \rho_{bw}(0)S(0)\left(V_{bw}(0) + Q_{sw}t\right) \quad (3) \qquad V_{salt}(t) = 0 \quad (4)$$

$S(t)$ is the salinity of the basin water in kg of dissolved salts / kg of brine and ρ_{bw} is the basin water density. $V_{bw}(z)$ is the total volume of basin water and V_{salt} is the volume of solid salt deposits. Gypsum and halite that deposit on basin margins introduce a time dependence in the functions $A(z)$ and $V_{bw}(z)$, but this effect is small for large basins (100,000 km^2 or more), and it will be neglected here. The condition required to create a salt basin is that the total evaporation rate is greater than the water intake; i.e., the initial value of the right member of Eq.1 must be negative. As evaporation takes place, the water level drops and basin water salinity increases gradually until the saturation concentration is reached for the least soluble salt mineral contained in the basin water. Calcium and magnesium carbonates precipitate first, followed by gypsum, and anhydrite under particular temperature conditions, followed by halite when the water density reaches ρ_{sat}=1214 kg/m^3 at 25^{o}C, and finally complex salts including carnallite, bischofite, and tachyhydrite that comes last. For clarity and simplicity we describe here a "one salt" model based on halite which occupies 75% of the evaporite layer volume.

When the water density reaches ρ_{sat} salt precipitates in amounts just sufficient to keep the basin water density equal to ρ_{sat}. Again here we consider a time step of several tens of years which allows for replacement of the stratified basin waters by well mixed waters with a uniform salinity equal to the average taken over the entire basin volume. The mechanisms taking place are in fact quite complex, involving seasonal currents governed by salinity and temperature gradients in the basin. During this steady state phase Eqs.3 and 4 are replaced by Eqs.5 and 6:

$$V_{salt}(t)\rho_{salt} = \rho_{sw}(0)S(0)\left(V_{bw}(0) + Q_{sw}t\right) - \rho_{sat}S_{sat}V_{bw}(t) \quad (5) \qquad \rho_{sw}(t) = \rho_{sat} \quad (6)$$

A fundamental property of Eq.1 is that the water level in the basin stabilizes at a constant value as soon as the right member reaches zero; i.e., when the water surface area reaches the critical value $A_c = (Q_{sw} + Q_{fw})/E_{bw}$ where E_{bw} is for salt-saturated basin waters (Eq.6). From then on, the absolute level of water (not the water depth!) remains practically unchanged unless a major climatic change happens. Salt deposition takes place and the thickness of salt gradually increases while the water surface stays at the same level to maintain the surface area $A(z)$ and the evaporation rate constant. This equilibrium has several feedback loops that make it remarkably stable:

1. Level down → Salinity increases → Evaporation rate decreases → Level up
2. Level down → Hydraulic head increases across “dam” → seawater flow rate increases through fractures → Level up
3. Level down → Water surface area decreases → Evaporation decreases → Level up
4. Level up due to water intake increase → Salinity decreases → Evaporation rate increases → Level down

