# Evaluating the origin of salt deposits and salt structures

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Several creationist hypotheses have been proposed to explain the origin of salt deposits without invoking solar evaporation. In this paper, I evaluate the hypothesis in a recent paper by Heerema and van Heugten that explains salt deposits by means of igneous activity. I argue for a sedimentary, cold-water origin of salt deposits and the formation of salt structures by means of solid-state salt flow. Any creationist model needs to account for all characteristics of salt deposits.

Salt[1] deposits are generally understood as the result of solar evaporation in an isolated or semi-isolated basin.[2] In an isolated basin, net evaporation will increase the concentration of salts in the water, eventually leading to precipitation. In a semi-isolated basin, precipitation can occur as long as the outflow of salt is less than the inflow. The Mediterranean Sea, which was a salt basin in the past, serves as a model for these two models. In the 1970s, the Messinian salt deposits were explained by a complete desiccation of the Mediterranean Sea.[3] In the last decades, modelling studies have demonstrated the possibility of salt deposition with a seaway between the Atlantic Ocean and the Mediterranean Seaway that continuously supplied salt.[4,5]

Although the theory of solar evaporation has been the consensus since the late 19th century, several geologists have advocated other interpretations. Rode[6] and Sozansky[7] proposed an igneous origin of salt deposits, but did not garner much support in the geologic community. Currently, Martin Hovland *et al.* advocate a hydrothermal origin of many salt deposits.[8] Since evaporation is a process that is too slow to create thick salt layers within a young-earth timeframe, creationists have also developed hydrothermal and igneous models. Most creationists favour a hydrothermal model, defended in most detail by David Nutting[9] and Andrew A. Snelling.[10] In contrast, Stef J. Heerema and Gert-Jan H.A. van Heugten have proposed an alternative hypothesis that tries to explain how salt deposits could have formed rapidly during the Flood.[11] Furthermore, their hypothesis also suggests an explanation for the origin of salt structures, such as diapirs. Heerema and van Heugten argue that salt deposits are the result of a salt magma that erupted underneath the sediment-rich waters of the Flood. Diapirism is explained by a buoyancy-driven process as a result of the density contrast between the liquid salt and the water-soaked sediments.

The hypothesis of Heerema and van Heugten will be examined and their arguments evaluated. I will argue that their hypothesis lacks explanatory power and sketch an alternative model.

### The sedimentary origin of salt deposits

Primary crystals in salt deposits can have a wide range of morphologies. B. Charlotte Schreiber provides examples of these morphologies from the salt deposits of the Mediterranean and Michigan Basin.[12] These morphologies (e.g. twinned gypsum crystals, lenticular gypsum, halite hoppers, and chevron halite) are also formed in laboratory evaporation experiments,[13] modern solar ponds,[14] and salt pans.[15] In the Messinian deposits of the Mediterranean, alternations of thin salt layers with shale can be found at multiple levels, which demonstrates a low-temperature, sedimentary origin of these salt layers.[16] Resedimented salts (salts that have been eroded and transported) can contain numerous sedimentary structures, e.g. cross-bedding and turbidite structures.[17] Despite the fact that large portions of salt deposits have lost their primary features as a result of diagenesis and salt tectonics, most formations contain several of the above characteristics that indicate a sedimentary origin.

It has not been demonstrated that an igneous model can account for many of these characteristics. In addition, most salt deposits contain several minerals that are unstable under high temperatures, such as gypsum, which loses its water between 100 and 150°C and becomes anhydrite.[18] The crystal morphology of gypsum in many salt deposits suggests a primary origin, whereas anhydrite can sometimes retain the structure of the gypsum it originated from, demonstrating a secondary origin.[19] Likewise, clay minerals that are present in small quantities in rock salt[20] and in siliciclastic layers interbedded in salt formations[21] exclude a high-temperature origin of salt deposits, as these minerals would have disappeared due to contact metamorphism.

