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Large Evaporite Provinces: Geothermal rather than Solar Origin?

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37 **Large evaporite provinces (LEPs) represent prodigious volumes of evaporites**
38 **widely developed from the Sinian to Neogene. The reasons why they often**
39 **quickly develop on a large scale with large areas and thicknesses remain**
40 **enigmatic. Possible causes range from warming from above to heating from**
41 **below. The fact that the salt deposits in most salt-bearing basins occur mainly in**
42 **the Sinian-Cambrian, Permian-Triassic, Jurassic-Cretaceous, and Miocene**
43 **intervals favours a dominantly tectonic origin rather than a solar driving**
44 **mechanism. Here, we analysed the spatio-temporal distribution of evaporites**
45 **based on 138 evaporitic basins and found that throughout the Phanerozoic,**
46 **LEPs occurred across the Earth's surface in most salt-bearing basins, especially**
47 **in areas with an evolutionary history of strong tectonic activity. The masses of**
48 **evaporites, rates of evaporite formation, tectonic movements, and large igneous**
49 **provinces (LIPs) synergistically developed in the Sinian-Cambrian, Permian,**
50 **Jurassic-Cretaceous, and Miocene intervals, which are considered to be four of**
51 **the warmest times since the Sinian. We realize that salt accumulation can**
52 **proceed without solar energy and can generally be linked to geothermal changes**
53 **in tectonically active zones. When climatic factors are involved, they may be**
54 **manifestations of the thermal influence of the crust on the surface.**

55
56 The traditional definition of evaporite is a chemically precipitated salt generally
57 containing carbonate, sulphate and chloride salts formed on the basis of their own
58 saturability in concentrated brine in a certain tectonic environment¹. Under this
59 paradigm, concentrated brine was usually considered to be the result of evaporation of
60 natural water by the solar energy. For example, the “Bar theory”², “Desert-basin
61 theory”³, and “Deep-water theory”⁴, etc., were the classical salt-forming theories of
62 seawater by evaporation of solar. However, the origin of salt giants thousands of
63 metres thick in marine environments are difficult to decipher by these traditional
64 models^{5,6}, e.g. the large evaporite deposits in the Mediterranean (~3 km in thickness),
65 Red Sea (>3 km in thickness) and Atlantic (>2 km in thickness)^{7,8,9,10}. These salt
66 giants were usually accumulated in active tectonic environments (subduction or rift)
67 and accompanied by some magmatic-hydrothermal events, which may occur as parts
68 of “Wilson cycles”^{5,6}. Meanwhile, the complicated hydrodynamics, thermodynamics
69 and properties of brines and the processes of solid-liquid phase transformations in

these salt giants were different from the traditional salt formation models^{5,6,9,10,11}. The current upsurge in the study of evaporite dynamics, the development of new evaporite mechanisms and the ensuing controversies^{5,6,8,9,10,11} have led to re-assessment of various roles in salt accumulation. Therefore, a new systematic salt accumulation mechanism is eagerly needed for these large salt deposits.

Throughout the Phanerozoic, a total of 138 evaporitic basins were collected around the world (Fig. 1 and Extended Data Table 1). Among them, 21 basins (15%) were on stable craton blocks, 50 basins (36%) were in convergent subduction tectonic settings, and 66 basins (49%) were in rifting environment. These evaporitic basins developed episodically, mainly in the Precambrian-Cambrian, Permian, Jurassic-Cretaceous, and Miocene periods (Fig. 2a). The Precambrian and early Palaeozoic intervals were characterized by cratonic basins, convergent basins were dominant in the Cambrian and Cenozoic, and rift basins were mainly distributed in the Mesozoic (Fig. 2a). In addition, the masses of evaporites (halite) were different in three types of tectonic basins through geological time¹². The evaporite mass was less than 4000×10^{15} kg (average 924×10^{15} kg) in all cratonic basins, while the maximum was approximately $11,000 \times 10^{15}$ kg (average 2343×10^{15} kg) in subduction settings and rift basins (Fig. 2b, c). Specifically, large amounts of halite was accumulated on the ocean floor, such as $\sim 8400 \times 10^{15}$ kg in the Gulf of Mexico in the Jurassic, $\sim 6000 \times 10^{15}$ kg on the seabed of the North and South Atlantic in the Cretaceous, and $\sim 2300 \times 10^{15}$ kg on the sea floor of the Mediterranean and Red Seas in the Miocene¹². These data indicated that the ocean floor, as subduction or rifting environments, was in favour of salt formation in seawater. Moreover, the rates of salt formation in different tectonic basins were calculated from statistical data (Extended Data Table 4). The rate of salt formation in cratonic basins ranged from $\sim 0.02 \times 10^{15}$ kg/Ma to $\sim 70 \times 10^{15}$ kg/Ma (average $\sim 19 \times 10^{15}$ kg/Ma), while it ranged from $\sim 0.9 \times 10^{15}$ kg/Ma to $\sim 290 \times 10^{15}$ kg/Ma (average $\sim 73 \times 10^{15}$ kg/Ma) in subduction settings and rift basins. For example, the rates of salt accumulation on the sea floor of the Mediterranean and Red Seas in the Miocene, the North and South Atlantic in the Cretaceous, and the Gulf of Mexico in the Jurassic were $\sim 134 \times 10^{15}$ kg/Ma, $\sim 76 \times 10^{15}$ kg/Ma and $\sim 156 \times 10^{15}$ kg/Ma, respectively (Fig. 2d). Accordingly, the masses and salt-forming rates of evaporite in different tectonic basins demonstrated that salt giants were more easily accumulated in active tectonic environments than in stable cratons. This might be related to the geothermal properties of subduction and rifting tectonic environments in specific

geological time, which were usually the breeding grounds of magmatic events and hydrothermal activity.

