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Salinization mechanism of lakes and controls on organic matter enrichment: From present to deep-time records

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ABSTRACT

Saline lakes have developed worldwide throughout geological history and continue to develop, is important for understanding deep-time climate evolution, lake evolution and extinction, terrestrial ecosystem evolution, and organic carbon burial processes. The basic conditions required for the formation of saline lakes are a sufficient source of salt, an arid or semi-arid climate, and a closed or semi-closed lake environment. There are four mechanisms of lake basin salinization: (1) seawater-derived salinized lake, salt irons are provided by seawater; (2) Inland evaporative saline lakes, the land is the source of salt substances following strong evaporation; (3) Deep hydrothermal fluids-based saline lakes, high-salinity hydrothermal fluids enter the basin through faults; and (4) Any combination of the above mechanisms. During the evolution of saline lake, one or more can be the main salinization mechanism, and the primary mechanism may change with the evolution of salinization periods. Hydrological characteristics of saline lakes control biome development, biogeochemical processes, sediment deposition, and organic matter enrichment. Due to high productivity and reducing conditions, the salinized lake basin environment is conducive to the formation of organic rich source rocks and/or type I and II sapropelic organic matter with high hydrocarbon generation potential. Future studies should focus on evolutionary processes of deep-time saline lake development based on Earth System Science and interactions between spheres, ecological reconstruction and biogeochemical processes in saline lakes, sediments burial diagenesis and physico-chemical-microbiological processes.

1. Introduction

Lakes are an essential part of terrestrial ecosystems and complex, comprehensive systems. They also reflect the interactions, migrations, and transformations of basins and watersheds, their water bodies, sediments, and various organic and inorganic substances. As the linkage between different zones of the Earth's surface, lakes play an important role in regional climates and water cycles, and are the balancer that sustains regional ecosystems and biodiversity (Zwart et al., 2019; Messager et al., 2016). Saline lakes developed extensively in various geological periods. The salinization process of lakes records detailed information regarding structural and paleoclimatic changes, which provides an essential window for understanding deep-time climate changes and terrestrial ecosystems, and also predicting current lake evolution (Mischke and Zhang, 2010). In addition, organic-rich shale formed in saline lakes acts as vital source rock, and almost all high-quality continental source rocks develop in salinized lake settings (Zou et al., 2019). Furthermore, saline lakes contain rich minerals such as potassium, lithium, boron, and salt (Zheng, 2010).

Salinized lake basins were widely developed in the Paleozoic (Southgate et al., 1989), and their number peaked in the Mesozoic (Carroll et al., 1992) and concentrated near the Mediterranean Sea in the Cenozoic. Today, saline lakes are concentrated in two zones (the northern and southern hemisphere salinized lake zones) and two regions (equatorial Africa and Antarctic salinized lake regions) (Zheng et al., 2016). Saline lake development is often closely associated with arid climate conditions. Whether a lake is closed is also an important influencing factor. Within a closed lake, there is no exchange of water with

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the outside environment, and the continuous accumulation of salt substances will cause the lake's salinity to increase. The introduction of abundant salt ions by deep hydrothermal fluids is also a major mode of lake salinization, especially in the formation of fault-controlled saline lakes, such as Lake Kivu in the East African Rift, Searles Lake in the USA, the Albert Basin in Uganda (Degens et al., 1973; Newman, 1976; Ross et al., 2014). The relatively closed hydrological conditions of saline lake basins produce vertical physicochemical stratification, such as by density, salinity, oxygen content, or thermodynamics (Colomer et al., 2003; Debelius et al., 2009; Belolipetsky et al., 2010; Warren, 2016). The distributions of various species of halotolerant and halophilic organisms differ, with different organism sequences within the stratified system. And also, stratified system will lead to a strong reducing environment in the lower part, which preserves organic matter.

An increasing number of studies have shown that the majority of high-quality lacustrine source rocks develop in saline lakes (Hao et al., 2011; Bechtel et al., 2012; Tänavsuu et al., 2017; Zou et al., 2019; Wang et al., 2019). Productivity and preservation conditions in lake basins are interactive and compensatory. Although fewer species of organisms are found in the saline environment, lake basins are highly productive due to the presence of a large number of halophilic bacteria and halotolerant organisms, which serve as a source of organic matter for source rocks. This, coupled with suitable preservation conditions, leads to the widespread development of organic-rich shale in saline lakes. For example, the TOC of sediments in Mono Lake in the USA has gradually increased to a mean of 6% and a maximum of 14% over the past 300 years (Benson et al., 2003).

This study looks at modern and ancient saline lake basins in various geological ages. It discusses their distribution principles and controlling factors, salinization mechanisms, hydrological characteristics, sediment features, and organic matter enrichment. This study has profound implications for understanding deep-time climate evolution, lake evolution and extinction, terrestrial ecosystem evolution, biological enrichment, and continental source rock development in salinized lake basins.

2. Salinity standards and classifications

Salinity is a major parameter in defining types of lake basins (Carroll and Bohacs, 1999). Many schemes have been devised to classify lake water salinity. Biologists usually define fresh water as a salinity of <1‰, slightly saline water as 1–3‰, low-salinity water as 3–20‰, moderately saline water as 20–50‰, and highly saline water as >50‰ (Hammer, 1986; Hofmann et al., 1993). Hydrogeologists, however, regard fresh water as a salinity of <1‰, brackish water as 1–10‰, saline water as 10–100‰, and brine as >100‰ (Warren, 2016). Geologists have used the following standards for classifying the salinity of water bodies (Fig. 1; Table S1).

Usiglio (1849) was the first to record the sedimentation sequence of minerals in salt water. Eugster and Hardie (1978) determined the evolution process of lacustrine brine. Carpenter (1978) and McCaffrey et al. (1987) refined the chemical change process of residual brine following salt mineral deposition. Warren (1986) subsequently proposed an evaporite mineral deposition sequence based on seawater evaporation experiments: carbonate minerals → sulfate minerals → halite → potassium chloride → bischofite. This study mainly uses Warren's classification scheme with some alterations. Based on the symbiotic relationship between water salinity and sedimentary minerals, lake water can be divided into five categories: freshwater (0–1‰), brackish lake (1–35‰), saline lake (35–140‰), hypersaline lake (140–350‰), and salt lake (>350‰).

3. Distribution of saline lakes

All continents on Earth have salinized lake basins. They generally occur beside continental uplifts, extensional basins, intermontane basins, and glaciers. However, not all lakes develop into saline lakes, depending on geological, environmental, and climatic conditions and material origins (Jones et al., 2009). Saline lakes occur more frequently in areas with frequent tectonic activity, abundant material sources, long sunshine hours, strong evaporation, and arid climatic conditions (Lowenstein et al., 2017; Michael et al., 2022).

3.1. Distribution of modern saline lakes

There are thousands of saline lakes of various sizes all over the world (Table 1), with many near the Mediterranean Sea, as well as in Central Asia, North America, Africa, Australia, and South America (Fig. 2). Most saline lakes are located in the Caspian Sea and West Asia, generally in foreland basins related to Cenozoic orogenies (Sun et al., 1997). Saline lakes are also found in ancient deep rift basins, such as the East African Rift, and Lake Turkana (Boone et al., 2018; Ragon et al., 2019). Evaporation that exceeds precipitation plays a crucial role in salinized lake formation, so salinized lake basins are more readily found in semi-arid or arid regions of the world (Verzilin and Utsal, 1990; Duan and Hu, 2001). In the most arid desert regions of the world, such as the Arabian or Atacama deserts, water bodies are absent due to extremely low precipitation (Cooke and Warren, 1973), so saline lakes are more likely to develop on the edges of deserts. For example, the Central Asian steppe

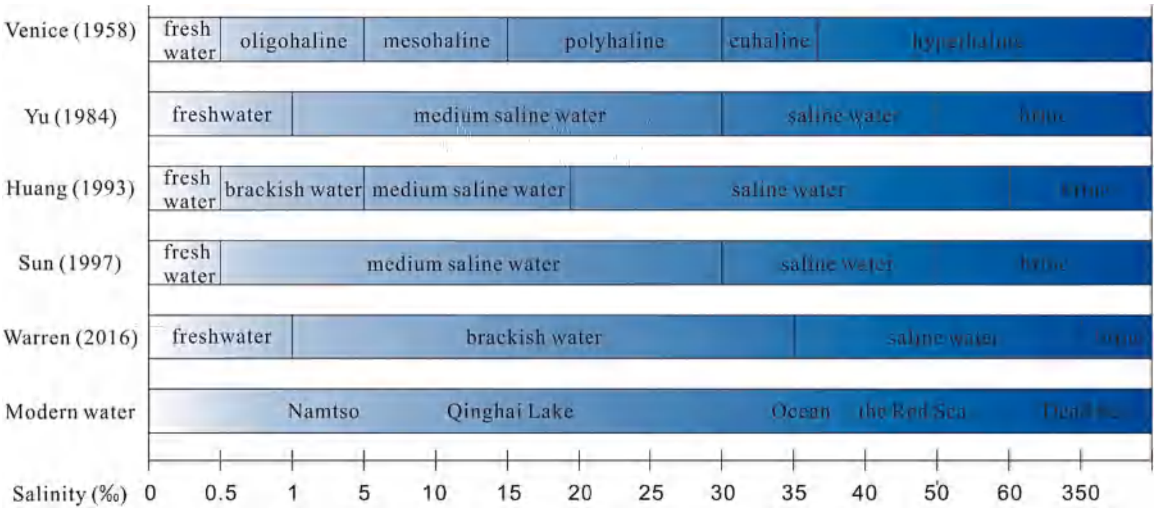

Fig. 1. Salinity division scheme of domestic and foreign scholars.

Table 1
Information of global modern saline lakes.

Name of lake	Lake type or salinity, ‰	Hydrochemical type	Location	Latitude
Kulonda Lake	40	Chloride type	Russia	N53°±
Tengiz Lake	salt water lake	Sulfate type	Kazakhstan	N50° ~ 50.5°+
Lake Ubsu	18.7	Chloride type	Mongolia	N50°
Elton Lake	salt water lake	Carbonate type	Russia	N49° + ~50°+
Kyrgyz Lake	7.5	Sulfate-carbonate type	Mongolia	N49° ~ 49°+
Aralsol Lake	salt water lake	Sulfate type	Kazakhstan	N49°
Sarygamysh Lake	salt water lake	Chloride type	Kazakhstan	N49°
Aral Sea	10–14	Carbonate type	Kazakhstan	N43° ~ 47°
Caspian Sea	1–13	Sulfate-chloride type	Central Asia	N37° ~ 47°
Garabogazköl Bay	70–300	Sulfate type	Turkmenistan	N40.5° ~ 42°
Southercole Lake	salt water lake	Sulfate type	Kazakhstan	N46.5°
Manech Lake	salt water lake	Carbonate type	Russia	N46° ~ 46.5°
Lake Aracone	salt water lake	Sulfate type	Kazakhstan	N46° ~ 46.5°
Balkash Lake	5–15	Sulfate-chloride type	Kazakhstan	N46°±
Issyk Kul Lake	5.8	Sulfate type	Kyrgyzstan	N43°
Great Salt Lake	150–288	Chloride type	America	N41°±
Pyramid Lake	5	Carbonate type	America	N40°
Kara Lake	salt water lake	Chloride type	Tajikistan	N39°±
Walker Lake	3.5	Carbonate type	America	N39°±
Van Lake	19–25	Carbonate type	Türkiye	N38° + ~39°
Lake Tuz	100–450	Chloride type	Türkiye	N38° + ~39°
Lake Urmia	8–28	Sulfate-chloride type	Iran	N37° ~ 38°+
Lake Namak	salt water lake	Chloride type	Iran	N34° ~ 35°
Salton Sea	salt water lake	Chloride type	America	N33°
The Dead Sea	332	Sulfate-carbonate type	west Asia	N31° ~ 31.6°
Lake Chad	0.75±	Carbonate-chloride type	Central African	N12° ~ 14°
Lake Turkana	3±	Carbonate type	Kenya	N3.5° ~ 4.5°+
Lake Natron	75–300±	Carbonate type	Tanzania	S2° ~ 2.5°
Lake Manyara	12.8–75	Chloride type	Tanzania	S3.5°
Lake Poopo	salt water lake	Carbonate type	bolivia	S19°±
Lake Amadeus	salt water lake	Chloride type	Australia	S24.5°±
Lake Eyre	salt water lake	Carbonate type	Australia	S28° ~ 29°
Frome Lake	salt water lake	Chloride type	Australia	S30° + ~31°
Chiquita Lake	salt water lake	Sulfate type	Argentina	S30.5° ~ 31°
Torrens Lake	salt water lake	Chloride type	Australia	S30° ~ 32°
Gairdner Lake	salt water lake	Chloride type	Australia	S31° ~ 32°

(an extremely arid desert steppe) is bordered by the Caspian Sea and the Aral Sea, with Lake Urmia to the southwest and Lake Balkhash in the east (Kelts and Shahrabi, 1986; Micklin, 1988). Qinghai Lake, the largest salinized lake in China, is located east of the Gobi Desert (Zheng et al., 2016), and Lake Chad in central Africa is located on the southern edge of the Sahara Desert (Gac et al., 1977).