Conclusion

During the Aptian, the northern part of the South Atlantic basin was located just north of the tropic of Capricorn, in the middle of the arid belt that contains most of the southern hemisphere modern deserts: Kalahari and Namibian deserts in Africa, Atacama desert in Chile, Australian desert. The initial evaporation rate was probably above E_{bw}=2 m/y net of rainfall. This is the current value observed in the Red Sea. However E_{bw} decreases significantly with increasing salinity. Models have been proposed by several authors such as Penman, Dalton, Asmar and Ergenzinger (see Warren, 2006). The set of equations leads to an average halite deposition rate of 2-3 cm/yr, assuming rift-margin slopes around 4%. Such a rate might apply to the bottom 600 m of the evaporite sequence in the Santos basin that contains only anhydrite and halite. It could have taken only 24,000 years to deposit these lowermost 600 m. However, above that level there are at least nine sequences containing complex salts and these can take much longer to deposit. Furthermore, most of these complex salt layers include tachyhydrite that precipitates at the terminal stage of the salt basin when the brine has a density above 1300 kg/m^3 and the evaporation rate is almost zero. In general, tachyhydrite cannot precipitate because water lost during the day is re-absorbed during the night from atmospheric humidity.
Tachyhydrite layers are clear markers of extremely arid climate episodes that can be correlated with Milankovitch orbital forcing cycles (e.g., 22,000 years). Detailed observation of evaporite cores should help determine the total deposition time (e.g., eolian deposit markers). The proposed sea-water intake through fissures across basaltic thresholds is suggested by observed, albeit small scale, modern analogs such as lake Assal in Afar (e.g., Manighetti et al., 1997; Audin et al., 2001). This natural process is of interest for additional reasons. First, the flow rate through cracks can only be limited, which is a requirement of the precipitation model. Second, because fissures in basalts can be tens to a hundred meters deep, it is less sensitive to ocean water level variations than simple “river-type” flow above a sill. Third, when the evaporation rate increases and the basin level drops, flow through cracks will tend to increase and raise the water level in the basin. Fourth, it provides a large contact surface between seawater and basalts, which favors the chemical alteration of the water required for a geochemistry compatible with tachyhydrite deposition.

References

Audin, L., et al., 2001, Fault propagation and climatic control of sedimentation on the Ghoubbet Rift Flooor: Insights from the

Tadjouraden cruise in the western Gulf of Aden, Geophysical Journal International, v. 144, p. 391-413.
Barberi, F. et al.,1971, Notice géologique de l'Afar septentrional, Carte Géologique de la dépression des Danakil, Afar Septentrional - Ethiopie, 1/500 000 : Centre National de la Recherche Scientifique (France) et Consiglio Nazionale delle Ricerche (Italy), p. 7-15.

Davison, I., 2007, Geology and tectonics of the South Atlantic Brazilian salt basins, *in* Ries, A.C., et al., eds., Deformation of the Continental Crust: The legacy of Mike Coward: Geological Society, London, Special Publications, v..272, p. 345-359.

Jackson, M.P.A., et al., 2000, Role of subaerial volcanic rocks and mantle plumes in creation of South Atlantic margins: Implications for salt tectonics and source rocks: Marine and Petroleum Geology, v. 17, p. 477-498.

Karner, G.D., and Gamboa, L.A.P., 2007, Timing and origin of the South Atlantic pre-salt sag basins and their capping evaporites: Geological Society, London, Special Publications, v. 285, p. 15-35.

Manighetti, I., et al., Propagation of rifting along the Arabia-Somalia plate boundary: Into Afar, J. of Geophys. Res., Vol. 103, no. B3, p. 4947-4974, 1998

Manighetti, I., et al.,2001, Strain transfer between disconnected, propagating rifts in Afar: Journal of Geophysical Research, v. 106/B7, p. 13613-13665.

Pucéat, E., et al., 2003, Thermal evolution of Cretaceous Tethyan marine waters inferred from oxygen isotope composition of fish tooth enamels: Paleoceanography, v. 18, no. 2, p. 1029.

Warren, J. K., 2006, Evaporites – Sediments, Resources and Hydrocarbons: Springer, 1035 p.