Fig.1 | Distribution of evaporitic basins around the world through geological time (redrawn

from^{1,25}) (Extended Data Table 1). Basin names: 1. Abenaki (N. Scotian), 2. Adavale, 3. Adelaide Fold Belt, 4. Adriatic-Albanian Foredeep, 5. Amadeus Basin, 6. Amadeus Basin (Chandler), 7. Amazonas, 8. Andean, 9. Andean, 10. Apennine, 11. Appalachian, 12. Aquitaine, 13. Arabian Basin (Gotnia Salt Basin), 14. Arabian Basin (Hith Salt Basin), 15. Arabian Basin (Hormuz central Saudi Arabia), 16. Arabian Basin (Hormuz Gulf region), 17. Arabian Basin (Hormuz-Kerman region), 18. Atlas (Algerian-Tunisian), 19. Atlas (Moroccan), 20. Baltimore Canyon, 21. Berrechid, 22. Betic-Guadalquivir Basin, 23. Bohai Basin, 24. Bonaparte (Petrel), 25. Brazilian Aptian Basin (Camamu), 26. Brazilian Aptian Basin (Campos-Santos), 27. Brazilian Aptian Basin (Ceara), 28. Brazilian Aptian Basin (Cumuruxatiba), 29. Brazilian Aptian Basin (Sergipe-Alagoas), 30. Cankiri-Corum, 31. Canning Basin, 32. Cantabrian-West Pyrenees, 33. Carnarvon Basin (Yaringa), 34. Carpathian foredeep, 35. Carson Basin (Grand Banks), 36. Chu-Sarysu (Devonian), 37. Chu-Sarysu (Permian), 38. Cicilia-Latakia, 39. Cuban, 40. Danakil, 41. Dead Sea, 42. Dniepr-Donets, 43. Dniepr-Donets, 44. Eastern Alps, 45. Ebro Basin, 46. Flemish Pass Basin (Grand Banks), 47. Georges Bank, 48. Green River Basin, 49. Gulf of Mexico (northern Gulf coast), 50. Gulf of Mexico (southern; Salina-Sigsbee), 51. Haltenbanken, 52. Haymana-Polatli, 53. Holbrook Basin, 54. Horseshoe Basin (Grand Banks), 55. Hudson Bay, 56. Ionian, 57. Jeanne d' Arc Basin (Grand Banks), 58. Jiangnan Basin, 59. Jura/Rhodanian, 60. Katangan, 61. Khorat Basin, 62. Kuqaforeland (Tarim Basin), 63. La Popa (Monterrey) Basin, 64. Lusitanian, 65. Mackenzie Basin, 66. Maestrat, 67. Majunga Basin, 68. Mandawa Basin, 69. Ma' Rib-Al Jawf/Shabwah (Hadramaut), 70. Maritimes Basin, 71. Mediterranean-Western, 72. Mediterranean-Adriatic, 73. Mediterranean-Andros Basin, 74. Mediterranean-Cretean Basin, 75. Mediterranean-Samothraki basin, 76. Mediterranean-Tyrrhenian, 77. Mediterranean-Central, 78.

Mediterranean-Eastern, 79. Mediterranean-Sicilian, 80. Michigan Basin, 81. Moesian, 82. Moose
 River Basin, 83. Neuquen Basin, 84. Nordkapp Basin, 85. Officer Basin, 86. Olduvai depression,
 87. Oman (Fahud Salt Basin), 88. Oman (Ghaba Salt Basin), 89. Oman (Ghudun Salt Basin), 90.
 Oman (South Oman Salt Basin), 91. Oriente-Ucayali (Pucara) Basin, 92. Orpheus Graben, 93.
 Palmyra, 94. Paradox Basin, 95. Parry Island Fold Belt, 96. Pricaspian Basin, 97. Pripyat Basin,
 98. Qaidam Basin, 99. Qom-Kalut, 100. Red Sea (north), 101. Red Sea (south), 102. Rot Salt
 Basin, 103. Ruvuma Basin, 104. Sabinas Basin, 105. Sachun Basin, 106. Salar Basin (Grand
 Banks), 107. Salt Range (Hormuz-Punjab region), 108. Salt Range (Kohat Plateau), 109. Saltville
 (Appalachian), 110. Scotian Basin, 111. Siberia, East, 112. Sirjan Trough, 113. Solimoes, 114.
 Somalia-Kenya, 115. South Whale Basin (Grand Banks), 116. Sverdrup Basin (Ellef Ringnes-NW
 Ellesmere), 117. Sverdrup Basin (Melville Is.), 118. Tabriz Salt Basin, 119. Tadjik Basin, 120.
 Takutu Salt Basin, 121. Transylvanian, 122. Tromso Basin, 123. USA Midcontinent, 124. West
 Africa (Angola-Gabon), 125. West Africa (Gambia-Guine Bissau), 126. West Africa
 (Mauritania-Senegal), 127. West Africa (Morocco-Spain), 128. Western Canada (Alberta Basin),
 129. Whale Basin (Grand Banks), 130. Williston Basin, 131. Zagros (Mesopotamian Basin), 132.
 Zagros (Mesopotamian Basin), 133. Zechstein (NW Europe), 134. Zechstein (onshore UK), 135.
 Zipaquira Basin, 136. Erdos Basin, 137. Sichuan Basin, 138. Lanping-Simao Basin.

Fig.2 | The relationship between mass of evaporate and tectonics in the geological time. a,
 Distribution of different tectonic types of evaporitic basins through geological time (data from¹). **b,**
 Total masses of halite in different geological periods(mass $\times 10^{15}$ kg). **c,** Masses of halite in different
 tectonic types of evaporitic basins through geological time (mass $\times 10^{15}$ kg). **d,** Rates of salt
 formation in different tectonic types of evaporitic basins through geological time (10^{15} kg/Ma);
 (data are from^{12, 26, 27}).