The world's saline lakes are mainly concentrated in two belts and two areas (Eugster and Hardie, 1978; Zhang et al., 2014). (1) Salinized lake belts: The salinized lake belt in the northern hemisphere is at 20°–50°N, and the one in the southern hemisphere is at 15°–35°S, and both largely coincide with the arid zones in the two hemispheres. The northern hemisphere saline lake belt comprises arid areas of North America, North Africa, and Asia. It includes Lake Chad in central Africa, the Dead Sea in southwest Asia, Lake Umir in Iran, Qarhan Playa in China, and the Great Salt Lake in the USA. The southern hemisphere salinized lake belt covers parts of South Africa, Australia, and South America. Australia has many saline lakes, including Lake MacLeod and Lake Eyre. South America's saline lakes are mainly on the Altiplano, such as Lake Salinas in Peru, the Atacama in Chile, Laguna de Guayatayoc in Argentina, and Uyuni in Bolivia (Deocampo and Jones, 2014). (2) Saline lake regions: The two salinized lake regions are equatorial Africa and Antarctica. The salinized lake region in equatorial Africa mainly includes Uganda, Kenya, and Tanzania. This is the only saline lake region near the equator due to the unique environment of the Great Rift Valley (Cooke and Warren, 1973; Smoot and Lowenstein, 1991; Zheng et al., 2016). It can be divided into the western and eastern Great Rift Valley saline lakes (Fig. 2). The Antarctic salinized lake region is at 71°–73°S in northern Antarctica, including southern Victoria Land, Bunger Hills, and Vestfold Hills (Gibson, 1999; Warren, 2010).

3.2. *Salinized lake distribution in geological history*

The development of ancient salinized lake basins occurred throughout the Precambrian to Neogene periods. They were most widespread in the Paleozoic (Southgate et al., 1989), most numerous in the Mesozoic (Carroll et al., 1992), and concentrated near the Mediterranean in the Cenozoic (Fig. 3). In modern and geological history, salinized lake basins have been mainly concentrated in the range of 30°–50°N, indicating that climate is the primary factor controlling their formation (Edwards et al., 2006). Additionally, statistics show that the salinization period of large saline lakes is usually 3–5 Ma but generally no longer than 20 Ma (Table S2).

During the Paleozoic period, salinized lake basins were distributed worldwide, mainly in Australia, Europe, the Arabian Peninsula, and North America (Benison and Goldstein, 1999). The Cambrian and Carboniferous-Permian were periods of abundant salinized lake basin development in the Paleozoic Era. In the Carboniferous Period, salinized lake basins were primarily in North America, northern Brazil, North Africa, Eastern Europe, and Kazakhstan (Trappe, 2000), such as the Williston Basin in the USA (Grasby and Betcher, 2000). In the Permian Period, salinized lake basin was broadly distributed along the margin of Pangea in northeastern North America, eastern Greenland, northern South America, and Europe.

During the Mesozoic Era, salinized lake basins were mainly found in Europe and the Mediterranean coast, the middle and low latitudes of North America, and the middle latitudes of South America (Leleu and Hartley, 2010). The Mesozoic is the era with the largest volume of salt deposits. It is when many large-scale salt deposits formed, including most residual evaporites of the Jurassic and Cretaceous periods (Hay et al., 2006). After the Jurassic, saline lakes began to appear in various parts of the world. The Cretaceous was a period of abundant salinized lake basin development during the Mesozoic Era. The sea-level curve produced by Vail et al. (1977) showed that the sea level fluctuated upward during the Cretaceous, reaching a peak in the Campanian age, which would have led to seawater intrusion of continental basins. Examples include the Wessex Basin in the UK (Gallois et al., 2018) and the Santos Basin in Brazil (Felipe et al., 2019) in the early and middle Cretaceous.

In the Cenozoic Era, there was large-scale development of salinized lake basins, mainly in the Mediterranean Sea, East African Rift, North America, and China (Vanden Berg and Birgenheier, 2017). In the Eocene

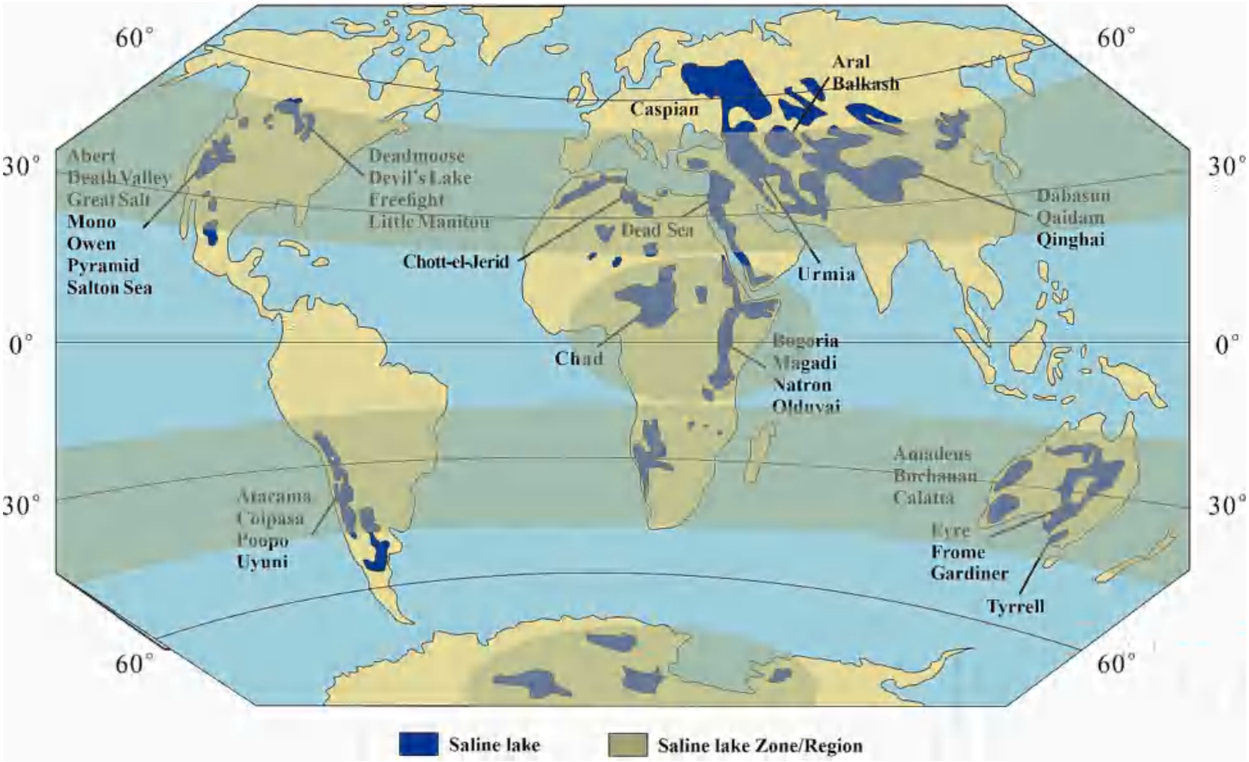

Fig. 2. Distribution of modern saltwater lakes in the world (modified after Cooke and Warren, 1973; Smoot and Lowenstein, 1991; Deocampo and Jones, 2014).

Fig. 3. Age distribution of global saline basins (modified after Warren, 2010).

epoch of the Paleogene Period the global climate became hotter and drier (Frakes, 1979), and many sizeable saline hydrocarbon-bearing lake basins developed, such as the Jianghan Basin, Nanxiang Basin, Bohai Bay Basin in China, the Uinta Basin in the USA (Vanden Berg and Birgenheier, 2017; Liang et al., 2018), and the Isle of Wight in the UK (Armenteros et al., 1997). The global climate cooled during the Oligocene epoch, and seawater temperature in the early Oligocene (Rupelian) was approximately 7–8 °C below that in the early Eocene (Shackleton and Kennett, 1975), and the number of salinized lake basins decreased. In the Neogene period, the global climate warmed, and the number of salinized lake basin increased worldwide, including the Calatayud and Ebro basins in Spain (Arenas et al., 1999; Aziz et al., 2003; Ortí and Rosell, 2000; Salvany et al., 2007), the Hualapai Basin in the USA (Faulds et al., 1997), and the Beypazari Basin in Turkey (Yagmurlu and Helvaci, 1994; Gundogan and Helvaci, 2001).

Regarding the current distribution of lakes around the world, no large lakes are located near the largest river, only a few relatively small ones exist (e.g., the Amazon, Congo, Orinoco, and Mississippi River). Likewise, in geological history, large salinized lake basins were often far from large rivers. As a result, ancient salinized lake systems show no strong correlation between lake size, climate, and river volume (Bohacs et al., 2003).

The development of saline lakes in modern and deep-time is mainly distributed in the mid-latitude, i.e., arid zone, which indicates the important role of climate (Eugster and Hardie, 1978; Warren, 2010). However, in the deep-time record, there are complex mechanisms of salinization, such as regional tectonic evolution, volcanism and hydrothermal activity besides climate (Details in Section 4). A typical case of the Eocene Bohai Bay faulted basin, located in the East Asian monsoon influence area, climate is not its primary controlling factor, its salt source is from seawater intrusion, deep hydrothermal fluids, and the salt weathering of surrounding uplift (Liang et al., 2018; Wei et al., 2018). Another case of the Green River Basin located in North America during the Eocene greenhouse period, deep hydrothermal fluids and the surrounding weathering of volcanic rocks are the main salinization mechanism of the lake (Vanden Berg and Birgenheier, 2017; Birgenheier et al., 2019). However, there are differences in different eras in the geological history: the distribution of saline lakes is also related to global and regional tectonic activity, climatic evolution, terrestrial ecological evolution, weathering of orogenic belts, palaeogeography, and the development of continental rift valleys (Carroll and Bohacs, 1999; Warren, 2010; Ragon et al., 2019). Studies suggested that large saline lakes in deep-time were often developed at the edge of the continents (Warren, 2016; Xia et al., 2020). This may be due to two reasons, one is the intrusion of seawater and saline water underground, and then faults are prone to be formed with the subduction boundary of the oceanic crust, bringing deep brine to lakes. Meanwhile, it is also related to the global climate, for example in the Paleoproterozoic, the saline lakes developed extensively during the Cambrian and Carboniferous-Permian when sea level was at a low level, which may be related to the low precipitation during the ice age. This variability in the distribution of saline lakes across different epochs reflects the complexity of salinization mechanism, and is a synthesis result of tectonics, palaeogeography and climate (Warren, 2010, 2016).

4. Salinization mechanisms

4.1. Formation conditions

The formation of a salinized lake is affected by many factors, including three main facets as follows: (1) a sufficient source of salt, so that the lake can become salinized in the course of material accumulation (Oviatt et al., 2015); (2) evaporation exceeding or close to water inputs, usually in an arid or semi-arid climate (Eugster and Hardie, 1978; Lowenstein et al., 2017); (3) a closed or semi-closed lake hydrological environment (Hammer, 1986; Jones et al., 2009). These conditions influence the formation, evolution, and extinction of saline lakes.

