Large evaporite provinces: Warming from above or heating from below?

Zhanjie Qin,[1,2] Chunan Tang,[3,4,]* Lijun Liu,[5,]* Tiantian Chen,[6,7] and Bin Gong[8]

[1] Key Laboratory of Comprehensive and Highly Efficient Utilization of Salt Lake Resources, Qinghai Institute of Salt Lakes, Chinese Academy of Sciences, Xining 810008, China

[2] Qinghai Provincial Key Laboratory of Geology and Environment of Salt Lakes, Xining 810008, China

[3] State Key Laboratory of Coastal & Offshore Engineering, Dalian University of Technology, Dalian 116024, China

[4] Computational Geoscience Research Center, Chengdu University of Technology, Chengdu 610059, China

[5] Department of Geology, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

[6] School of Resources and Civil Engineering, Northeastern University, Shenyang 110819, China

[7] State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (Wuhan), Wuhan 430074, China

[8] Department of Civil and Environmental Engineering, Brunel University London, London UB8 3PH, UK

*Correspondence to: tca@mail.neu.edu.cn (C.T.); ljliu@illinois.edu (L.L.)

INTRODUCTION

As chemical sedimentary rocks, evaporite deposits generally originate from brine evaporation, concentration, and crystallization in lakes or marine basins. Conventional wisdom states that the formation of evaporites is linked to arid climate conditions in bays, lagoons, and continents, with solar evaporation as the main driver.[1] However, this cannot explain the occurrence of widespread, ultrathick evaporites from many geological periods, *e.g.*, deep-sea evaporites a few kilometers thick in the Mediterranean–Red Sea–Zagros region and the Gulf of Mexico–Central South Atlantic. Additionally, many ancient evaporites with large areas and thicknesses were frequently deposited in relatively concentrated areas within short periods of time.[2] These observations all challenge the solar evaporation model. In recent years, it has been realized that the formation of these giant salt deposits may be related to rifting or orogeny, which may be explained by magmatic or hydrothermal activity, i.e., endogenesis. Holland et al.[3] proposed the submarine supercritical fluid theory. Until now, the role of geotherm and hydrothermal fluids in the formation of giant evaporite deposits has been unclear and controversial.

On the basis of analysis of the spatiotemporal relationships between evaporites, large igneous provinces (LIPs), global sea surface temperature and CO_2 concentration during the Phanerozoic, we propose that giant evaporite deposits are mainly controlled by periodic tectonic activity and the associated geothermal driver, which is dictated by the thermal fluctuation model for Earth evolution.[4] This bottom-up geothermal mechanism provides insights into the internal relationships between salt giants, LIPs and paleoclimate.

Large evaporite provinces

The global spatiotemporal distribution of evaporite deposits (halite and sulfate) suggests a correlation between evaporite formation and active tectonic zones. We collected data from 128 evaporite deposits formed during different geological periods of the Phanerozoic. Geographically, 19.5%, 35.9% and 44.6% of evaporite deposits occur in cratons, convergent plate margins and rift settings, respectively. Temporally, they were formed mainly during high-temperature periods such as Cambrian, Permian, Triassic, Jurassic, Cretaceous and Miocene times. In our study, salt deposits with volumes of more than 500×10^3 km^3 are defined as large evaporite provinces (LEPs). Accordingly, we found that LEPs were mostly deposited during active tectonic periods in both continental and submarine environments. In addition, the LEP volume is large at deep-sea rift boundaries and convergent boundaries where geothermal channels may exist. Other LEPs are relatively small, especially in cratonic settings. During almost all LEP-formation periods, there was significant tectonic activity, crustal deformation, and paleogeographic pattern modification, such as the Caledonian, Hercynian, and Indosinian orogenies and the breakup of Pangea. These tectonic episodes were also frequently accompanied by major geothermal events, especially LIP eruptions.