To reveal the inter-relationships between evaporite and geothermal events in
 active tectonic settings around the world, the salt giant with a mass of
 halite $>2000 \times 10^{15}$ kg and a rate of salt formation $>70 \times 10^{15}$ kg/Ma is preliminarily
 defined as a large evaporite province (LEP) based on the tectonic types of the basin,

masses of evaporite, and rates of salt formation. For instance, the East Siberian evaporite province in the Cambrian, Zechstein evaporite province in the Permian, Gulf of Mexico evaporite province in the Jurassic, Atlantic evaporite province in the Cretaceous and Mediterranean and Middle East evaporite provinces in the Miocene can be considered as the LEPs. During four main salt-forming geological times, we compared the LEPs with the Large Igneous Provinces (LIPs), an extreme magmatic thermal event, and found that the LIPs were always accompanied by the LEPs (Fig. 3). In detail the LIPs of European-Northwest African (EUNWA)/Skagerrak (~300 Ma), the Central Atlantic magmatic province (CAMP) (~201 Ma), the Paraná-Etendeka (~132 Ma), the Afro-Arabia (~30 Ma), and the Pan-Mediterranean (~6.0 Ma) occurred in association with the Zechstein LEP in the late Permian¹⁴, the Gulf of Mexico LEP in the Middle Jurassic¹⁵, the South Atlantic LEP in the Middle Cretaceous¹⁶, the Red Sea and the Mediterranean LEPs in the Miocene¹⁷, respectively (Extended Data Table 5). The LIP is a mainly mafic magmatic province with an areal extent $>0.1 \text{ Mkm}^2$ and an igneous volume $>0.1 \text{ Mkm}^3$. It usually has intraplate characteristics and is often emplaced in a short duration pulse or multiple pulses (less than 1-5 Ma) with a maximum duration of $\sim 0.50 \text{ Ma}$ ¹⁸. In spite of the intervals between the LIPs and LEPs, there might be a positive promoting effect to accumulation of the LEPs from the LIPs. Recently, Hovland et al.^{5,6} suggested a model of large salt accumulation based on hydrothermal processes within Wilson cycles and proposed that solid salt was easily formed in subduction and rifting tectonic environments, such as the Andean subduction zone (oceanic-continental subduction), the Mediterranean ridge subduction zone (oceanic-oceanic subduction), and the East African and Red Sea rifts. This is consistent with our analysis of statistical data of distributions, masses, and salt-forming rates of evaporite deposits in the world. Sternai et al.²² also found that the formation of the Messinian salinity crisis (MSC) in the Mediterranean was associated with volcanic activity (igneous rock) and considered that the MSC promoted the production and eruption of magma. However, the heat and denser brines produced by magma activity might also contribute to the formation of the MSC, and the potential heat transfer between brines and magmas could not be concluded exactly.

Fig.3 | Comparisons between Large Igneous Provinces (LIPs) (data are from¹⁸), and Large Evaporite Provinces (LEPs) (data are from^{12,26,27}) in different tectonic settings through the geological time (data are from^{28,29}). a-d show the corresponding relationships of locations and ages. a. The Pan-Mediterranean igneous province and the Mediterranean evaporite, and the Afro-Arabian igneous province and the Red Sea evaporite in the Miocene; b. the Parana Etendeka igneous province and the South Atlantic evaporite in the Cretaceous; c. the Central Atlantic Magmatic Province and the Gulf of Mexico evaporite in the Jurassic; d. the Eunwa igneous province and the Zechstein evaporite in the Permian.

Based on the discoveries of hot brines in the Atlantis II Deep of the Red Sea¹⁹ and hot vents or ‘black smokers’ on the East Pacific Rise²⁰, Hovland et al.⁵ inferred that ‘forced convection’ in seawater circulation is caused by the heat from the underlying mantle. In particular, concentrated brines and solid salt below the sea surface formed when the temperatures of the hydrothermally circulating seawater are greater than 400°C and the sediment thickness is >3 km. In addition, these authors proposed that salt accumulation on the sea floor is associated with serpentinization of mantle rocks (peridotite) because mineral dissolution and hydrolysis in mantle rock were caused by seawater-rock exothermic interactions. This process resulted in significant releases of Cl⁻, Mg²⁺, and Na⁺, which was favourable to formation of denser brines and/or solid salts^{9,10,11}. Meanwhile, the accumulating process of salt from serpentinization was further verified by the theoretical calculation that 10.5 kg of salt will be produced by changing one m³ of peridotite to serpentinite²¹. Therefore, this salt-forming phenomenon resulting from serpentinization might be a new model for the salt giant in the deep ocean. The coupling of heat of the magma, brines and complicated transforming process between water and salt in the subduction and rifting

218 tectonic settings may be a perspective formation mechanism for the LEPs.

219 In fact, the Precambrian-Cambrian, Permian, Jurassic-Cretaceous, and Miocene
220 were four of the warmest intervals since the Sinian. Very active geological events
221 occurred during these periods, such as active orogenic belts, the break-up and
222 assemblage of supercontinents, and changes in sea level, imply that they are not
223 simply caused by climatic warming which cannot trigger such significant strong
224 geological activity. The wide distribution of salt giants generally found in plate
225 margins, deep oceanic basins in the Tethyan orogenic belt, transitional zones from sea
226 to land, epicontinental seas and platform centres of isolated plates¹³ also need a more
227 reasonable explanation than climatic factors. Current ideas involve either the solar
228 evaporite hypothesis that triggers salt accumulation by warming from above^{1, 4, 24} or a
229 hypothesis involving active lithospheric processes that provide heat from below^{5, 6, 9, 10,}
230 ¹¹. At the least, from available evidence, researchers have realized that solar energy
231 may not be the ultimate driving force for salt accumulation; that is, salt deposits can
232 generally be linked to geothermal changes in plate boundaries and in the overall
233 regime of plate tectonics, rather than solar energy. When climatic reasons are involved,
234 they may have been manifestations of the thermal influence of the crust on the surface.
235 Therefore, the LEPs may favour a dominantly tectonic origin rather than a solar
236 evaporite theory. We believe that the LEPs formed in active tectonic settings are
237 mainly controlled by heat from the upper lithospheric crust or mantle, which is
238 obviously different from surficial evaporites controlled by solar evaporation.