A source of salt ions is an important basis for the evolution of a salinized lake. Reserves of salt substances are thought to directly affect the lifespan of a lake (Jones et al., 2009; Deocampo and Jones, 2014). Nevertheless, this does not mean that a long lifespan will necessarily lead to a salinized lake, as it is crucial that salt sources can provide large volumes of salt substances (Su et al., 2006; Lerman, 2009). Sources of salt include the following. (1) Seawater: This can be subdivided into seawater remaining from ancient oceans and seawater intrusion. An example is saline lakes in Spain in the late Miocene, where the evaporite sequence is mainly thick layers of gypsum, glauberite, and halite due to frequent Mediterranean transgressions (Salvany et al., 2007). Sulfate minerals developed in Jurassic–Cretaceous Lanping–Simao Basin in China. In addition to the remnant seawater after the closure of the Paleo–Tethys, transgressions during the Meso–Tethys were also an essential replenishment (Miller et al., 2005; Haq, 2014). (2) Terrigenous supply: This involves atmospheric precipitation and surface runoff carrying salt ions released by the weathering of parent rock into the basin (Rosen, 1994). An example of this is Santos Basin in Brazil, which underwent salinization in the Early Cretaceous following terrigenous input and strong evaporation, which led to the development of alkaline mineral-rich carbonate rocks in the Barra Velha Formation and Ariri Formation (Felipe et al., 2019; Li et al., 2021). (3) Deep hydrothermal fluids: Examples include the Lake Albert Basin in East Africa since the Miocene (Simon et al., 2017) and Wagoner Lake in Türkiye (Sumita and Schmincke, 2013), whose salinization was mainly related to inputs from calc-alkaline volcanic activities or mantle-derived hydrothermal fluids (Renaut et al., 1994). Furthermore, chloride saline lakes in rift baisns may be linked to the input of $CaCl_2$ hydrothermal fluids from faults (Hardie, 1990), such as the thick layer of halite in Bohai Bay Basin and Jianghan Basin in China. Thus, salt irons in a lake can be from a single source or multiple sources, and the main salt irons supply method can change in different stages (Fayazi et al., 2007; McGlue et al., 2013).

Climate plays a vital role in the lake salinization. Evaporation exceeding replenishment (precipitation + runoff) is an important mechanism of salinization. The distribution of the salinized lake belt is closely related to the precipitation, mainly in latitudes 20°–50°N and15°–35°S, as showed in Fig. 2. This is because after hot and humid air rising in the equatorial region loses moisture, it becomes dry air and descends (Hammer, 1986; Zheng, 2010; Long et al., 2010; Tweed et al., 2011). This furtherly contributes to reducing precipitation in this latitudinal belt, which is the arid and desert belt of the globe (Eugster and Hardie, 1978; Gasse et al., 2008; Chen, 2020), where evaporation is greater than the replenishment of lake waters, causing an increase in the salinity and controlling the development of saline lakes (Zheng, 2010; Zhang, 2021). In addition to latitude, monsoons, and topography also affect precipitation. For example, the Thar Desert (Great Indian Desert), located at 24°–30°N in western India, has an annual rainfall of only 150–250 mm. Cherrapunji, however, which is at the same latitude in eastern India, is humid and has one of the highest levels of precipitation in the world due to the influence of the southern Indian Ocean monsoon and its topography (Murata et al., 2017). Monsoons can also cause severe fluctuations in lake water systems. For example, brief monsoon floods can cause large volumes of Ca^{2+} to enter lake basins, impacting lake water's salinization and chemical properties (Jones et al., 2009).

A closed or semi-closed hydrological system is a key element of saline lakes. In the closed environment, inputs of salt substances accumulate in the lake and are not destroyed, with natural evaporation causing a saline lake to form. Closed lake basins are formed by various processes, including tectonic rifts, thrust faults, lava flows, and glacier erosion (Eugster and Hardie, 1978). Saline lakes such as Qinghai Lake on the Tibetan Plateau in China, the Dead Sea and the Caspian Sea in the Mediterranean, Lake Titicaca in South America, and Mono Lake in the USA are all closed, so salts irons are not lost or gradually diluted (Rosen, 1994; Lerman, 2009; Oviatt et al., 2015).

The salinization of lakes is extraordinarily complex processes. Although a lake basin salinization may involve one or multiple processes that evolve with different periods of salinization, we attempted to discuss the main mechanisms and analyze the salinization process with typical examples.

4.2. Seawater-derived saline lakes

Affected by regional tectonics and sea level changes, marine environments can become inland basins, with the original seawater providing the salt irons for a lake basin. The remaining seawater continuously evaporates, and salinity gradually increases, with the closed environment preserving salt irons substances. Thus, a salinized lake can be formed from residual seawater (Fig. 4A). Tectonic movements play a decisive role in marine transgression and regression events. They determine the start and end of such events by opening and closing channels for the movement of seawater at the edges of basins (Schulz

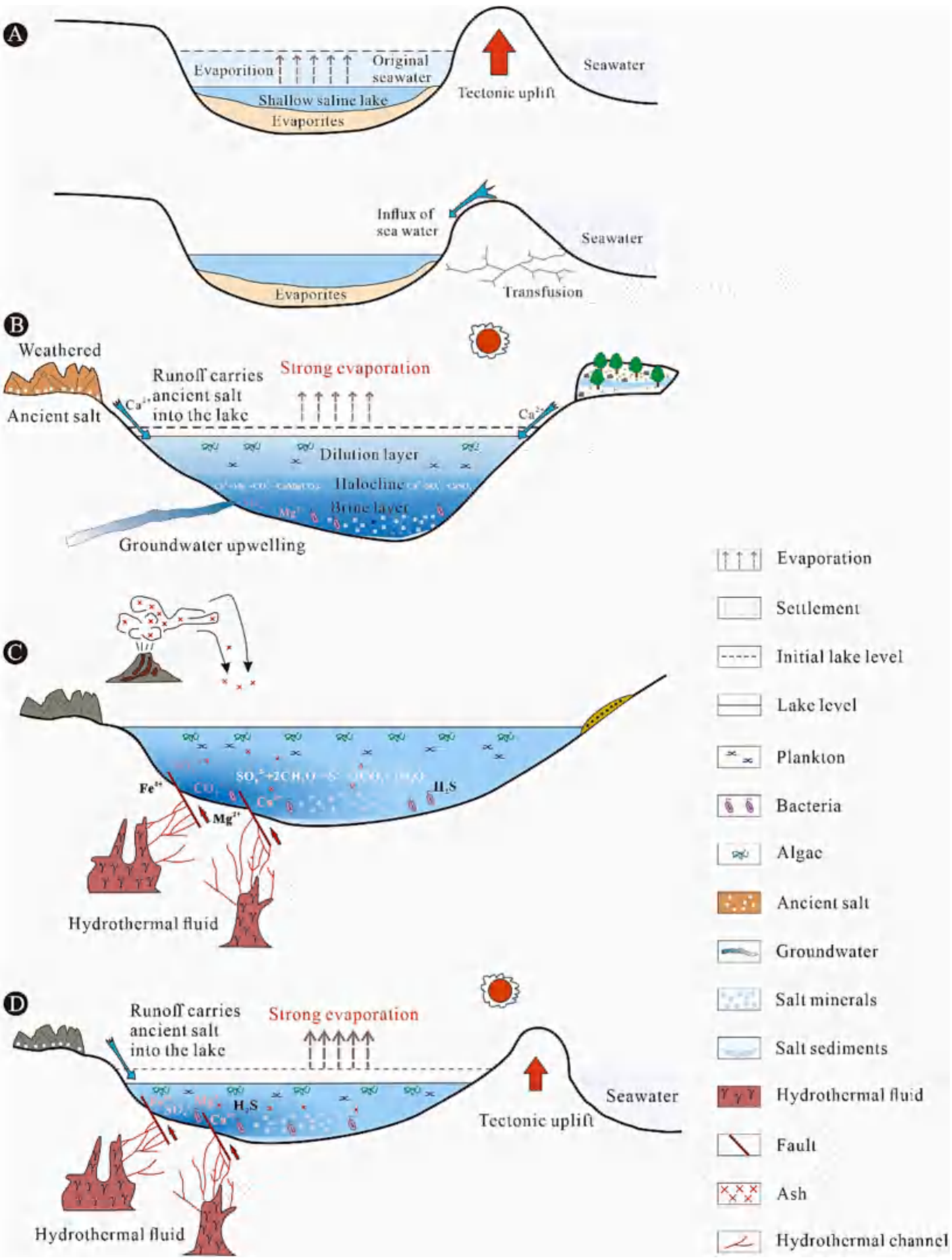

Fig. 4. Salinization model of lake basins.
A. Seawater genetic type; B Inland steam type; C. Deep hydrothermal type; D. Mixed type.

et al., 2005; Sun et al., 2016; Nara et al., 2022). Global sea level fluctuations generally only significantly impact lake basins when transgression channels are open and there is tectonic stability. Examples of lakes of this genesis include the Caspian Sea and the Paleogene Tarim Basin (Xi et al., 2016).

The Caspian Sea is the largest inland body of water and the largest saltwater lake in the world today, accounting for 41% of global saline lake volume. In the late Eocene and early Oligocene (ca 34 Ma), due to falling global sea levels and collision of the African and Arabian plates with the Indian plate, the Tethys Ocean completely closed (Fig. S1) (Berggren et al., 1995; Popov et al., 2004). It gradually evolved into the Ancient Mediterranean and Paratethys, eventually becoming the Mediterranean Sea connected to the Atlantic Ocean between Europe and Africa as well as residual seas such as the Black Sea, Caspian Sea, and Aral Sea between Europe and Central and East Asia (Steininger and Wessely, 2000; Schulz et al., 2005). The Caspian Sea is a remnant of the ancient ocean. This type of lake has developed in various geological periods following changes in regional tectonics, ocean and land patterns, and global sea level.

The Tarim Basin is a typical example of this type of salinized lake. During the Late Cretaceous and early Paleocene epochs, the Tarim block was a bay connected to Central Asia forming an epeiric sea. It was a northeast branch of the Eastern Tethys Ocean and was also called Tarim Bay (Hao and Zeng, 1984; Bosboom et al., 2011, 2014). Late Paleocene-late Late Eocene, accompanied by multiple sea transgression and regression, resulted in the interactive occurrence of marine and lacustrine deposition, and eventually exited Tarim Basin (Tang et al., 2015), transforming to a lake basin dominated by lacustrine sedimentation (Fig. 5). The evaporation of residual seawater resulted in widespread deposits of evaporites (Xi et al., 2016).

4.3. Inland evaporative saline lakes

Saline lakes formed from inland evaporation mostly develop in inshore areas with relatively flat terrain. They are not directly linked to fault activity and are predominantly affected by climate (Sun et al., 1997; Huvaz, 2009; Yao et al., 2022). Saline lakes of this type are found in arid areas at 30°–50°N (Figs. 2 and 3), where evaporation levels are high (Zheng et al., 2016). In the formation process, the weathering of parent rock released rock salt (Wu et al., 2014; Guo et al., 2017), which was carried into the lake by surface runoff or groundwater upwelling (Legler et al., 2011; Li et al., 2022). Strong evaporation caused the water body to shrink markedly, and continuous material replenishment and concentration caused the lake to eventually evolve into a salinized lake (Fig. 4B). Salinized lake basins formed in this way often the first to precipitate large amounts of salts at the lake edges. Due to salt's strong water absorption and heat absorption capacities, the climate becomes drier and hotter. This cycle causes the regional climate system to become more arid, leading to the growth and development of saline lakes (Jiang et al., 2022a). Arid or semi-arid climate conditions are a prerequisite for developing saline lakes formed by inland evaporation (Huang and Hinnov, 2019).