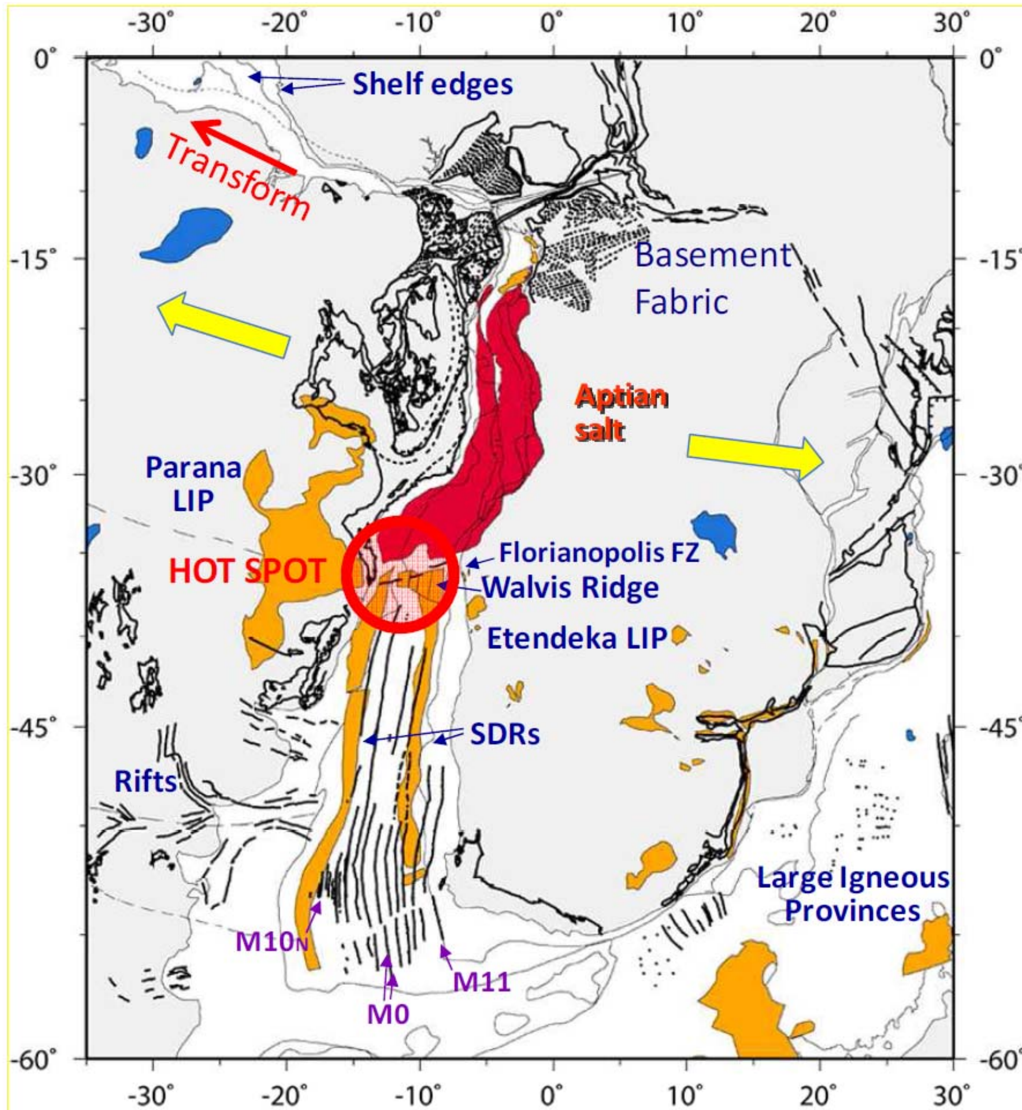

Figure 1. South Atlantic restoration (modified after Jackson et al., Bureau of Economic Geology, 2007). Aptian (120 Ma) basin, 1700-km-long, restricted by hot spot and transform "flood-gates" to the south and north, respectively, like the Miocene Red Sea.