239 But, what and how did the magmatic events happen and be controlled, which
240 further influenced the formation and distribution of the LEPs in the geological time.
241 Our recent studies on Earth's thermal evolution, as shown in Fig.4, suggest that Earth
242 may experience extreme warming and cooling periods in terms of Earth's geothermal
243 cycles²³. The thermal expansion of the lithosphere induces uplift and then rifting,
244 leading to the collapse of Earth's crust³⁰, with volcanism and magmatism as the
245 global-scale response. This shallow process may reach a critical state with a positive
246 feedback loop, resulting in LIPs, which may remove large amounts of heat from
247 erupted lavas by radiation into the atmosphere. Endothermic phase changes during
248 de-compressive melting also absorb large quantities of heat energy from Earth's
249 interior, which cools their surroundings. This process may end a warming cycle and
250 initiate a new cycle of climatic cooling, even a new ice age. To fully determine the
251 exact geothermal cycles, one must determine all the starting point parameters and

ingredients, as well as their evolution during the geologic processes. Of course, at the moment, reaching a very high degree of accuracy is not possible. Therefore, our model can only be regarded as a new perspective, and much more additional work has to be done to explain the details. However, if we accept the concept that the Earth evolves as a thermal system²³, it is natural to consider that over geological time spans, salts and brines may survive in the deep crust or mantle and that they may experience heat energy supply from several geological stages of the Wilson cycle before the salt clearly accumulated. The Earth has undergone several supercontinental cycles of assembly and break-up. The supply of heat energy and the availability of seawater during the long history of Earth's evolution make deep salt and brine production unavoidable. Therefore, the salt accumulations we observe today may be results of longer times than the latest stage in the Wilson cycle of the area⁵.

Fig.4 | The corresponding relationships among evaporate (halite), Large igneous provinces (LIPs) and Thermal cycle in the geological time (the colour in the figure indicates the relative temperature of Earth's surface layer, with yellow, red, blue and white representing temperature from warm to cool, respectively). **a**, Temporal distribution of masses of evaporites (redrawn from^{12, 26, 27, 31-37}). **b**, Temporal distribution of area of the large igneous provinces (redrawn from^{1, 18}). **c**, Schematic diagram of the global thermal cycle in Earth evolution (redrawn from²³).

To all scientists in geology and geophysics who are familiar with solar evaporite

theory, the debate about a solar or non-solar origin for LEPs is very thought-provoking. The profusion of LEPs in deep sea regions and the presence of canyons and magmatic provinces spatially related to the known LEPs suggest that the locations of LEPs, such as the Mediterranean Sea, could have been heated by large underlying shallow thermal anomalies rather than warmed by solar energy from above. A regional heat anomaly could be fed by deep-sourced heat accumulation incubating beneath the oceanic crust, with the heat unable to escape because of the crust's insulating effect. If this were true, the combination of changes in plate tectonic forces and uplift above a regional heat anomaly could have been sufficient to cause rifting and release enough heat energy to generate LEPs. We believe that hydrothermal processes may explain the locations and durations, as well as the amounts, of salt deposits in a better way than solar evaporation. However, as pointed out by Schreiber et al.²⁴, this interpretation does not exclude solar energy as one of the active contributors to brine densification and precipitation of solid salt in many cases.

Many debates concerning LEPs can be advanced only by improved imaging of geothermal regimes, which may lead to a better understanding of geodynamics. The questions of thermal anomalies in terms of their sizes, durations and distribution in the underlying mantle are very important and have to be answered. Further constraints on these hypotheses and models can also come with more precise dating of the relationships between thermal anomalies and the onset of LEPs by more clearly defining geothermal anomalies in large tectonic rifting and magmatic provinces and by exploring the thermal regime at the time of evaporite emplacement. Of most importance, however, is to achieve a better understanding of the whole plate tectonic regime at the times of LEPs such as the MSC. In the future, geothermal evaporites will receive increasing attention. We will not be able to address the full picture of evaporites until we have a better understanding of Earth's thermal history²³. If we can determine the meaning of and controls on LEPs formed during Earth's evolution history, we will be in a far better position to understand their mechanisms and assess the relative contributions of heat energy from above as a consequence of solar radiation or from below with deep mantle processes in a plate tectonic regime.

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Methods:

In Fig. 2b, the masses of halite in different geological intervals are calculated by the following equation:

$$M_{TH}=M_{RH}+M_{OH}$$

where M_{TH} is the total mass of reconstructed halite on the Earth in different geological intervals, M_{RH} is the original recyclable halite mass reconstructed by the sum of total mass of recyclable halite and eroded halite since deposition and M_{OH} is the mass of halite on ocean floor (not recyclable). All the masses of halite are from the maximum estimates (i.e., Hay et al.¹²), because 1) the exploration of evaporites in the ocean basins and marginal seas is not sufficient to date and 2) many estimates of volumes and masses of halite in the deep sea are based on seismic data. However, future discoveries and corrections are unlikely to be large enough to invalidate the estimates. The reasonable assumptions and detailed calculation procedures for the masses of

recyclable halite and eroded halite are from¹² (Extended Data Table 2). In Fig. 2c, the masses of halite on the ocean floor (M_{OH}) and platforms (M_{PH}) are calculated according to the data from ^{12, 26}. The masses of halite on non-platform areas (excluding the ocean floor) are calculated by M_{TH} minus M_{OH} and M_{PH} (Extended Data Table 3). In Fig. 2d, the rates of halite formation in different tectonic regimes (platform, non-platform excluding ocean floor, and ocean floor) are calculated by the ratios of total masses of halite to the length of age for halite formation (Extended Data Table 4). The equation is $R=M/t$.

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Competing interests: The authors declare no competing interests.