The Uinta Basin in Utah, USA, is an intermountain basin without faults. The Green River Formation in the Eocene comprises typical saline and alkaline lake deposits. Its evolution can be divided into five climate-driven stages (Fig. 6): (1) During the late Paleocene to early Eocene (55.8–54.6 Ma), the climate gradually changed from being humid to semi-arid. There were freshwater inputs during this period, creating an extensive freshwater lake. Sedimentation largely consisted of shallow-lake carbonates. (2) In the early Eocene (54.6–51 Ma), the temperature peaked, and frequent high-temperature events led to large-scale evaporation. The lake was shallow in this seasonal, semi-arid subtropical climate, and the salinity was lower than during the late Paleocene. Deep-water facies were well developed in the sedimentary center of the

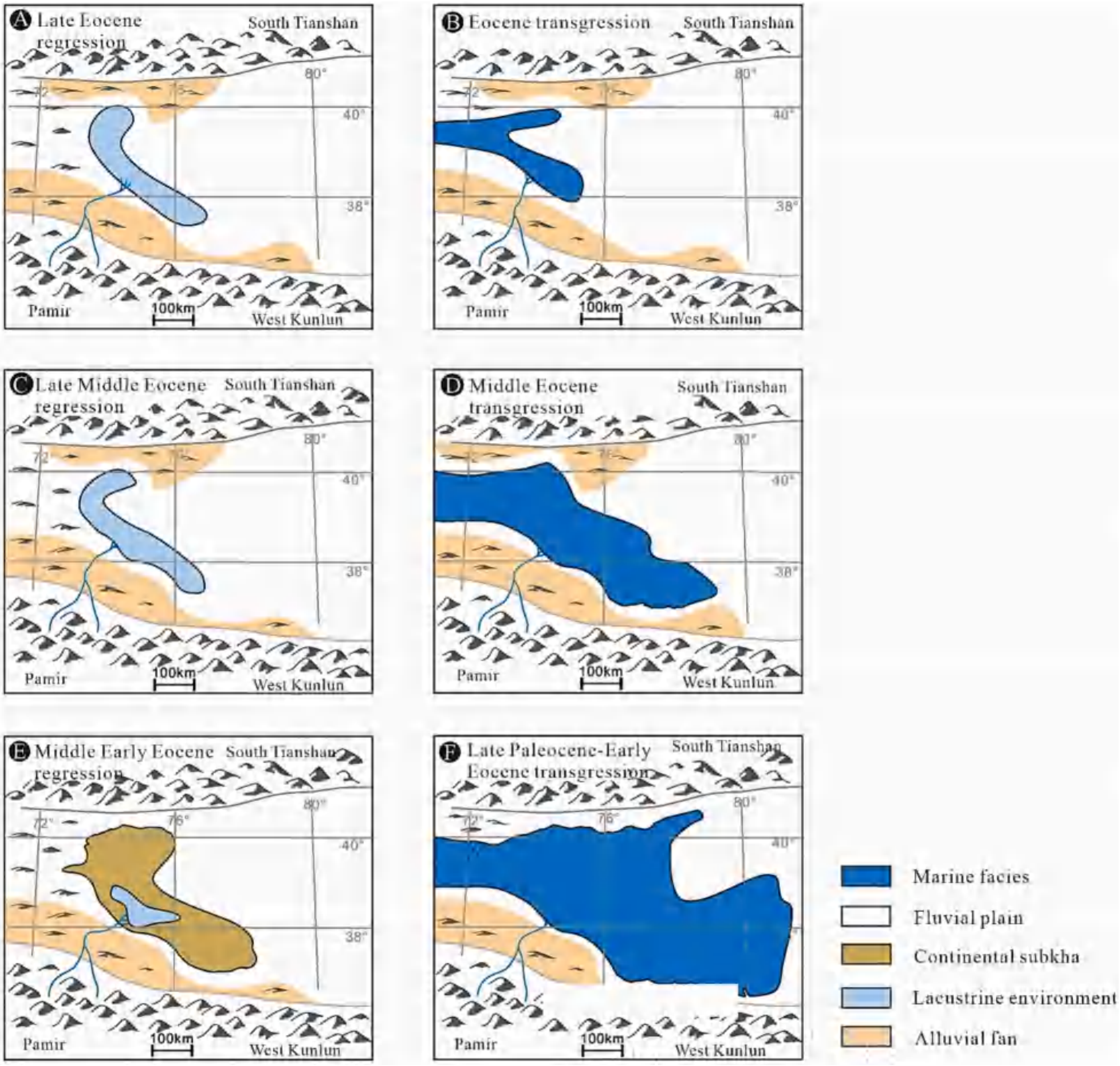

Fig. 5. Paleogeographic evolution of the Late Cretaceous-Eocene in the western Tarim Basin (modified after Zhang et al., 2018).

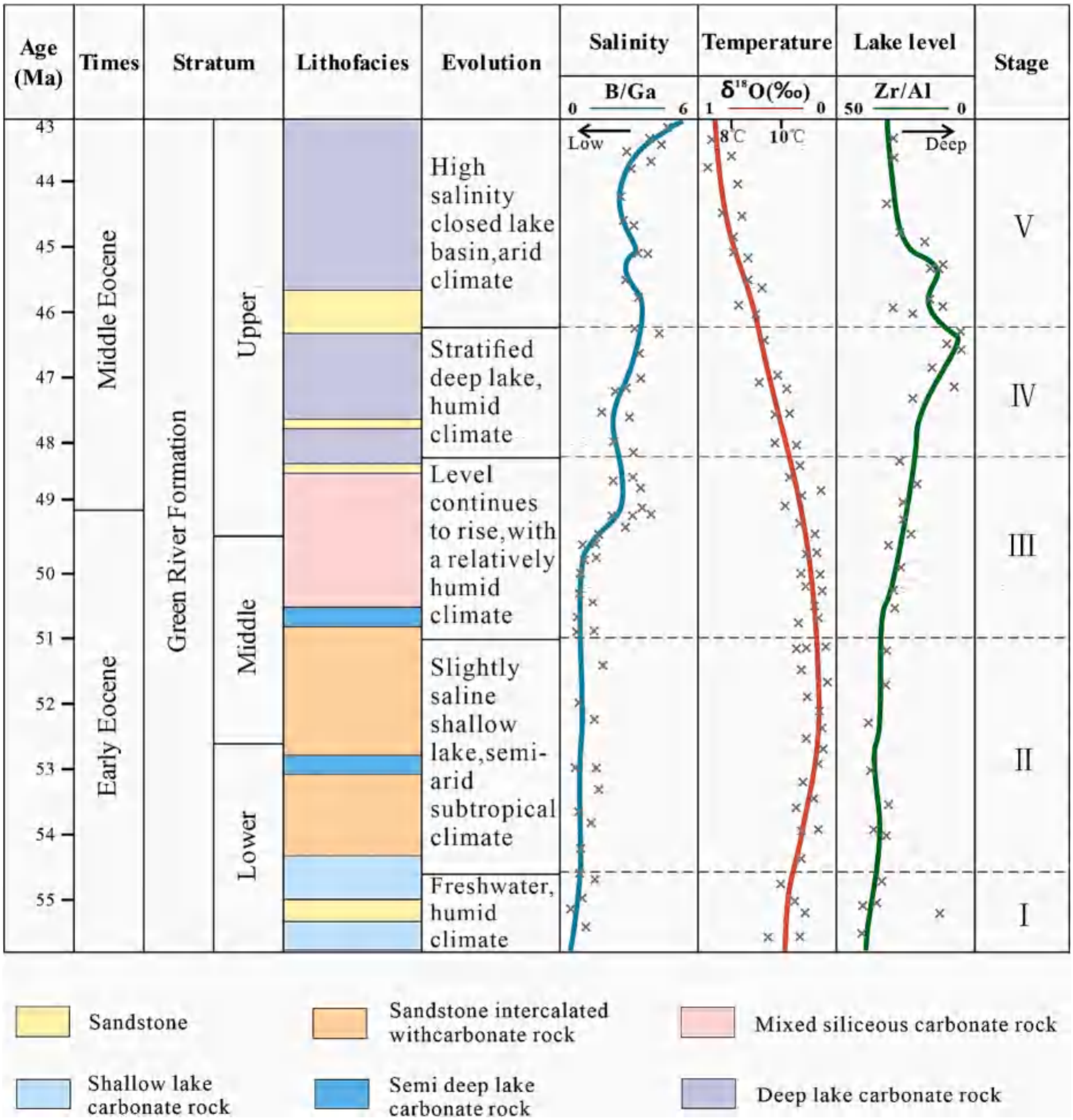

Fig. 6. Comprehensive Histogram of Green River formation in Uinta Basin (modified after Rosenberg et al., 2015; Birgenheier et al., 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

basin. (3) During a period of cooling in the oldest stage of the early Eocene (51–48.2 Ma), the temperature dropped, and the climate changed from semi-arid to relatively humid. As the climate fluctuated, river inputs increased, the lake level rose as the lake deepened, and salinity decreased (Sexton et al., 2006). (4) During high temperatures in the middle Eocene (48.2–46.2 Ma), the climate was humid, and there was little evaporation. An increase in water inputs to the lake caused the lake level to rise. The low-salinity-reducing environment led to the accumulation of a large volume of organic-rich shale deposits (Johnson et al., 2010). (5) During a period of cooling in the late Eocene (46.2–43.0 Ma), Uinta Basin was a terminal lake basin. An arid climate and strong evaporation led to a continuous rise in its salinity, becoming a closed basin (Vanden Berg and Birgenheier, 2017). The climate change during the depositional period of the Green River Formation was as follows: cool→semi-arid→relatively humid→humid→dry. Lake water salinity changed as follows: fresh water→slightly saline water→slightly saline water (decreasing) → slightly saline water (decreasing further) → salt water (Rosenberg et al., 2015; Birgenheier et al., 2019).

It can be seen that climatic conditions mainly determined the salinity changes during the deposition of the Green River Formation. Notably, as mentioned in 4.1 Section, an adequate salt supply is an important factor in the formation of saline lakes. During Stage III and IV, the climate is humid and chemical weathering is intense, which brings a large amount of saline material into the basin. The lake level reaches its maximum at the end of stage IV, but also accumulates a large amount of saline material, and after entering stage V, the evaporation shrinks the lake sharply and salinity increases rapidly (Fig. 6). This also indicates that the salinization of lakes is a complex and continuous process, which needs to be studied comprehensively in terms of multiple factors, such as the lake basin formation, climate evolution, the supply of saline substances, and lake ecology.