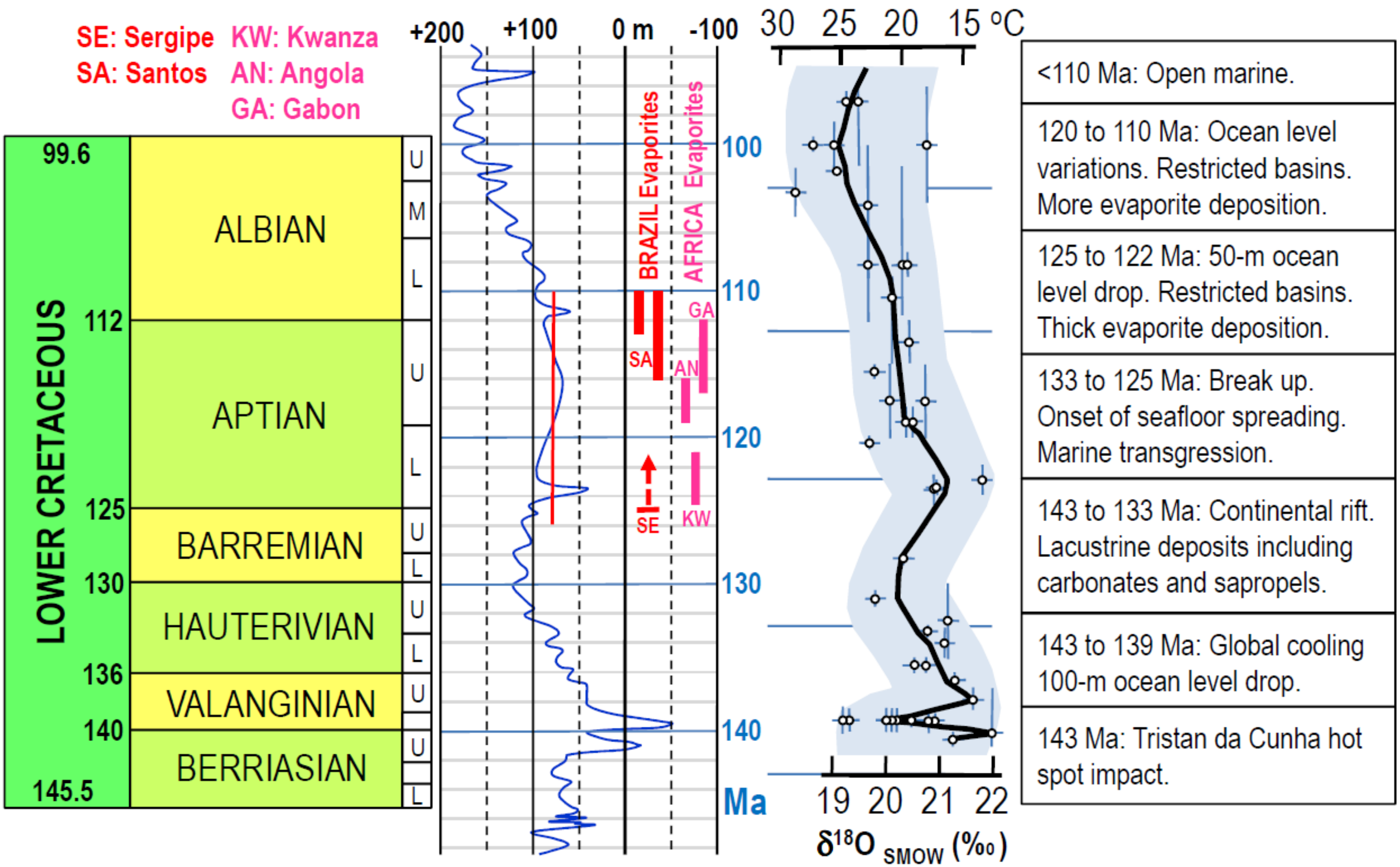

Figure 2. Stratigraphy, eustasy, ages, temperature, and main events of Early Cretaceous, Brazil and West Africa.