Extended Data Table 1: The tectonic setting of halite-bearing basins

Divergent	1. Abenaki (N. Scotian), 3. Adelaide Fold Belt, 4. Adriatic-Albanian Foredeep, 10. Apennine, 12. Aquitaine, 13. Arabian Basin (Gotnia Salt Basin), 14. Arabian Basin (Hith Salt Basin), 18. Atlas (Algerian-Tunisian), 19. Atlas (Moroccan), 20. Baltimore Canyon, 21. Berrechid, 22. Betic-Guadalquivir Basin, 25. Brazilian Aptian Basin (Camamu), 26. Brazilian Aptian Basin (Campos-Santos), 27. Brazilian Aptian Basin (Ceara), 28. Brazilian Aptian Basin (Cumuruxatiba), 29. Brazilian Aptian Basin (Sergipe-Alagoas), 32. Cantabrian-West Pyrenees, 35. Carson Basin (Grand Banks), 41. Dead Sea, 47. Georges Bank, 49. Gulf of Mexico (northern Gulf coast), 50. Gulf of Mexico (southern; Salina-Sigsbee), 51. Haltenbanken, 54. Horseshoe Basin (Grand Banks), 56. Ionian, 57. Jeanne d' Arc Basin (Grand Banks), 59. Jura/Rhodanian, 60. Katangan, 63. La Popa (Monterrey) Basin, 64. Lusitanian, 66. Maestrat, 67. Majunga Basin, 68. Mandawa Basin, 69. Ma' Rib-Al Jawf/Shabwah (Hadramaut), 81. Moesian, 84. Nordkapp Basin, 86. Olduvai depression, 92. Orpheus Graben, 93. Palmyra, 100. Red Sea (north), 101. Red Sea (south), 102. Rot Salt Basin, 103. Ruvuma Basin, 104. Sabinas Basin, 106. Salar Basin (Grand Banks), 110. Scotian Basin, 114. Somalia-Kenya, 115. South Whale Basin (Grand Banks), 119. Tadjik Basin, 120. Takutu Salt Basin, 122. Tromso Basin, 124. West Africa (Angola-Gabon), 125. West Africa (Gambia-Guine Bissau), 126. West Africa (Mauritania-Senegal), 127. West Africa (Morocco-S. Spain), 129. Whale Basin (Grand Banks), 133. Zechstein (NW Europe), 134. Zechstein (onshore UK), 138. Lanping-Simao Basin.
Convergent	2. Adavale, 6. Amadeus Basin (Chandler), 8. Andean, 9. Andean, 15. Arabian Basin (Hormuz central Saudi Arabia), 16. Arabian Basin (Hormuz Gulf region), 17. Arabian Basin (Hormuz-Kerman region), 23. Bohai Basin, 30. Cankiri-Corum, 34. Carpathian foredeep, 36. Chu-Sarysu (Devonian), 37. Chu-Sarysu (Permian), 38. Cilia-Latakia, 39. Cuban, 40. Danakil, 42. Dniepr-Donets, 43. Dniepr-Donets, 44. Eastern Alps, 45. Ebro Basin, 46. Flemish Pass Basin (Grand Banks), 48. Green River Basin, 52. Haymana-Polatli, 53. Holbrook Basin, 58. Jiangnan Basin, 61. Khorat Basin, 62. Kuqaforeland (Tarim Basin), 71. Mediterranean-Western, 72. Mediterranean-Adriatic, 73. Mediterranean-Andros Basin, 74. Mediterranean-Cretean Basin, 75. Mediterranean-Samothraki basin, 76. Mediterranean-Tyrrhenian, 77. Mediterranean-Central, 78. Mediterranean-Eastern, 79. Mediterranean-Sicilian, 83. Neuquen Basin, 87. Oman (Fahud Salt Basin), 88. Oman (Ghaba Salt Basin), 89. Oman (Ghudun Salt Basin), 90. Oman (South Oman Salt Basin), 94. Paradox Basin, 96. Pricaspian Basin, 98. Qaidam Basin, 99. Qom-Kalut, 105. Sachun Basin, 107. Salt Range (Hormuz-Punjab region), 108. Salt Range (Kohat Plateau), 116. Sverdrup Basin (Ellef Ringnes-NW Ellesmere), 117. Sverdrup Basin (Melville Is.), 118. Tabriz Salt Basin, 121. Transylvanian, 128. Western Canada (Alberta Basin), 131. Zagros (Mesopotamian Basin), 132. Zagros (Mesopotamian Basin), 135. Zipaquira Basin, 137. Sichuan Basin.
Intracratonic	5. Amadeus Basin, 7. Amazonas, 11. Appalachian, 24. Bonaparte (Petrel), 31. Canning Basin, 33. Carnarvon Basin (Yaringa), 55. Hudson Bay, 65. Mackenzie Basin, 70. Maritimes Basin, 80. Michigan Basin, 82. Moose River Basin, 85. Officer Basin, 91. Oriente-Ucayali (Pucara), 95. Parry Island Fold Belt, 97. Pripyat Basin, 109. Saltville. (Appalachian), 111. Siberia, East, 113. Solimoes, 123. USA Midcontinent, 130. Williston Basin, 136. Erdos Basin.

Data are from ^{1,25}.

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Extended Data Table 2: The masses of halite in geological time

Geological Time	Length of Age	Halite on ocean floor-not recyclable	Reconstructed original recyclable halite mass	Reconstructed halite mass on the Earth
		my10 ¹⁵ kg	10 ¹⁵ kg	10 ¹⁵ kg
Pliocene	3.52	0.000	8.846	8.846
Miocene	17.7	2376.000	3655.161	6031.161
Oligocene	10.87	4.320	63.246	67.566
Eocene	21.9	0.000	36.505	36.505
Paleocene	9.7	0.000	11.216	11.216
Cretaceous	80	6048.000	1594.729	7642.729
Jurassic	54.1	8424.000	3756.226	12180.226
Triassic	51.4	0.000	2363.125	2363.125
Permian	48	0.000	11093.842	11093.842
Carboniferous	60.5	0.000	995.552	995.552
Devonian	56.8	0.000	2633.091	2633.091
Silurian	27.7	0.000	220.267	220.267
Ordovician	44.6	0.000	249.446	249.446
Cambrian	53.7	0.000	14304.822	14304.822
Ediacaran	88	0.000	8018.430	8018.430

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Data are from ¹².