The Great Salt Lake is the largest salinized lake in the USA (Fig. 7A) and one of the largest perennial saline lakes in the world. It is approximately 120 km long and 55 km wide, with a water area of 4180 km^2 and

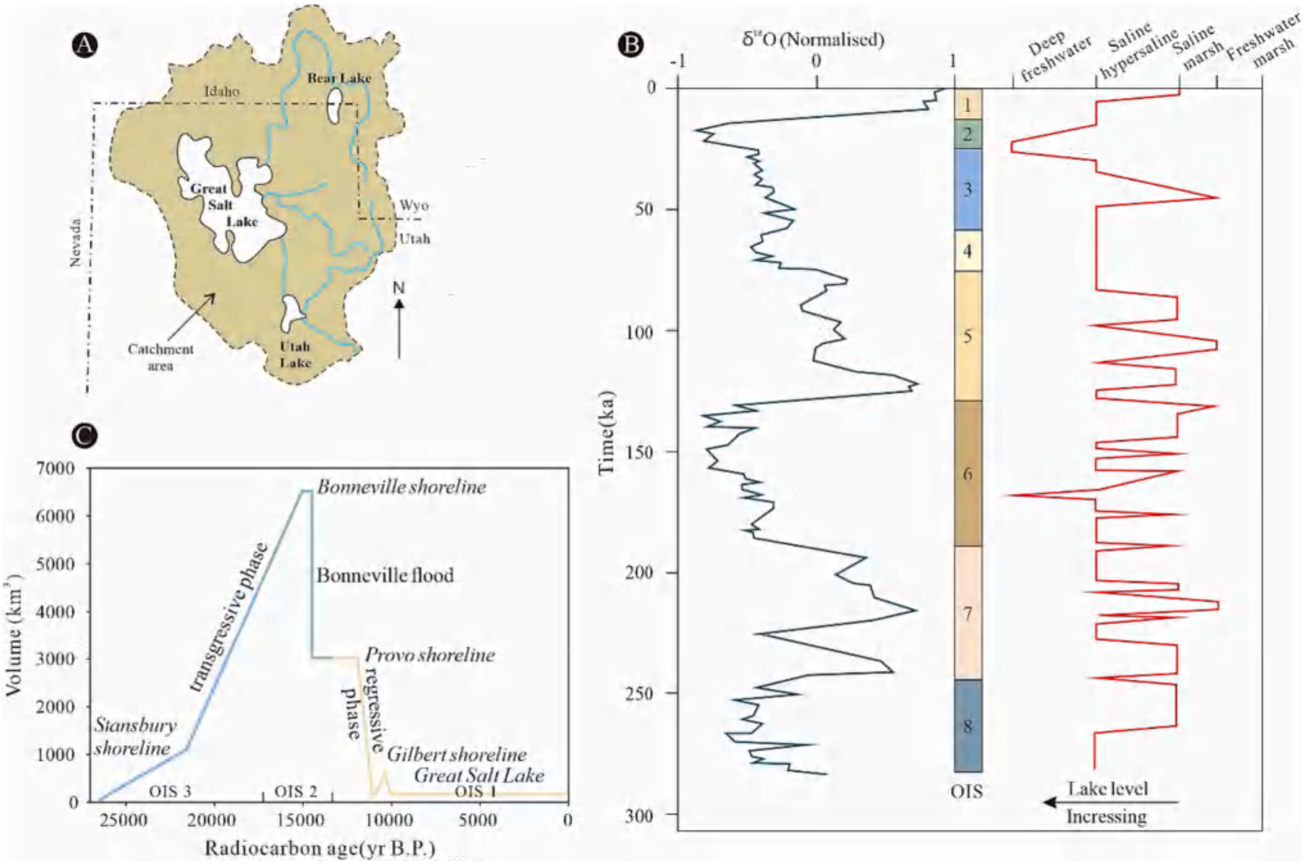

Fig. 7. Location and evolution of the Great Salt Lake.

a maximum depth of 10 m. The main rivers entering the lake are the Bear River in the north, the Weber River and Ogden River in the east, and the Jordan River in the south (Jones et al., 2009), with lake water lost mainly through evaporation. Most of the salt irons in the Great Salt Lake is from the nearby Bonneville Salt Flats. A total of 2 million tons of dissolved salt flow into the lake every year from rivers and springs (Godsey et al., 2005). Changes in salinity and depth of the Great Salt Lake were closely related to climate. Saltwater lakes are more common in interglacial periods, whereas freshwater lakes are more common in glacial periods (Jones et al., 2009). In Fig. 7B, the second stage is a deep freshwater lake, and corresponding marine oxygen isotope values indicate a maximum global ice volume, i.e., the humid climate of the glacial environment formed a deep freshwater lake. In stage one, the temperature rose, and the dry climate in the interglacial period led to the formation of saline lakes, which is consistent with the evolution of the Great Salt Lake (Balch et al., 2005). The following is the evolution process of the Great Salt Lake (Fig. 7C): before 32 ka, the Great Salt Lake Basin was a salt marsh; from 32 to 25 ka, there were inputs of river water, which formed a perennial and slightly saline lake; from 25 to 19.5 ka, the depth of the lake increased, but salinity also increased due to intense evaporation and considerable inputs of materials, causing it to become a brackish lake; from 19.5 to 16 ka, a large volume of fresh water poured into the basin, causing the depth to increase, and the relatively closed nature of the lake meant the lake's water was relatively fresh, with an average water depth of 195 m and maximum depth of 310 m; between 16 and 14 ka, the depth of the lake dropped sharply, with the lake basin overflowing around 15.3 ka and rapid erosion and downward cutting causing the height of the lake to fall by approximately 100 m (Oviatt et al., 1992; O'Connor, 1993); as glaciers retreated, the climate became arid, and the lake shrank and salinity increased due to intense evaporation; between 14 and 10 ka, the lake depth continued to decrease; at approximately 12 ka, the lake retreated and fell to a similar height to the modern Great Salt Lake at approximately 11 ka (Oviatt et al., 2005). During this period, the lake's water level was extremely low due to the arid climate, and it was occasionally split into two saline lakes. Between 10 ka and the present, the lake level fluctuated around its current position.

A. Distribution location of the Great Salt Lake (Balch et al., 2005); B. Marine oxygen isotope (OIS) with corresponding δ18O curve shows water elevation variations and corresponding environments of the Great Salt Lake in the past 300,000 years (Balch et al., 2005); C. The volume of the Great Salt Lake has changed since 25,000 years (modified after Jones et al., 2009).

4.4. Deep hydrothermal fluids-based saline lakes

This type of salinized lake is formed by transporting high-salinity hydrothermal fluids into a lake through large, deep faults (Fig. 4C). Such lakes tend to develop in areas with strong tectonic activity, often in faulted basins and foreland basins. Fault activity affects paleogeographic features and determines the formation and extinction of water storage space in the lake basin. It is also one of the main channels for transporting salt substances (Shanks and Callender, 1992; Lameck et al., 2023), providing the lake with hydrothermal fluids rich in Ca^{2+}, Na^{+}, and Cl^{-}, which promote lake salinization. The density, temperature, and salinity at the top and bottom of the lake differ considerably. It is common for stable stratification (temperature, salinity, oxygen content, etc.) to form, preventing desalination and removal of water below the halocline due to mixing (Colomer et al., 2003; Belolipetsky et al., 2010). Deep hydrothermal fluids are usually alkaline, so saline lakes of this type are more likely to be alkaline (Xia et al., 2020). Under this mode of salinization, the lake basin has considerable subsidence, and it is easy for a lake with a large relative depth (ratio of depth to the area) to form. Strong evaporation is not the main controlling factor of this type of lake, with the influx of deep high-salinity hydrothermal fluids being the main cause of lake salinization (Biazar et al., 2020).

Searles Lake in California, USA, depends largely on the Owens River for its water supply. Due to the terrain of the Sierra Nevada, Searles Lake is closed and arid (Fig. 8A). The lake's salinization took place in four stages (Fig. 8B): (1) Between 2.04 Ma and 1.27 Ma, the solutes in the lake water came from nearby ground surface weathering, with inflows through atmospheric precipitation (Lowenstein et al., 2016). Periodic changes in salinity were mainly affected by the depth of the lake basin, with evaporites (mainly halite) deposited during shallower intervals and mud deposited during deeper stages. The general environment was freshwater. (2) From 1.27 Ma to 570 Ka, Owens River flowed into the lake basin and provided salt substances. Two large-scale volcanic activities occurred at 767 and 610 Ka. Salt substances in the Owens River came from highly alkaline hydrothermal fluids in the Long Valley Caldera (Sorey et al., 1991; Sorey, 1985; Pretti and Stewart, 2002), as well as salt ions (Na^+, K^+, Cl^-, HCO_3, CO_3^{2-}, and SO_4^{2-}) carried in river water that entered the lake, which made Searles Lake an alkaline brackish water lake and deposited minerals such as halite and trona (Earman et al., 2005). (3) There was a dry climate between 570 ka and 130 ka when the volume of water replenishment decreased, and salt substances from deep hydrothermal fluids in river water increased, causing Searles Lake to become a salinized lake and producing large deposits of alkaline evaporites rich in halite and trona due to intense evaporation. (4) The lake depth has fluctuated since 130 ka due to climate change (Lowenstein et al., 2016). It is currently a dry salt pan containing many salt minerals, including gypsum and trona.

The Lower Permian Fengcheng Formation in the Mahu Depression of the Junggar Basin in China was a saline-alkaline lake during its deposition period. It is one of the oldest known alkaline lakes (Cao et al., 2020). During the intense development period of the foreland basin on the northwestern margin of the Junggar Basin, the depositional environment was that of a low-energy shallow to semi-deep lake (Bian et al., 2010), when many alkaline minerals developed, such as trona ($Na_2CO_3 \cdot NaHCO_3$), sodium bicarbonate ($Na_5H_3(CO_3)_4$), and shortite $Ca_2Na_2(CO_3)_3$, and reedmergnerite ($Na_3BSi_3O_4$). During the depositional period of the Fengcheng Formation, there was strong volcanic activity and notable hydrothermal activity (Fig.S2). There were fewer terrigenous salt inputs than that from hydrothermal fluids along large, deep large faults. The climate was arid during the entire period, and both volcanic activity and paleoclimate influenced salinization. The arid climate caused intense evaporation, which accelerated salinization. Most importantly, hydrothermal action introduced a large volume of salt into the lake, increasing salinity and promoting the formation of an alkaline lake (Tang et al., 2022).

4.5. Combined mechanisms of salinization

Many salinized lake were not formed by a single mechanism, but rather by combining the mechanisms outlined above. During the evolution of salinized lake basins, one or more modes can be the main salinization mechanism, and the main mechanism may change with the evolution of salinization periods. A salinized lake basin formed by multiple salinization mechanisms is called a combined-mechanism salinized lake (Fig. 4D).

The Bohai Bay Basin is eastern China's most important oil- and gas-bearing basin, covered an area of approximately 2×10^5 km^2 (Zhao et al., 2005). Salinization occurred in the Bohai Bay Basin approximately from 50.8 to 23 Ma (Hu et al., 2001), and the lake's average salinity was approximately 27.3‰ (Wei and Algeo, 2020). Its main source rocks

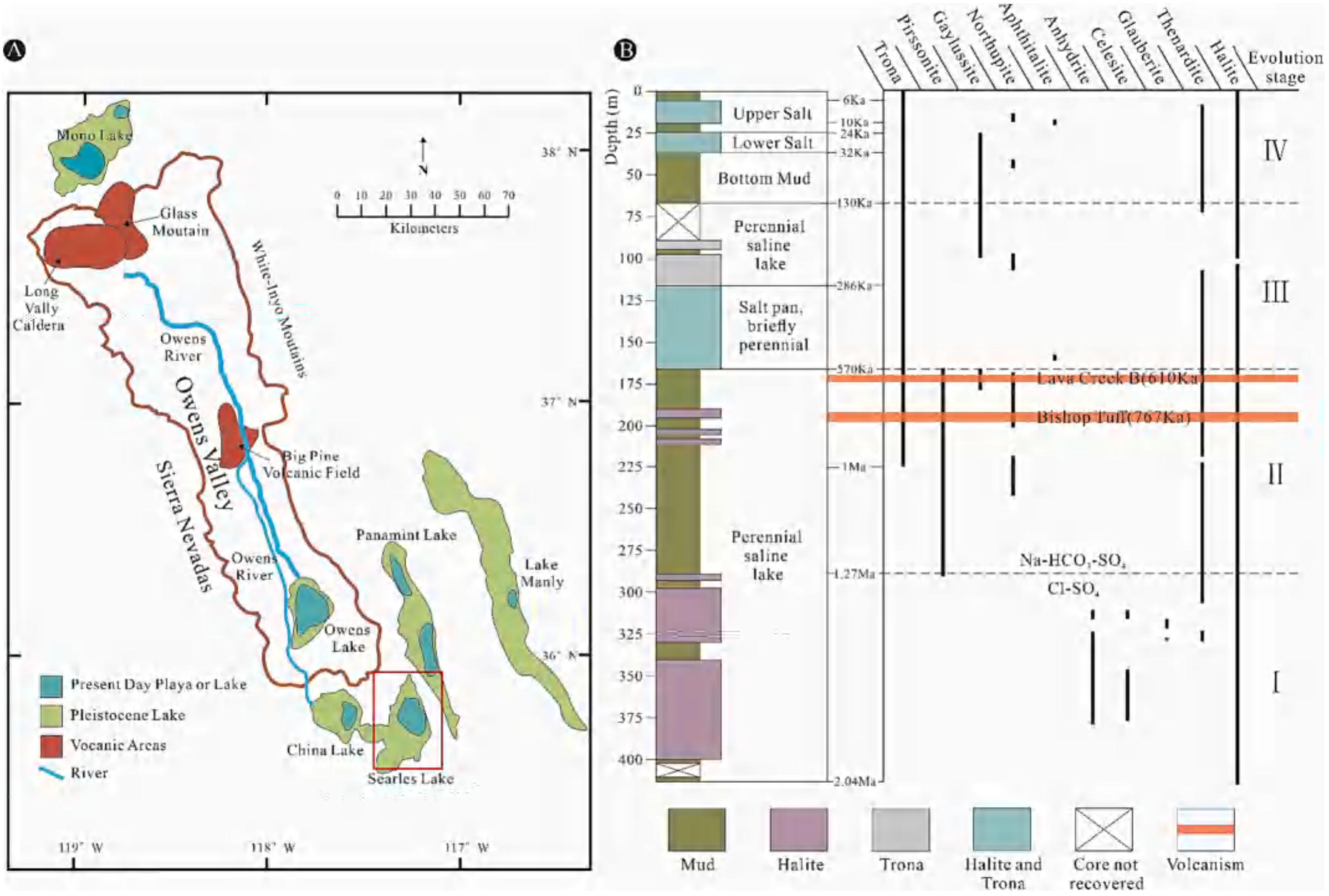

Fig. 8. Location and sedimentary evolution characteristics of Searles Lake (modified after Lowenstein et al., 2016).