Heerema[22] pointed out that many salt deposits contain almost no siliciclastic sediment or fossils and used this as an argument against the theory of evaporation. The absence of large amounts of siliciclastic sediments can be explained by the difference between the precipitation rate of salt and the average rate of siliciclastic sediment deposition in a

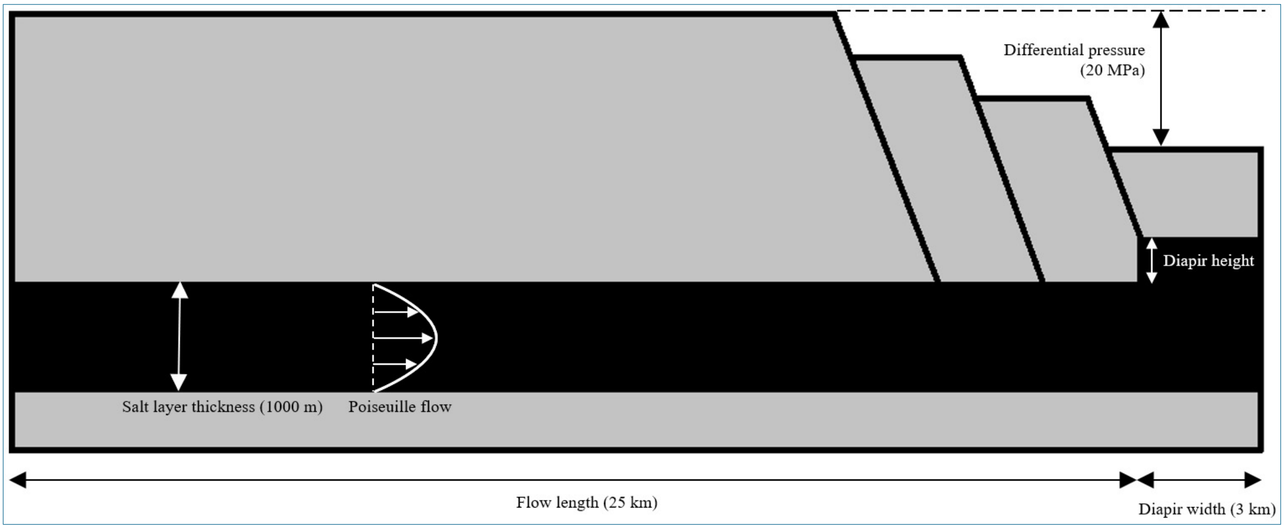


**Figure 1**. Sketch (not to scale) of the situation used to model the rise of a salt diapir in figure 2

large basin. Moderate evaporation rates can lead to the precipitation of 2–5 cm of gypsum and 2 to >10 cm of halite,[23] while the present clastic sedimentation rate is < 0.1 cm/yr.[24] Since hypersaline environments are almost entirely devoid of multicellular life,[25] the absence of macrofossils can easily be explained. Microfossils such as pollen,[26] bacteria,[27] and microbial laminations[28] are regularly found in salt deposits, consistent with a sedimentary origin.

### The origin of salt structures

A common feature of salt deposits is the presence of salt structures, such as walls and diapirs. These structures are generally interpreted as the result of solid salt flowing like a fluid over long periods of time.[29] Strain in samples of natural rock salt was measured at differential stresses as low as 0.2 MPa,[30] indicating that salt will deform in various geological situations. Processes like dislocation creep and pressure-solution creep make it possible that solid salt behaves like a viscous fluid. For example, salt deposits often act as décollements in thrust belts, as is the case in the Pyrenees, which are called "a salt-based folded belt".[31] If the pressure is lowered at some point above a salt layer (e.g. because of the formation of a graben), salt will move upwards until the pressure is balanced. If the average density of the overburden is higher than the density of the salt (which is 2,200 kg/m$^3$ or even lower[32]), the salt will even reach the surface and spread out.

Heerema and van Heugten criticize the differential loading model of salt tectonics by referring to the difference in pressure gradient between laboratory and natural settings.[33] However, the laboratory experiments they refer to do not work with pressure gradients, since the entire salt cylinder is subject to the same anisotropic vertical and horizontal stresses. The creep behaviour of salt in these experiments demonstrates that we can model salt as a Newtonian fluid with a viscosity that is given by the relationship between differential stress and strain rate. In most natural settings, the dynamic viscosity of rock salt lies between $10^{17}$ and $10^{20}$ Pa.s.[34] Using the equation for two-dimensional plane Poiseuille flow between two plates and assuming no elevation difference, we can determine the discharge per unit width in a salt layer:[35]