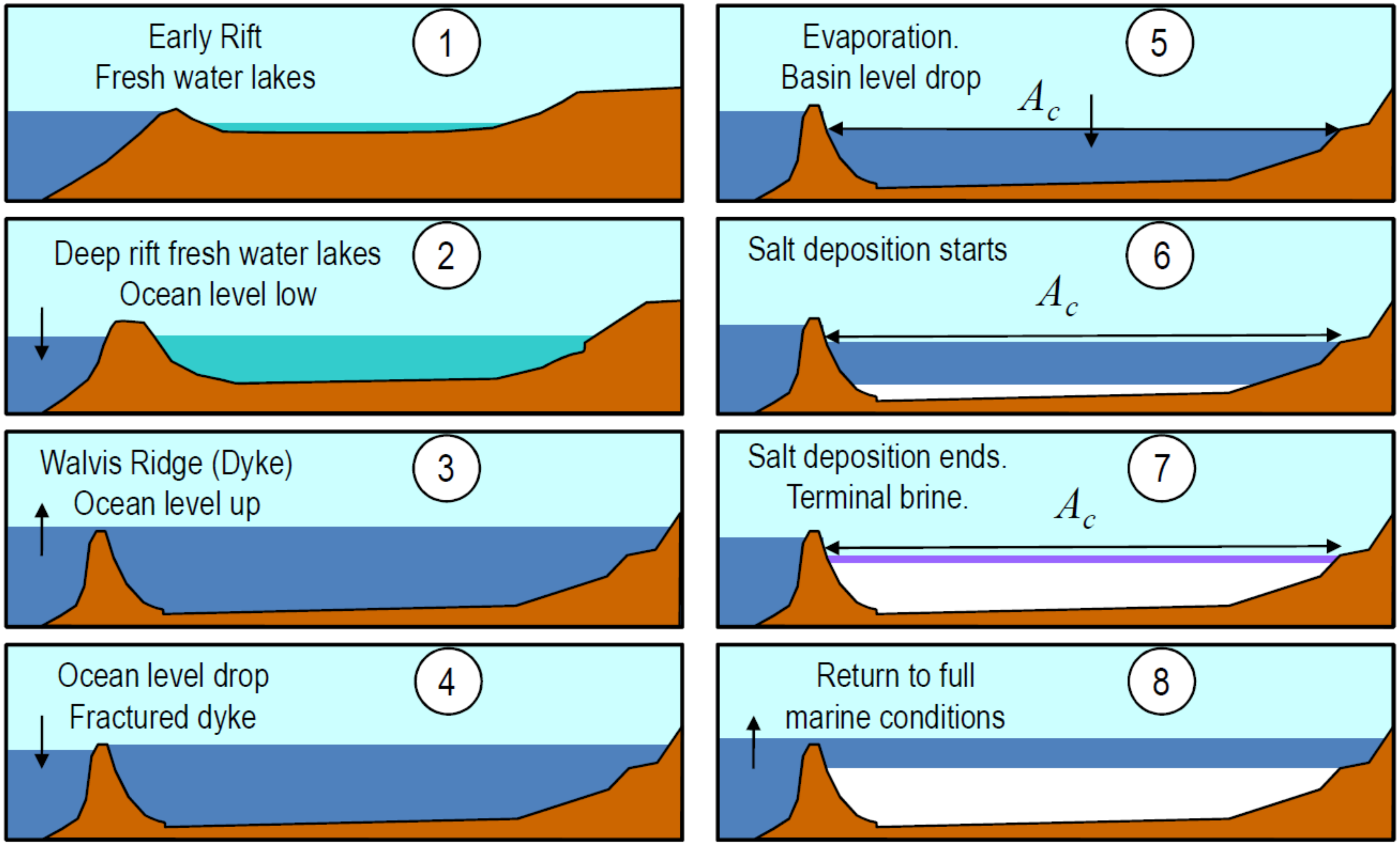

Figure 3. S implified scenario with "one salt m odel." Step 1 : Ocean level increases and seawater invades the rift d epression around 134-130 Ma. Step 2: at 123 Ma in the early Aptian, the ocean level drops by 50 m. Basin(s) are isolated from open ocean waters. Step 2: The evaporation rate is greater than water intake from rivers, rainfall, and seawater springs; water salinity gradually increases and the basin water level drops until the surface area of the water stabilizes at a critical value A_c. Step 4: The water surface area no longer changes significantly. Water keeps evaporating with a relatively stable 100-year average seawater intake until salt starts precipitating. Salinity is m aintained at salt satu ration concentration. The thickness of the salt layer gradua lly increases until re aching the critical water level (surface area A_c). Step 5: Return to open marine conditions.