DISCUSSION

Formation mechanism of LEPs

The conventional view is that the formation of evaporites is controlled by three basic factors: tectonics, source and climate. Among these factors, tectonic factors provide salt storage sites, mainly as various types of basins. The source factor is the salt-forming material, which mainly comprises fluids, including seawater, terrestrial waters, deep hot water or hydrothermal fluids. The climate factor (solar evaporation) is considered the main driving force of the continuous evolution (concentration or desalination) of salt-forming fluids in the basin, especially within the subtropical high-pressure zone where arid and hot climate conditions are favorable for evaporite formation.

Among these three factors, tectonics and sources are analogous to reactants in a chemical reaction, while solar evaporation may be likened to a catalyst. Evaporites can form by the coupling of these three factors. However, solar evaporation is not the only catalyst. The geothermal effect can also increase the fluid salinity, leading to supersaturation of salt minerals and consequential precipitation of salt to form evaporite deposits. For example, the salinization of supercritical fluids in the deep sea is mainly controlled by submarine geothermics (serpentinization and high-temperature water–rock interaction in rift tectonics). High-salinity thermal springs in orogenic belts are the main source of surface salt lakes, and their genesis is closely related to high-temperature water–rock interactions or magmatic hydrothermal fluids. In extreme cases such as LIP formation, high temperatures prevail on Earth, and more intense geothermal activity occurs. Even the temperature of the Earth's atmosphere significantly increases, further enhancing the surface evaporation effect.

To investigate the formation mechanism of LEPs, we compared the records of LEPs, LIPs, global sea surface temperature and CO_2 concentration during the Phanerozoic. We found that the spatiotemporal correlation between Earth's sea surface temperature and LEPs is weak and inconsistent with the solar evaporation hypothesis as the main controlling factor for evaporite formation. Similarly, the temporal correlation between the CO_2 concentration, generally considered the key controlling factor of global warming, and LEPs is also nonsignificant. The long-term trends of decreasing CO_2 concentrations and sea surface temperatures throughout the entire Phanerozoic are accompanied by an increasing occurrence frequency of LEPs. Instead, LEPs show a strong connection with LIPs. The eruption of LIPs lags slightly behind that of LEPs. For example, the time difference between Paleozoic LEPs and LIPs is smaller than that between the formation of LEPs and periods of the maximum sea surface temperature. The latter during the Mesozoic-Cenozoic reached as much as 50 Myr, much greater than the former. This indicates the presence of near-surface thermal anomalies prior to the formation of LIPs. This inference also agrees with the latest finding that atmospheric warming could precede LIP eruption ~1 Myr.[5]

These observations indicate that the crust may have been heated by geothermal energy for a prolonged period prior to LIP eruption. Moreover, lithospheric thinning resulting from tectonic extension or delamination can further enhance the heating of the crust. The observed spatiotemporal correlation between LEPs and LIPs with LIPs occurring slightly later suggests that LEP formation results from crustal heating prior to LIP eruption. In some cases, LEP formation can be promoted by both magmatic hydrothermal liquids or hot water associated with the heating process and an external warm environment (Figure 1).

We therefore conclude that the spatiotemporal development of LEPs directly reflects the thermal state of the underlying crustal rock. Physically, the Earth's interior heats the lithosphere through thermal conduction. With the aid of tectonic activity, heat can accumulate and warm the lithosphere to a critical point where magma eruption and LIP formation occur. Choosing 20-50 Myr as the time needed from initial crustal warming to magmatic eruption, the sequential development of LEPs, LIPs and global high temperatures verifies the bottom-up geothermal mechanism.