formed when it was a saline lake basin, and the various sources of salt substances were influential in different stages, so salinization was due to a combination of mechanisms (Fig. 9). Transgressions, arid climate, and deep hydrothermal fluids all contributed to the salinization process. In the early stage, the intrusion of high saline seawater was primarily responsible for introducing salt, and a large number of studies suggest that three seawater intrusion events occurred during the depositional period of the Shahejie Formation (Liang et al., 2018; Wei et al., 2018, Wei and Algeo, 2020). In the middle and late stages, terrigenous, volcanic, and magmatic activities and deep brine, jointly contributed to salinization (Wu et al., 2014). Paleosalt release from Lower Paleozoic carbonate strata provided a large amount of salt ions, which, together with the hot and arid climate of the period, accelerated the evaporation of lake water and the salinization of the lake basin (Hao et al., 2011; He et al., 2020; Zhao et al., 2019). In addition, the Bohai Bay Basin is a faulted basin where deep thermohaline water upwells along the fractures and enters the lake to accelerate the salinization process (Huang et al., 2012; Li, 2018; Chang et al., 2018), which is an important mechanism for the salinity increase under the humid climate during the Es3x depositional period.

The Campos Basin is located on a passive continental margin in southeast Brazil, and its salinization has features of combined formation mechanisms (Fig.S3). (1)During the Neocomian and Barremian stages of the Early Cretaceous, the development of tectonic rifts led to the upwelling of high salinity hydrothermal fluids and the salinization of lake (Contreras, 2011). (2)In the Barremian and early Aptian ages, the basin experienced a period of down-warping, with seawater entering the basin periodically. Especially, following the opening of the Walvis Ridge at the end of the Aptian age, seawater flooded into the basin from the south (Smith, 2000; Chaboureau et al., 2013), providing rich salt materials and depositing evaporite rocks. (3) The mid-Cretaceous saw a significant increase in the greenhouse effect, and the Albian and Cenomanian ages were the hottest (Sellwood and Valdes, 2006; Thompson et al., 2015). The climate was typically hot and dry, and less precipitation, and increased evaporation caused the salinity in the Campos Basin to increase, forming an alkaline saline lake.

The development of saline lakes in modern and deep-time is mainly distributed in the mid-latitude, i.e., arid zone, which indicates the important role of climate. Today, tectonic activity is relatively weak and the salted lake is mainly influenced by climate. However, there are differences in different eras, and studies suggested that large saline lakes in deep-time are often developed at the edge of the continents (Warren, 2016; Xia et al., 2020), such as the Eocene Bohai Bay Basin, the largest saline lake in China (Feng et al., 2013). This may be due to two reasons, one is the intrusion of seawater and saline water underground, and then faults are prone to be formed with the subduction boundary of the oceanic crust, bringing deep brine to lakes. Meanwhile, it is also related to the global climate, such as the Paleoproterozoic period, the saline lakes flourish during the Cambrian and Carboniferous-Permian, sea level was at a low level, which may be related to the low precipitation during the Ice Age. This variability in the distribution of saline lakes across different epochs reflects the complexity of salinization mechanism, and is a synthesis result of tectonics, palaeogeography and climate.

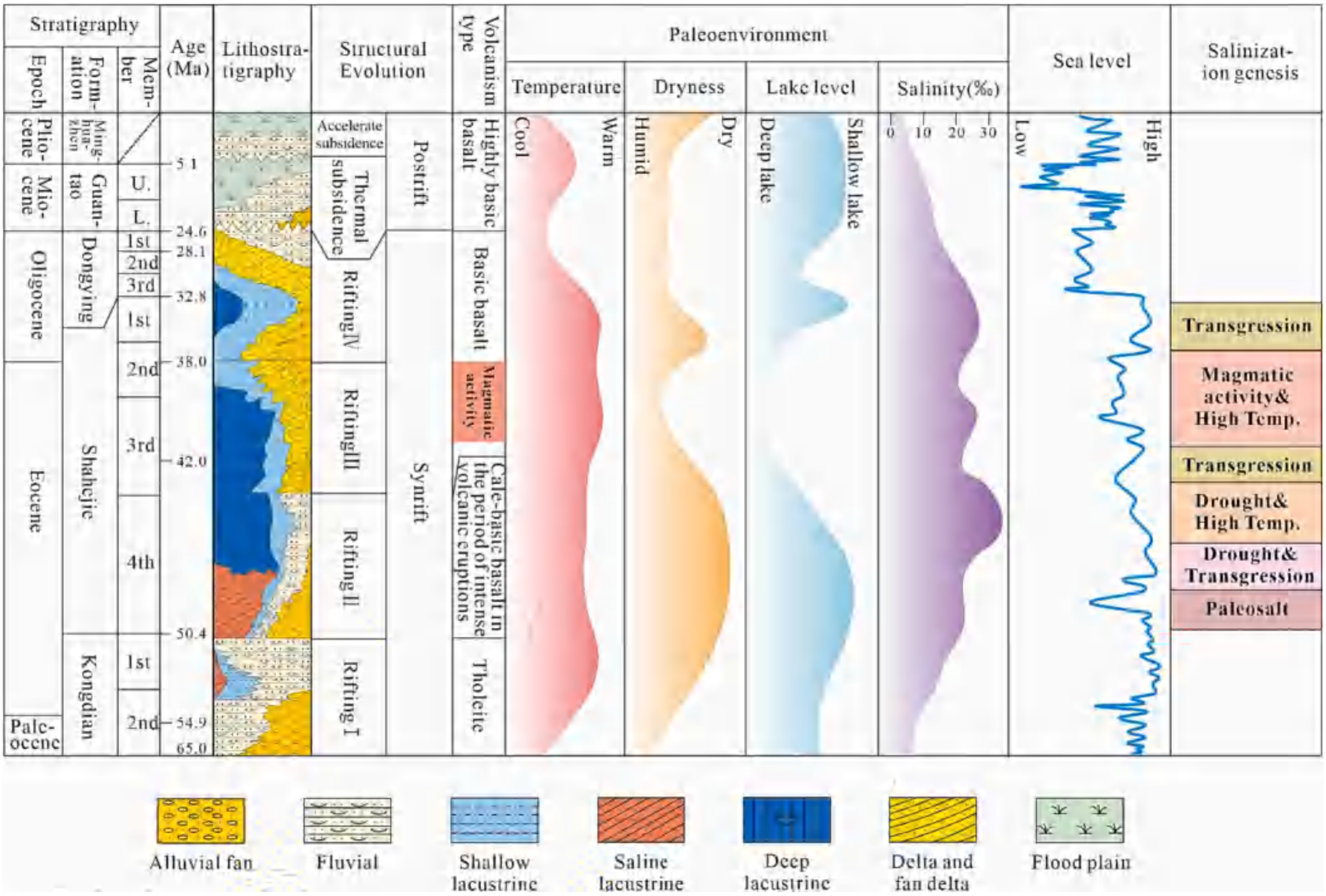

Fig. 9. Salinization mechanisms and evolution of Dongying Sag, Bohai Bay Basin (modified after Hardenbol et al., 1998; Feng et al., 2013; Zhao et al., 2019). Schematic sea-level curve is modified from Hardenbol et al., 1998; Schematic temperature, dryness, and lake level curves are modified from Feng et al., 2013; Schematic salinity curve is modified from Wei et al., 2018; Lithofacies map from Zhao et al., 2019.

5. Hydrological characteristics of saline lakes

5.1. Overview of hydrological characteristics

Salinity, water depth, redox condition, stratification, and open/closed environment are essential aspects of lake hydroecology. Saline lakes have hydrological features that are distinct from freshwater lakes, especially, the biological distribution and physical and chemical properties changing based on salinity, which will influence the type and composition of sediments, distribution of biological communities, and preservation of organic matter(Fig. 10) (Sharqawy et al., 2012; He et al., 2020).

Specific heat capacity decreases as salinity increases (Fig. 11A). Compared to freshwater lakes, saline lake water has a smaller specific heat capacity. During the day when the solar radiation intensity is high, saline lake water temperature rises quickly, and at night, declines quickly, thus resulting in large diurnal temperature differences (Hammer, 1986; Warren, 2010, 2016). For example, the temperature in hypersaline lakes in Crimea, India, and USA can reach 55–60 °C in summer, and temperatures can fluctuate in the range of 19–45 °C in the course of a day (Shadrin et al., 2016).

Thermal conductivity decreases as salinity increases (Fig. 11B). This reduces the thermal conductivity of the water body, making thermodynamic stratification more likely in saline lakes than in freshwater ones. Often, even shallow saline lakes can have thermal stratification, with a temperature difference of up to 14 °C in water just 2 m deep (Debelius et al., 2009).

Gas solubility usually decreases as salinity increases (Nishri and Ben-Yaakov, 2004; Debelius et al., 2009), and oxygen content is an important parameter affecting the biological composition and organic matter preservation. Oxygen commonly enters the water through atmospheric diffusion and photosynthesis of aquatic organisms. As shown in Fig. 11C, the dissolved oxygen content is affected by temperature and salinity, decreasing as water temperature and salinity increase. As salinity increases, the oxygen diffusion coefficient in water decreases (Fig. 11D), which leads to the formation of an oxygen concentration gradient in saline lakes and stratification (Fig.S4). Scholars have discovered that a common feature of hypersaline water bodies is significant fluctuations in oxygen concentration daily, with saturation dropping from 200% during the day to 0% at night (Shadrin, 2012; Shadrin and Anufriieva, 2013; Shadrin et al., 2016).

Saturated vapor pressure (when the rate of evaporation equals that of condensation) affects the evaporation of saline lakes. The higher the saturated vapor pressure, the easier it will be for the water in the lake to evaporate. The main factors affecting saturated vapor pressure are ambient temperature and salinity. The saturated vapor pressure decreases when salinity increases and ambient temperature decreases (Fig. 11E and F). Under a constant temperature, higher salinity results in a lower evaporation rate confirmed at Mono Lake in the USA and the saline lakes of the Crimean Peninsula.

5.2. Stratification

(1) **Physicochemical stratification.**

Although not all saline lakes are stratified, most of them tend to be, which is related to lake salinity, water depth and other factors (Vachon et al., 2019; Woolway et al., 2020). Undoubtedly, stratification is an important feature of the hydrological ecology of saline lakes, maybe stratified by temperature, density, salinity, and oxygen content. High-salinity water sinks under gravity, which increases salinity at the bottom of the lake and produces salinity stratification in which the lower part is brine, and the upper part is brackish water (Zavialov et al., 2003). When river water and rainwater enter the lake, they float on saline water, intensifying the stratification. It can be seen from the relationship between salinity and water depth in Qinghai Lake that there is a close correlation between deep water and high salinity (Fig. 12). Areas with strong tectonic activity often have lakes with a large relative depth (ratio of depth to the area), which can prevent mixing of stratified lake water due to factors including wind velocity, freshwater inflows, and lake currents. Studies have found that the stratification of saline lakes with a relative depth >0.01 tends to remain stable, such as the Dead Sea, Lake Kivu, and Lake Turkana (Mazumder et al., 2013). It is worth noting that the depth of lake water does not determine whether stratification will form. For example, the bottom of Lake Lugano in Switzerland experiences periodic oxygen enrichment at a depth of 270 m (Niessen and Kelts, 1989), while there is 4 mg/L of dissolved oxygen at a depth of 100 m in Fuxian Lake in Yunnan, China (Chu et al., 2000).