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510 **Extended Data Table 3: The masses of halite in different tectonics in geological time**

Geological Time	Length of Age	Reconstructed halite mass on the Earth	Halite on ocean floor	Total halite on platform	Halite on non-platform (exclude on ocean floor)
	my	10 ¹⁵ kg	10 ¹⁵ kg	10 ¹⁵ kg	10 ¹⁵ kg
Pliocene	3.52	8.846	0.000	0.110	8.736
Miocene	17.7	6031.161	2376.000	942.190	2712.971
Oligocene	10.87	67.566	4.320	35.860	27.386
Eocene	21.9	36.505	0.000	17.280	19.225
Paleocene	9.7	11.216	0.000	0.220	10.996
Cretaceous	80	7642.729	6048.000	1000.080	594.649
Jurassic	54.1	12180.226	8424.000	2209.680	1546.546
Triassic	51.4	2363.125	0.000	1169.640	1193.485
Permian	48	11093.842	0.000	3306.960	7786.882
Carboniferous	60.5	995.552	0.000	358.560	636.992
Devonian	56.8	2633.091	0.000	631.260	2001.831
Silurian	27.7	220.267	0.000	59.270	160.997
Ordovician	44.6	249.446	0.000	38.160	211.286
Cambrian	53.7	14304.822	0.000	2792.140	11512.682
Ediacaran	88	8018.430	0.000	1296.000	6722.430

511 Data are from ^{12,26}.

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526 **Extended Data Table 4: The rate of halite formation in different tectonic regimes**

Geological Time	Length of Age	Total halite on platform	Rate of halite formation on platform	Halite on non-platform (exclude on ocean floor)	Rate of halite formation on non-platform	Halite on ocean floor	Rate of halite formation on ocean floor
	my	10 ¹⁵ kg	10 ¹⁵ kg/my	10 ¹⁵ kg	10 ¹⁵ kg/my	10 ¹⁵ kg	10 ¹⁵ kg/my
Pliocene	3.52	0.110	0.031	8.736	2.482	0	0.000
Miocene	17.7	942.190	53.231	2712.971	153.275	2376	134.237
Oligocene	10.87	35.860	3.299	27.386	2.519	4.32	0.397
Eocene	21.9	17.280	0.789	19.225	0.878	0	0.000
Paleocene	9.7	0.220	0.023	10.996	1.134	0	0.000
Cretaceous	80	1000.080	12.501	594.649	7.433	6048	75.600
Jurassic	54.1	2209.680	40.844	1546.546	28.587	8424	155.712
Triassic	51.4	1169.640	22.756	1193.485	23.220	0	0.000
Permian	48	3306.960	68.895	7786.882	162.227	0	0.000
Carboniferous	60.5	358.560	5.927	636.992	10.529	0	0.000
Devonian	56.8	631.260	11.114	2001.831	35.244	0	0.000
Silurian	27.7	59.270	2.140	160.997	5.812	0	0.000
Ordovician	44.6	38.160	0.856	211.286	4.737	0	0.000
Cambrian	53.7	2792.140	51.995	11512.682	214.389	0	0.000
Ediacaran	88	1296.000	14.727	6722.43	76.391	0	0.000

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Extended Data Table 5: LIPs and interpreted LIP fragments and Silicic LIPs

Age (Ma)	LIPs name	Type	Location	Area(Mkm ²)
6	Pan-Mediterranean		Mediterranean	
20	Columbia River	C	North America	0.24
30	Afro-Arabian(Afar)	C	Arabian Penn.& Africa	2
30	Sierra Madre Occidental	S	Southwestern USA	0.4
60	North Atlantic Igneous Province(NAIP)	C	Greenland/Northern Canada & Europe (UK)	1.3
70	Deccan	C	India	1.8
70	Sierra Leone (-Ceara)	O	Atlantic Ocean	0.9
90	Caribbean-Colombian	O/C	Central America, South America	1.1
90	Madagascar	C	Africa	1.6
100	Hess	O	Pacific Ocean	0.8
130	HALIP	C	Circum-Arctic	0.5
120	Southeast African (Agulhas, Maud, Georgia)	O/C	Africa	3.5
120	Greater Ontong Java (Ontong Java +Nauru basin, etc.)	O	Pacific Ocean	4.27
120	Manihiki	O	Pacific Ocean	0.8
120	Hikurangi	O	Pacific Ocean	2.7
130	Parana-Etendeka	C	South America & Africa	2
130	Comei	C	Greater India	0.04
140	Trap	C	Greenland (southwest)	0.02
160	NW Australian margin (Greater Exmouth, Gascoyne, Wallaby, Scott, Browse, Argo)	O	Australia(northwest margin)	0.16
130	Mid-Pacific Mountains	O	Pacific Ocean	1.1
140	Shatsky-Tamu	O	Pacific Ocean	0.2
150	Magellan	O	Pacific Ocean	0.5
200	CAMP	C	North America, South America, Africa, Europe(Iberia)	10
200	Angayucham	O/C	Alaska	0.15
250	Siberian Trap	C	Asia	7
260	Emeishan	C	Asia	0.25
280	Tarim	C	Asia (central)	0.25
280	Qiangtang-Panjal	C	Asia (Tibet)	0.04
300	Jutland, Oslo, Skaggerak, EUNWA (European-NW Africa)	C	Europe	0.15
330	Tianshan	C	China	1.7
380	Yakutsk-Vilyui	C	Siberia	0.8
380	Kola-Dnieper	C	Baltica	3
510	Kalkarindji	C	Australia	2.1
540	Wichita	C	Laurentia (south)	0.04
590	CIMP (Grenville)	C	Laurentia (east) &Baltica	0.14
620	CIMP (Long Range, Baltoscandian,	C	Laurentia (east) &Baltica	0.1