$$q(t) = \frac{h^3}{12\eta}\frac{\Delta P(t)}{L} \qquad (1)$$

where

$$\Delta P(t) = \Delta P_0 - h_d(t)\rho_s g \qquad (2)$$

where

$$h_d(t) = \int_0^t \frac{q(t)}{w}\,dt \qquad (3)$$

Here *q(t)* denotes discharge per unit width, *h* thickness of the salt layer, *η* the dynamic viscosity, *ΔP(t)* the differential pressure, *L* the flow length, $\Delta P_0$ the initial differential pressure, $h_d(t)$ the diapir height, $\rho_s$ the salt density, *g* the gravitational acceleration, and *w* the width of the diapir. Following Heerema and van Heugten, we can assume an initial differential pressure of 20 MPa and salt flow over a length of 25 km, which entails an initial pressure gradient of $8 \times 10^{-4}$ MPa/m. I further use a salt layer thickness of 1,000 m, a viscosity of $10^{18}$ Pa·s, a density of 2,200 kg/m$^3$, a gravitational acceleration of 9.8 m/s$^2$ and a diapir width of 3,000 m. Figure 1 gives an overview of these constants and variables in the model. If we run this model, a diapir height of almost 500 m is reached after a million years (figure 2).

This demonstrates the possibility of diapir formation within the timeframe of uniformitarian geology.

This simplified model can be made more realistic by adding several factors that enhance or resist salt flow. Instead of lifting up the overburden, the diapir can push its roof aside, which lowers the pressure above the diapir; erosion of the roof also lowers the pressure. Compressional tectonic forces, a lower viscosity due to lower grain sizes or higher temperature, an elevation head gradient, and thermal loading can also drive salt flow. Weak salts such as bischofite and carnallite can result in higher strain rates, lowering the overall viscosity of salt.

On the other hand, the strength of the overburden, the movement of the overburden in the opposite direction, and the presence of salts with a high viscosity (e.g. anhydrite) are factors that resist salt flow. Equation (1) shows that discharge is proportional to the cube of the salt layer thickness. As a result, salt flow decreases due to thinning of the salt layer.[36] Numerical models that take these factors into account demonstrate the possibility of the formation of salt diapirs in millions of years.[34,37,38]

The formation of salt structures can take place in numerous settings, creating various types of diapirs and other structures. However, tectonic faults are in almost all cases needed to create a differential pressure (in extensional regimes) or pierce the roof of the diapir (in compressional regimes). The standard model of salt tectonics predicts therefore a strong association between faults and diapirs. This prediction is confirmed by salt structures worldwide. For example, Miocene salt walls in the Red Sea all lie in grabens[39] and diapirs of the Carboniferous Paradox Formation of Utah and Colorado are correlated to the Late Paleozoic Uncompahgre Uplift, which triggered the formation of a sequence of salt walls.[40]

## Evaluating the evidence for igneous salt

Barnhart[41] has already commented on the evidence for salt magmas that is put forward by Heerema and van Heugten. The natrocarbonatite magma of Ol Doinyo Lengai, Tanzania, mainly consists of nyerereite and gregoryite and is probably the result of considerable differentiation.[42] The magma contains small quantities of halite and sylvite, which crystallize together into a solid solution during a late stage of magma cooling. An igneous model for salt formations needs to account for the fact that halite layers in salt deposits contain almost no sylvite, but sylvite may occasionally be found in separate layers on top of the halite. The late crystallization creates the possibility that further differentiation of a natrocarbonatite would result in a NaCl-rich magma. However, such a far-reaching differentiation is unlikely to have happened quickly during the Flood, and it is unclear how such a complex process could have led to the enormous volumes of salt that are present in salt deposits.

Another indication of a salt magma would be the existence of primary igneous anhydrite.[43] In various igneous rocks, anhydrite occurs as phenocrysts or inclusions. It often co-nucleates together with apatite, a mineral that is not present in salt deposits. Its $\delta^{34}S$ value is comparable to other igneous rocks and well outside the range of $\delta^{34}S$ values of anhydrite in salt deposits.[44] The isotopic differences and context of igneous anhydrite make a comparison with anhydrite in salt deposits unwarranted.

According to Heerema and van Heugten, the layering of salt deposits could potentially be explained by the solidification behaviour of ionic liquids (i.e. liquids composed entirely of ionic compounds). However, ionic liquids often form a structure of microscopic *lamellae* and other structures that are not present in salt deposits.[45] The macroscopic layering of salt deposits poses a problem for an igneous model as well, since many salt deposits contain an anhydrite or gypsum layer both near the bottom and near the top of the formation. This is generally explained as the result of the increase and decrease of the salinity in the basin, respectively.