Vestfold Hills in Antarctica covers an area of approximately 400 km^2 and has a large number of meromictic lakes and permanently stratified lakes (Burton, 1981; Gibson et al., 2009). After continental ice sheets receded approximately 10,000 years ago, the area rose from the ocean, creating hundreds of lakes, mostly saline lakes. (Fig. 13). These saline lakes provide good examples for studying the stratification of lake waters. Studies have shown that the location of the salinity, oxygen content, and temperature stratification are not always consistent, and are interacting with each other. Taking the oxycline as an example, the oxycline is at 12–20 m in Ekho Lake, while it has an anoxic environment from the surface to the lake bottom in Deep Lake with a similar water depth (Fig. 14A, B, C) , which may be due to its ultra-high salinity (ten times that of seawater). Studies have shown that the location of the oxycline is controlled by the depth of subglacial thermohaline convection (Andrassy and Gibson, 2007; Gibson et al., 2009). For example, the oxycline of Ace Lake in eastern Antarctica is at a depth of 7 m. Still, oxygenation periodically occurs at 12 m (Fig. 14C), which may be due to inflow of freshwater reducing the surface salinity and promoting

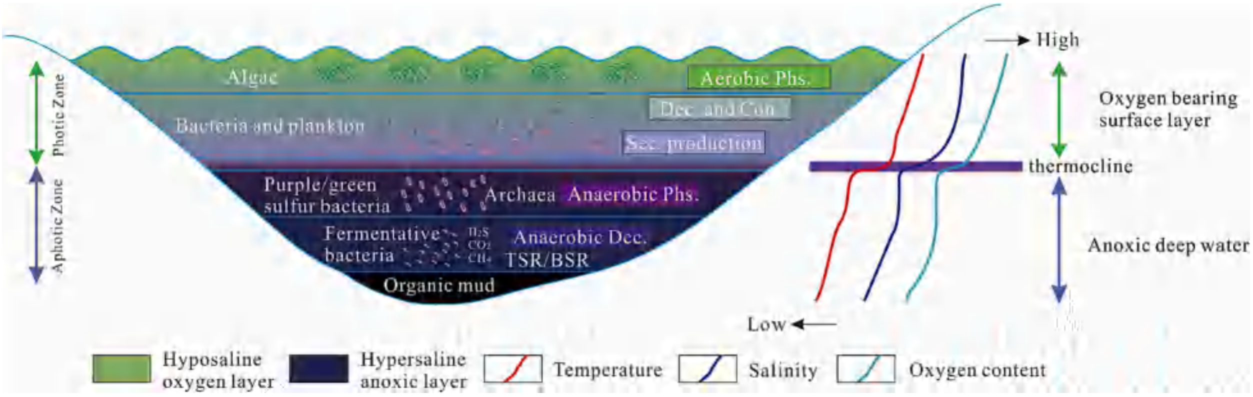

Fig. 10. Hydrological characteristics model of saline lake basin. The abbreviations mentioned in the figure are: Phs.(photosynthesis); Dec.(decomposition); Con.(consumption); Sec.(secondary); TSR (thermochemical sulphate reduction); BSR (bacterial sulphate reduction).

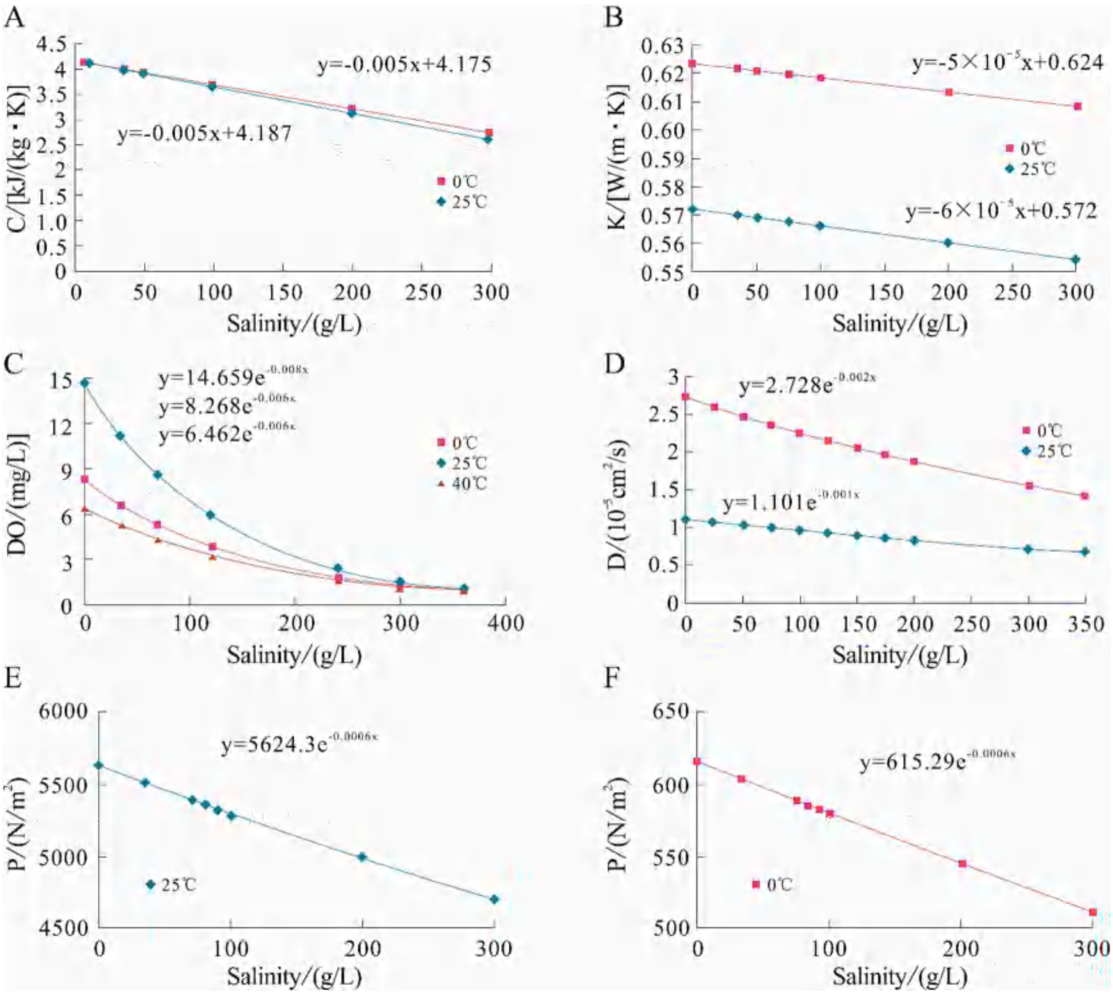

Fig. 11. Relationship between physical properties of water body and salinity (modified after Shadrin and Anufriieva, 2013). A-F ordinates are: A. Specific heat capacity; B. Coefficient of thermal conductivity; C. Dissolved Oxygen; D. Coefficient of diffusion; E and F. Saturated vapor pressure.

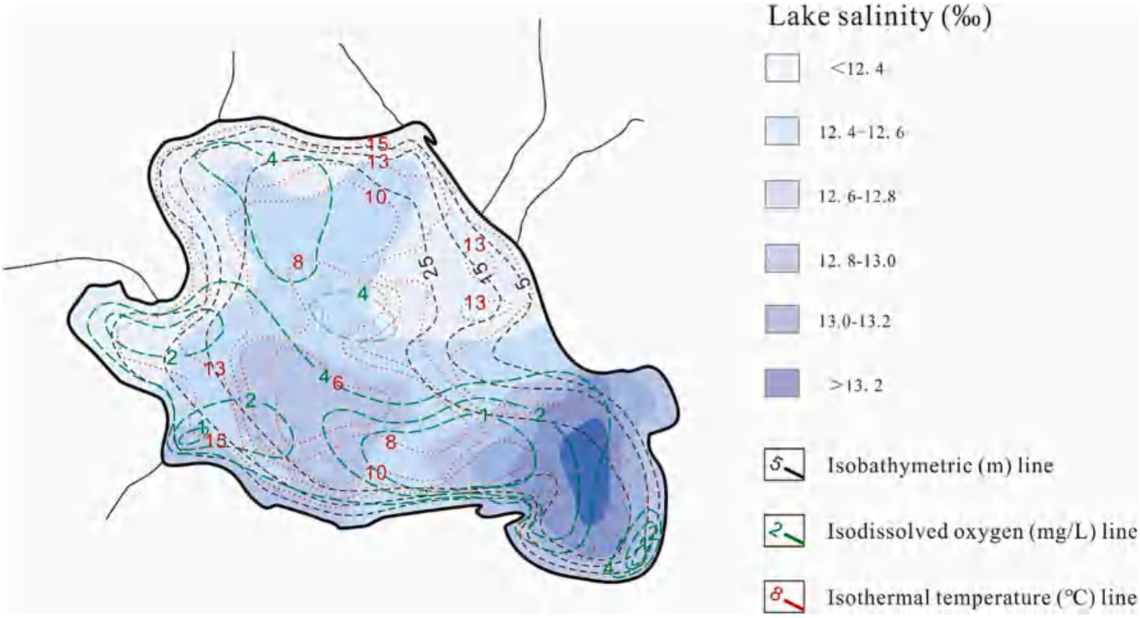

Fig. 12. Relationship between salinity and water depth of Qinghai Lake (modified after Sun et al., 1997).

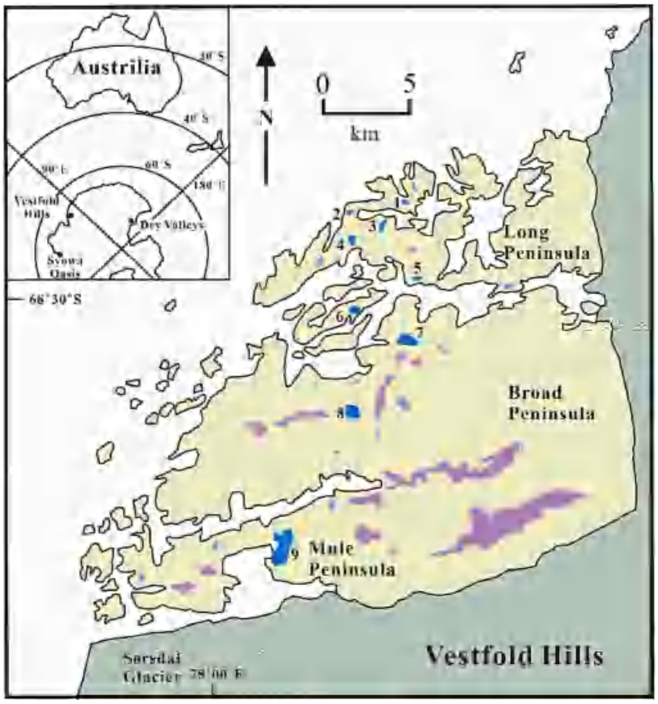

Fig. 13. Location of meromictic lake in Vestfold Hills (modified after Gibson, 1999).The lakes not mentioned in the text are purple filled, and the lakes mentioned are: 1.Bayly Lake; 2. Organic Lake; 3.Pendant Lake; 4.Ace Lake; 5. Abraxas Lake; 6.Deprez Lake; 7. Ekho Lake; 8. Deep Lake; 9.Burton Lake. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

subglacial convection. In addition, if the convection depth increases below the oxycline, lakewater containing hydrosulfide is carried to the surface, causing the surface water to approach anoxic conditions. For example, in the winter of 1988, the mixing depth of Lake Burton increased sharply, causing the oxygen in the surface water to suddenly drop from 10 to 11 mg/L to below 1 mg/L (Fig. 14D) (Burke and Burton, 1988; Mazumder et al., 2013; Laybourn and Bell, 2014).