Egersund)				
720	Franklin-(Thule)	C	Laurentia-north	2.25
720	Dovyren-Kingash	C	Siberia-south	0.13
720	Mutare	C	Kalahari craton	0.05
760	Mundine Well	C	Australia craton-northwest	0.18
760	Malani	S	Greater India	0.02
760	Shaba &Ogcheon	C/S	South China block	0.33
760	Mount Rogers-Southeast Laurentia	C	Laurentia-east	0.06
780	Gunbarrel	C	Laurentia-west	0.49
780	Kangding	C	South China craton	1.16
780	Kudi	C	Tarim craton	0
780	Boucaut	C	Australia-south	0
790	Gannakouriep	C	Kalahari craton-southwest	0.03
800	Rushinga group-Madondi belt	C	Kalahari-norht	0
800	Suxiong-Xiaofeng	C/S	South China craton	0
800	Niquelandia-inludes other intrusions	C	Sao Francisco	0.03
830	Qiganbulake-Kuruketage	C	Tarim craton	0
830	Gairdner-Willouran	C	Australia craton	0.63
830	Guibel	C/S	South China craton	1.34
880	Iguerda-Taifast	C	West Africa craton	0
920	Gandil-Mayunbian	C	Congo craton	0.34
920	Bahia	C	Sao Francisco craton	0.03
930	Dashigou	C	North China craton	0.65
1050	SetteDaban	C	Baltica	0.09
1080	Warakurna	C	Siberia-east	0
1090	SW Laurentia-SW USA Diabase Province	C/S	Laurentia	1.13
1110	Umkondo	C	Kalahari craton	2.08
1110	GN	C	Congo craton	0
1110	Rincon del Tigre-Huanchaca	C	Amazonia	0
1110	Mahoba	C	Greater India	0
1120	Keweenawan	C	Laurentia	0.41
1140	Abitibi	C	Laurentia	0.26
1170	Late Gardar	C	Laurentia	0
1210	MarndaMoorn	C	Australia craton	0.59
1220	Protogine Zone	C	Baltica	0.02
1240	Sudbury	C	Laurentia	0.12
1250	Mealy-Seal Lake	C	Laurentia	0.02
1250	Vestfold-Hills-S	C	East Antarctica	0.01
1270	Mackenzie	C	Laurentia	2.7
1270	Harp	C	Laurentia	0.06
1270	Central Scandinavian	C	Baltica	0.14
1320	Derim-Derim (Roper)	C	North Australis craton	0.01
1320	Yanliao	C/S	North China craton	0.08
1380	Hart River-Salmon Arch	C	Laurentia	0.02

1380	Midsommerso-Zig Zag Dal	C	Laurentia	0.06
1380	Vestfold-Hills-4	C	East Antarctica	0.01
1380	Kunene-Kibaran	C	Congo craton	0.1
1380	Pilanesberg	C	Kalahari craton	0.16
1380	Mashak	C	Baltica	0.5
1460	Tuna-Lake Ladoga	C	Baltica	0.13
1460	West Bangemall-Edmund	C	North Australis craton	0.03
1470	Moyie	C	Laurentia	0.12
1460	Michael-Shabogamo	C	Laurentia (eastern)	0.05
1500	Kuonamka	C	Siberia craton	0.06
1520	Essakane	C	southern West African	0.38
1580	Korsimoro	C	south West African	0.2
1590	Gawler Range	C	South Australian craton	0.131
1600	Breven-Hallefors	C	Baltica	0.059
1630	Melville-Bugt	C	Laurentia (Greenland)	0.22
1670	Hame	C	Baltica	0.04
1750	Timpton	C	Siberia	0.06
1750	Cleaver-Hadley Bay-Kivalliq (Pitz-Nueltin)	C/S	Rae craton	0.3
1750	Tagragra of Akka		West Africa craton	0.01
1780	Xiong'er-Taihang	C	North China craton	0.27
1790	Avanavero	C	Amazonian craton	0.3
1790	Florida (Uruguayan)	C	Rio de la Plata craton	0.02
1830	Hart-Carson	C	Northern Australian craton	0.11
1830	Sparrow-Christopher Island	C	Rae craton	0.1
1870	Kalaro-Nimnysky		Siberia craton	0.1
1880	Circum-Superior-Pan Superior	C	Superior craton	0.6
1880	Ghost-Mara River-Morel	C	Slave craton	0.06
1880	Mashonaland	C	Zimbabwe craton	0.16
1890	Uatuma	S	Amazonian craton	1.5
1890	Cuddapah-Bastar	C	Dharwar-Bastar cratons	0.03
1930	Xuwujia	C	North China craton	0.01
1980	Pechenga-Onega	C	Karelia-Kola	0.6
1980	Jhani		Bundelkhand	0.02
2030	Lac des Gras-Booth River	C	Slave craton	0.04
2050	Kangamuit-MD3	C	North Atlantic craton	0.04
2060	Bushveld (includes other intrusions)	C	Kaapvaal craton	0.25
2070	Fort Frances	C	Superior craton	0.08
2100	Marathon	C	Superior craton	0.06
2100	Indin	C	Slave craton	0.03
2100	Karelia	C	Karelian craton	0.21
2110	Griffin	C	Hearne craton	0.08
2170	Biscotasing	C	Superior craton	0.35
2180	Dandeli	C	Dharwar craton	0.06
2190	Southwest Slave Magmatic Province (Dogrib)	C	Slave craton	0.01

2190	Tulemalu-(MacQuoid)	C	Rae craton	0.02
2210	Ungava-Nipissing	C	Superior craton	0.5
2210	Mackay-Malley	C	Slave craton	0.04
2210	Somala	C	Dharwar craton	0.05
2220	BN1	C	North Atlantic craton	0.05
2370	Bangalore-Karimnagar	C	Dharwar craton	0.14
2420	Widgiemooltha	C	Yilgarn craton	0.64
2480	Matachewan	C	Superior craton	0.36
2510	Baltic LIP East Scandinavian	C	Karelian craton	0.5
	Paleoproterozoic LIP			
2510	Kaminak	C	Hearne craton	0.18
2510	Mistassini	C	Superior craton	0.1
2580	Great Dyke of Zimbabwe	C	Zimbabwe craton	0.06
2700	Eastern Goldfields	C	Yilgarn craton	0.1