Geothermal vs. solar forcing and LEP formation

From the above analysis, giant evaporites are most likely formed in areas with high heat flow. Indeed, the strong spatiotemporal correlation between LEPs and LIPs at rifts and convergent margins clearly indicates the dominant role of geothermal anomalies in LEP formation. Examples include the spatiotemporal relationship between the Mediterranean LEPs (5.9–5.6 Ma) and Pan-Mediterranean LIPs (~6.0 Ma). The lithosphere thicknesses in these regions are relatively small (only approximately 20-30 km), indicating high geothermal gradients. The latest research shows that even stable cratonic regions may experience lithospheric thinning and heating during supercontinent breakup. Thus, the geothermal state of the lithosphere may be an important factor in governing the Earth's surface environment, driving atmospheric temperature fluctuations and inducing LEP and LIP events. Although our research suggests that the geothermal evaporation model can explain the time, space and volume of LEPs better than the traditional solar evaporation model, the model does not exclude the role of solar evaporation in the formation of evaporite deposits.

Our study provides insights into the internal processes that result in surface heat anomalies by investigating the global geothermal flux at the Earth's surface. Previous lithospheric thermal models mostly assumed that Earth loses heat mainly by conduction through the lithosphere. Heat flow in Earth's tectonic regions can reach approximately 1 W/m^2. More importantly, this represents the long-term (one-to-ten-million-year timescale), enduring effect of heat sources. In contrast, solar radiation, although attaining a much higher mean value (>1000 W/m^2 in summer), remains extremely stable over time, with little recorded variation during past LEP events. Consequently, a steady heat supply from inside the Earth is generally considered be the main mechanism driving large-scale tectonic activity and major magmatic processes, including LIP formation. We therefore suggest that LEPs are associated with the same geothermal driver as LIPs. Compared to the solar evaporation model, a geothermal energy driver can better explain the basic characteristics of associated geological events, such as the short duration and large volume of LEPs.

CONCLUSION

We propose that LEPs strongly correlated with tectonic events are mainly controlled by periodic geothermal activity in the crust and shallow mantle. Although the exact physics of how the geothermal process drives LEP formation should be further researched, the geothermal evaporation model proposed here provides a new perspective for understanding the origin of these salt giants.

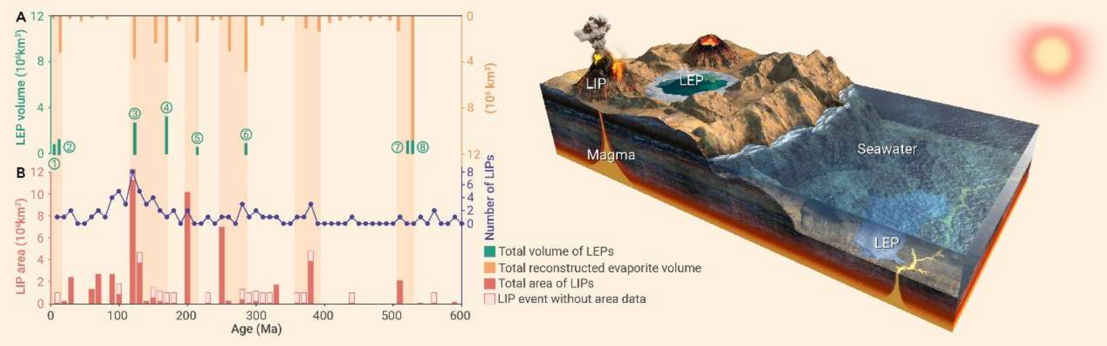

Figure 1. Models of the formation of LEPs controlled by geothermal energy in different geologic settings, volumes of reconstructed evaporites and LEPs, and areas and numbers of LIPs at different geologic times. **(A)** Plot of the formation age vs. The volume for the reconstructed evaporites and LEPs formed during the Phanerozoic (1–Mediterranean, 2–Red Sea, 3–South Atlantic, 4–Gulf of Mexico, 5–Northern Sahara, 6–Eastern European, 7–Iran-Pakistan, 8–East Siberian). **(B)** Plot of the area vs. the age for the LIPs formed during the Phanerozoic; the pink boxes indicate LIPs without area data. The orange bars represent six periods of occurrence of LEPs during the Phanerozoic. Link to dataset: https://www.scidb.cn/s/AFr6vm, and the DOI is 10.57760/sciencedb.08249

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DECLARATION OF INTERESTS

The authors declare no competing interests.