## Evaluating the evidence for magmatic diapirism

Heerema and van Heugten argue that diapirism in solid state is impossible and suppose that diapirism took place when the salt deposit was still a magma and the overlying sediments were soft and unconsolidated. They compare the structure of a Rayleigh-Taylor instability to salt diapirs in a compressional basin. However, the superficial similarity between these structures can be explained by the fact that solid salt indeed behaves like a buoyant fluid, whereas the differences can be explained by the brittle behaviour of the overburden. The turbulence of a real Rayleigh-Taylor instability would lead to vortices with intricate mixing of salt and sediments.

Several characteristics of diapirs contradict an origin in liquid phase. For example, diapirs often retain the structure of distinct layers of the undeformed salt.[46] Turbulent flow in liquid phase would have mixed these layers. The relatively high density of a salt magma would have made it difficult to pierce through the unconsolidated sediments of the overburden and flow over the surface or sea bottom. Unlike magmatic intrusions, salt diapirs do not contain a contact metamorphic halo. The igneous model of diapirism also lacks an explanation for the relation between diapirs and faults, especially since the model suggests that the sediments of the overburden were water-soaked during diapirism, which would have prevented the formation of faults. These characteristics make it highly improbable that salt structures are the result of magmatic diapirism.

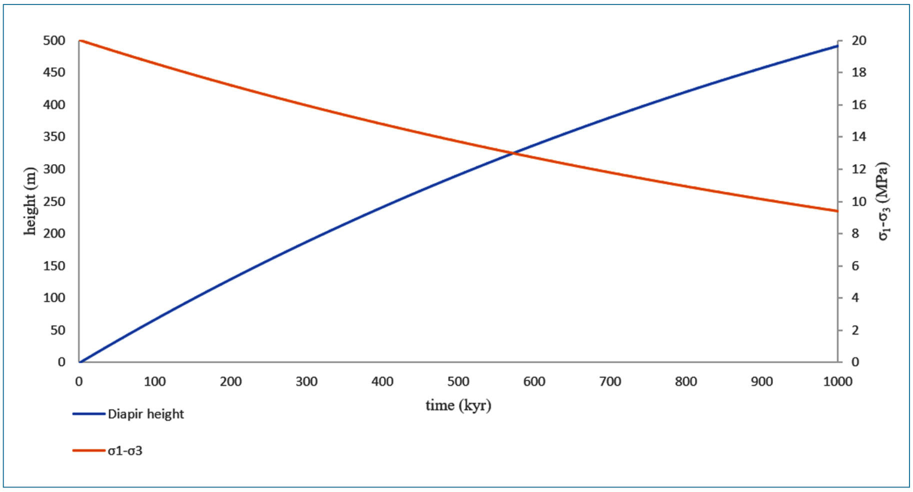


**Figure 2**. Development of diapir height and differential pressure with a salt viscosity of $10^{18}$ Pa·s and a density of 2,200 kg/$m^3$. Other variables are specified in figure 1.

## Creationists need to consider other mechanisms

Creationists need to take the arguments in favour of a cold-water sedimentary origin of salt deposits into account. There are some processes that may explain salt deposits within a young-earth framework. First, serpentinized lithosphere can host large volumes of salt, which escape as NaCl-rich brines during subduction.[47,48] Upon cooling, these brines will result in large flows of brine and particulate salt, which can presently be observed at the bottom of the Red Sea.[49] Evaporation could further enhance precipitation from the concentrated brine. Second, large tectonic forces during and after the Flood, combined with a very low viscosity of salt as a result of high temperatures, small grain sizes and high water content, can enhance the flow rate of salt in solid state.[34] Using equations (1) to (3) in the same way as before but with a viscosity which is a thousand times lower (i.e. $10^{15}$ Pa·s) results in a diapir that rises a thousand times faster, i.e. 500 m in about 1,000 years. This very low viscosity falls within the range of viscosities observed in salt glaciers,[50] which indicates that it is possible under highly favourable conditions.

These processes could account for more of the characteristics of salt deposits than the hypothesis of igneous salt. However, a detailed examination of individual salt deposits is needed to determine their validity.

## Conclusion

Crystal morphologies and sedimentary structures show that salt deposits most likely have a sedimentary origin. The physics governing salt tectonics demonstrate the possibility of diapirism as a result of the flow of solid salt. On the other hand, the hypothesis that tries to explain salt deposits and salt structures as the result of igneous activity during the Flood fails to account for a large array of data. Therefore, creationists should develop an alternative sedimentary model that accounts for the origin of salt deposits and rapid solid-state salt flow that accounts for the origin of salt structures.

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