542 Data are from ¹⁸. Type: C=continental, O=oceanic and S=silicic. Bold =LIPs, not bold= interpreted LIP fragments.

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Figures

Figure 1

Distribution of evaporitic basins around the world through geological time (redrawn from 1,25) (Extended Data Table 1). Basin names: 1. Abenaki (N. Scotian), 2. Adavale, 3. Adelaide Fold Belt, 4. Adriatic-Albanian Foredeep, 5. Amadeus Basin, 6. Amadeus Basin (Chandler), 7. Amazonas, 8. Andean, 9. Andean, 10. Apennine, 11. Appalachian, 12. Aquitaine, 13. Arabian Basin (Gotnia Salt Basin), 14. Arabian Basin (Hith Salt Basin), 15. Arabian Basin (Hormuz central Saudi Arabia), 16. Arabian Basin (Hormuz Gulf region), 17. Arabian Basin (Hormuz-Kerman region), 18. Atlas (Algerian-Tunisian), 19. Atlas (Moroccan), 20. Baltimore Canyon, 21. Berrechid, 22. Betic-Guadalquivir Basin, 23. Bohai Basin, 24. Bonaparte (Petrel), 25. Brazilian Aptian Basin (Camamu), 26. Brazilian Aptian Basin (Campos-Santos), 27. Brazilian Aptian Basin (Ceara), 28. Brazilian Aptian Basin (Cumuruxatiba), 29. Brazilian Aptian Basin (Sergipe-Alagoas), 30. Cankiri-Corum, 31. Canning Basin, 32. Cantabrian-West Pyrenees, 33. Carnarvon Basin (Yaringa), 34. Carpathian foredeep, 35. Carson Basin (Grand Banks), 36. Chu-Sarysu (Devonian), 37. Chu-Sarysu (Permian), 38. Cicilia-Latakia, 39. Cuban, 40. Danakil, 41. Dead Sea, 42. Dniepr-Donets, 43. Dniepr-Donets, 44. Eastern Alps, 45. Ebro Basin, 46. Flemish Pass Basin (Grand Banks), 47. Georges Bank, 48. Green River Basin, 49. Gulf of Mexico (northern Gulf coast), 50. Gulf of Mexico (southern; Salina-Sigsbee), 51. Haltenbanken, 52. Haymana-Polatli, 53. Holbrook Basin, 54. Horseshoe Basin (Grand Banks), 55. Hudson Bay, 56. Ionian, 57. Jeanne d' Arc Basin (Grand Banks), 58. Jiangnan Basin, 59. Jura/Rhodanian, 60. Katangan, 61. Khorat Basin, 62. Kuqaforeland (Tarim Basin), 63. La Poma (Monterrey) Basin, 64. Lusitanian, 65. Mackenzie Basin, 66. Maestrat, 67. Majunga Basin, 68. Mandawa Basin, 69. Ma' Rib-Al Jawf/Shabwah (Hadramaut), 70. Maritimes Basin, 71. Mediterranean-Western, 72. Mediterranean-

Adriatic, 73. Mediterranean-Andros Basin, 74. Mediterranean-Cretean Basin, 75. Mediterranean-Samothraki basin, 76. Mediterranean-Tyrrhenian, 77. Mediterranean-Central, 78. Mediterranean-Eastern, 79. Mediterranean-Sicilian, 80. Michigan Basin, 81. Moesian, 82. Moose River Basin, 83. Neuquen Basin, 84. Nordkapp Basin, 85. Officer Basin, 86. Olduvai depression, 87. Oman (Fahud Salt Basin), 88. Oman (Ghaba Salt Basin), 89. Oman (Ghudun Salt Basin), 90. Oman (South Oman Salt Basin), 91. Oriente-Ucayali (Pucara) Basin, 92. Orpheus Graben, 93. Palmyra, 94. Paradox Basin, 95. Parry Island Fold Belt, 96. Pricaspian Basin, 97. Pripyat Basin, 98. Qaidam Basin, 99. Qom-Kalut, 100. Red Sea (north), 101. Red Sea (south), 102. Rot Salt Basin, 103. Ruvuma Basin, 104. Sabinas Basin, 105. Sachun Basin, 106. Salar Basin (Grand Banks), 107. Salt Range (Hormuz-Punjab region), 108. Salt Range (Kohat Plateau), 109. Saltville (Appalachian), 110. Scotian Basin, 111. Siberia, East, 112. Sirjan Trough, 113. Solimoes, 114. Somalia-Kenya, 115. South Whale Basin (Grand Banks), 116. Sverdrup Basin (Ellef Ringnes-NW Ellesmere), 117. Sverdrup Basin (Melville Is.), 118. Tabriz Salt Basin, 119. Tadjik Basin, 120. Takutu Salt Basin, 121. Transylvanian, 122. Tromso Basin, 123. USA Midcontinent, 124. West Africa (Angola-Gabon), 125. West Africa (Gambia-Guine Bissau), 126. West Africa (Mauritania-Senegal), 127. West Africa (Morocco-Spain), 128. Western Canada (Alberta Basin), 129. Whale Basin (Grand Banks), 130. Williston Basin, 131. Zagros (Mesopotamian Basin), 132. Zagros (Mesopotamian Basin), 133. Zechstein (NW Europe), 134. Zechstein (onshore UK), 135. Zapaquira Basin, 136. Erdos Basin, 137. Sichuan Basin, 138. Lanping-Simao Basin. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

The relationship between mass of evaporate and tectonics in the geological time. a, Distribution of different tectonic types of evaporitic basins through geological time (data from1). b, Total masses of halite in different geological periods(mass $\times 10^{15}$ kg).c, Masses of halite in different tectonic types of

evaporitic basins through geological time (mass $\times 10^{15}$ kg). d, Rates of salt formation in different tectonic types of evaporitic basins through geological time (10^{15} kg/Ma); (data are from 12, 26, 27).

Figure 3

Comparisons between Large Igneous Provinces (LIPs) (data are from 18), and Large Evaporite Provinces (LEPs) (data are from 12, 26, 27) in different tectonic settings through the geological time (data are from 28, 29). a-d show the corresponding relationships of locations and ages. a. The Pan-Mediterranean igneous province and the Mediterranean evaporite, and the Afro-Arabian igneous province and the Red Sea evaporite in the Miocene; b. the Parana Etendeka igneous province and the South Atlantic evaporite in the Cretaceous; c. the Central Atlantic Magmatic Province and the Gulf of Mexico evaporite in the Jurassic; d. the Eunwa igneous province and the Zechstein evaporite in the Permian. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

The corresponding relationships among evaporate (halite), Large igneous provinces (LIPs) and Thermal cycle in the geological time (the colour in the figure indicates the relative temperature of Earth's surface layer, with yellow, red, blue and white representing temperature from warm to cool, respectively). a, Temporal distribution of masses of evaporites (redrawn from 12, 26, 27, 31-37). b, Temporal distribution of area of the large igneous provinces (redrawn from 1, 18). c, Schematic diagram of the global thermal cycle in Earth evolution (redrawn from 23).