Stratification significantly influences lake water temperature, salinity, ion distribution, and oxygen content. (1) Stratification influences changes in salinity and temperature. For example, the mixing layer and aquiclude of Ekho Lake form at a depth of approximately 20 m (Fig. 14A). Warm, dense water beneath the ice sheet sinks, transporting salt and heat to the bottom of the mixing layer. Thus, the salinity and temperature (50 g/L and approximately 0 °C) of the water column increase with depth and finally reach their maximum levels near the cline (165 g/L and 16–18 °C) (Gibson, 1999). (2) Stratification affects the distribution of lake organisms and metal ions. In Organic Lake, the peak of DMS concentration is above the oxic-anoxic interface (oxycline), where bacteria and Dunaliella are most abundant. Lake water in the monimolimnion has a reducing environment, so the number of anaerobic bacteria is much higher. Redox reactions in lakes are vital for controlling the distribution of trace metal ions. The reductive dissolution of metal oxides and anaerobic digestion of organic matter usually occur near the oxycline. (3) Studies have previously been conducted on the many lakes in the Vestfold Hills in Antarctica that gathered temperature, salinity, oxygen content, and electrical conductivity data by depth, which found that clines are primarily related to changes in conductivity and salinity (Fig. 14E–H). Sometimes there are slight fluctuations, such as the oxycline deviation relative to other clines in Ace Lake (Fig. 14C).

(2) **Stratification fluctuations.**

Lake water stratification is impermanent and affected by temperature, salinity, and water depth. Short-term influences include seasonal changes in temperature and precipitation, and long-term effects include changes in the regional climate.

Lake Van is the largest alkaline lake and the fourth-largest closed lake in the world (Fig. 15A and B) (Reimer et al., 2009). Its current salinity is approximately 22‰, and its pH is around 9.5, so the lake water is strongly alkaline (≈153 meq/L). Approximately 200 ka ago, Nemrut volcano blocked the drainage of Lake Van to the Murat River, turning the lake into an endorheic lake basin (Fig. 15A, B). The lake basin has a continental climate with hot, dry summers and long, cold winters. Inflows of large volumes of freshwater and high temperatures in summer lead to the lake becoming stratified (Fig. 15C). The temperature at the top of the lake water gets as high as 19–20 °C, while the water temperature is 3 °C below 50 m. Dissolved oxygen is present throughout the water column but falls to <1 mg/L near the lake bottom.The stratification can last until fall. Lower temperatures in winter causing the water body to overturn due to thermodynamics, thereby removing the stratification until it reforms in the summer of the following year.

Stratification in the Dead Sea has changed dramatically over time. In 1959, there was a significant jump in temperature and density at a depth of 50 m in the Dead Sea (Neev and Emery, 1967) (Fig. 16A). During the 1960s and 1970s, due to the drier climate inflows of fresh water from the Jordan River decreased, resulting in increased salinity of water, and stratification at a depth of 80 m (Fig. 16B). In February 1979, the density of the upper and lower layers equalized and turned over, causing the water column to mix and stratification to disappear (Steinhorn, 1983) (Fig. 16C). During the subsequent two decades, stratification reformed in the Dead Sea, with clines at depths of between 15 and 30 m (Fig. 16D). Stratification usually formed in May and lasted until fall, with the lake turning over in November and stratification disappearing until the following May (Fig. 17A). In addition, stratification also occurs in the bottom layer. The temperature profile of the bottom layer exhibits a step-like feature (Fig. 17B), showing that the physical properties at the lake bottom are not uniform, with saltier, warmer, and denser water gathering in the lowest part of the Dead Sea (Gertman and Hecht, 2002).

(3) **Influencing factors.**

Lake stratification is determined by thermodynamics. Thermal stratification of lakes has many impacts on the water body, including establishing an anoxic or anaerobic hypolimnion, and preserving deposited organic matter. Density stratification caused by thermal stratification inhibits vertical exchanges between the surface and bottom lake water. This hinders the exchange of materials between different depths, prevents water with different salinities from mixing, and limits the transfer of dissolved oxygen. These results are in stark contrast between the surface and bottom layers. The surface layer is nutrient-poor and has low salinity and high oxygen, while the bottom layer is nutrient-rich and has high salinity and low oxygen (Macintyre et al., 1999). Lake thermal stratification determines dissolved oxygen and salinity levels.

The establishment of lakes stratification is influenced by three major factors: water temperature (heat flux), transparency, and water depth. Water depth mainly affects the spatial variation of clines, whereas water temperature and transparency significantly influence the seasonal variation and spatial distribution of thermal stratification (David et al., 1994; Fee et al., 1996). (1) Ambient temperature: The establishment of lake stratification is affected by temperature in different seasons. In the northern hemisphere, clines start to form in May, and they are generally stable by July, and then stratification is gradually destroyed. It then started to reform in May of the following year. Surface layer temperature is negatively correlated with the depth of clines, and the influence is more significant when stratification is stable or destroyed but less during the formation of stratification (Zhang et al., 2014). This is due to the high diurnal range, which means stratification does not have time to respond to changes in water temperature. (2) Transparency:

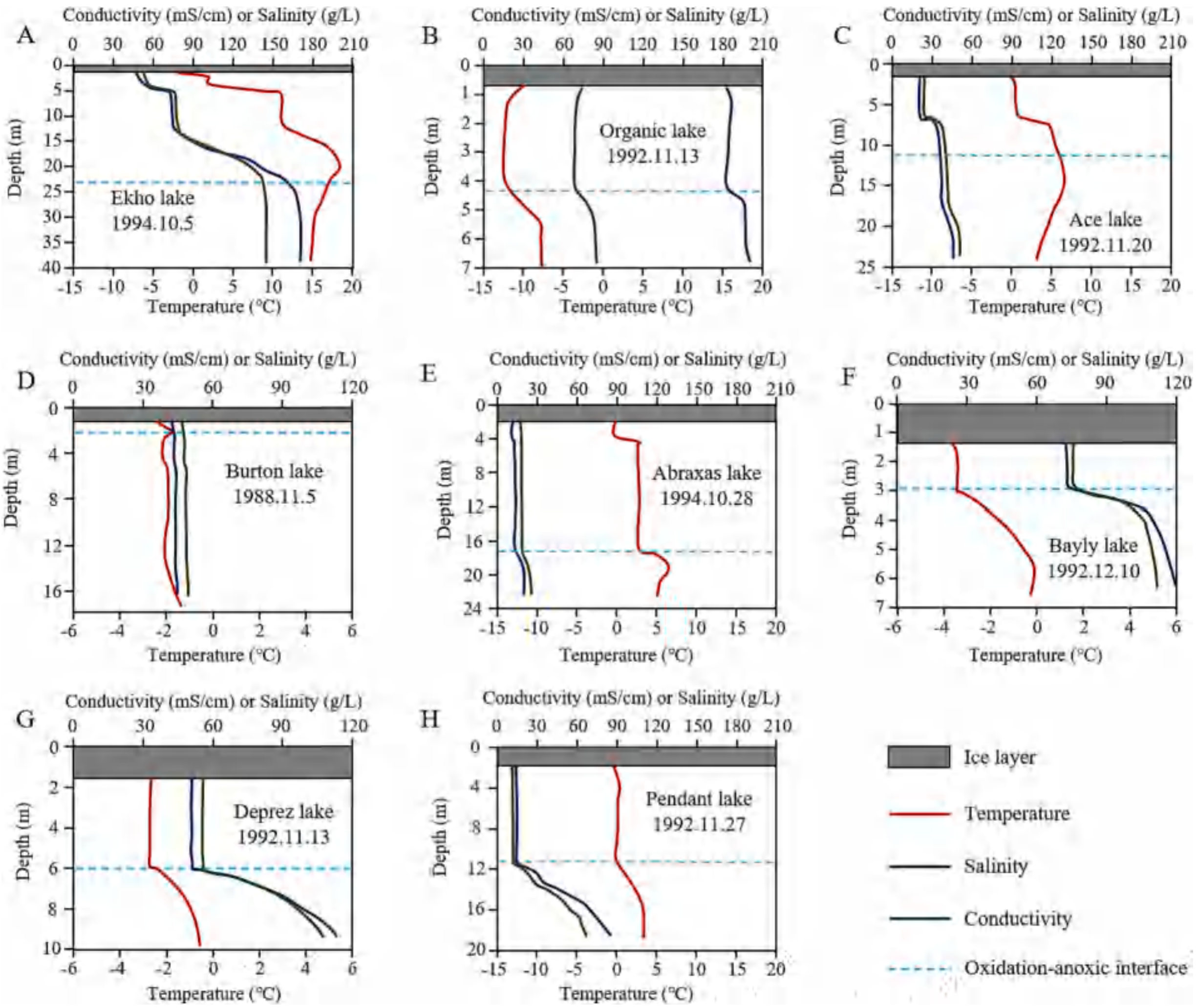

Fig. 14. Parameter variation diagrams of Vestfold Hills lakes (modified after Gibson, 1999).

Transparency affects the depth that solar radiation can penetrate the lake, affecting the amount of solar radiation energy received. As a result, transparency affects water temperature at different depths, causing different stratification of the water body and affecting the depth of clines (Nowlin et al., 2004; Kraemer et al., 2015). Transparency in stratification stable period is significantly positively correlated with cline depth. The greater the transparency, the greater the cline depth. There is no apparent correlation between the two during stratification formation. (3) Water depth: The lake's depth does not significantly influence the stratification depth during its establishment, but it does when stratification is stable. Other conditions being equal, the greater the water depth, the greater the stratification depth.

5.3. Closed lakes

An open or closed environment is another important factor in creating a salinized lake, influenced by terrain, faults, and climate. A closed or semi-closed lake is conducive to the salinization of the lake basins and enrichment of organic matter. Compared with open lakes, closed ones are more sensitive to their environment, so climate factors have a more significant impact. Inflows to closed basins are only consumed by evaporation; therefore, climate controls lake water storage, and excessive or insufficient precipitation causes the water level to rise and fall (Almendinger, 1990).

A closed lake basin environment affects the water's carbon and oxygen isotope composition, with evaporation playing a prominent role in controlling their concentrations (Talbot and Kelts, 1990). As evaporation increases, lighter ^{16}O, and ^{12}C-rich CO_2 escape from the lake surface, increasing ^{18}O and ^{13}C in the lake (Gallois et al., 2018; Yu et al., 2018a). The longer the period of water stagnation, the more evaporation will occur, and the more pronounced this effect will be. Furthermore, closed saltwater lakes are mostly highly productive and have abundant algae. Under photosynthesis, algae plants prefer to absorb lighter ^{12}C, increasing δ^{13}C in the lake. The greater a lake's productivity, the more δ^{13}C there will be in the lake (McKenzie, 1985; Kelts and Shahrabi, 1986; Davis et al., 2008; Della Porta, 2015). There is a notable correlation between δ^{18}O and δ^{13}C in closed saline lakes (Talbot, 1990; Felipe et al., 2019; Benavente et al., 2015), with the correlation coefficient (r) generally >0.7 (Meng et al., 2012). The more closed the environment, the higher the correlation coefficient. Prime examples include the Great Salt Lake, Lake Turkana, Lake Natron, and Lake Magadi (Fig. 18). When a lake's water stagnation period is short, there is almost no isotope evolution, so carbon and oxygen isotopes are more reflective of the isotopic features of freshwater inflows. Water inflows include surface runoff (river water), groundwater, and atmospheric precipitation. The composition of oxygen and carbon isotopes differs in each of them (Lister, 1998; Janssen et al., 2007), so there is no correlation or only a slight correlation between δ^{18}O and δ^{13}C, and both are negative. Examples are Greifensee Lake in Switzerland, Henderson Lake in the USA, and Lake Huleh in Israel (Fig. 18).

Studies on recent lakes, as well as large-scale continental lakes throughout geological history, have discovered that four freshwater lake

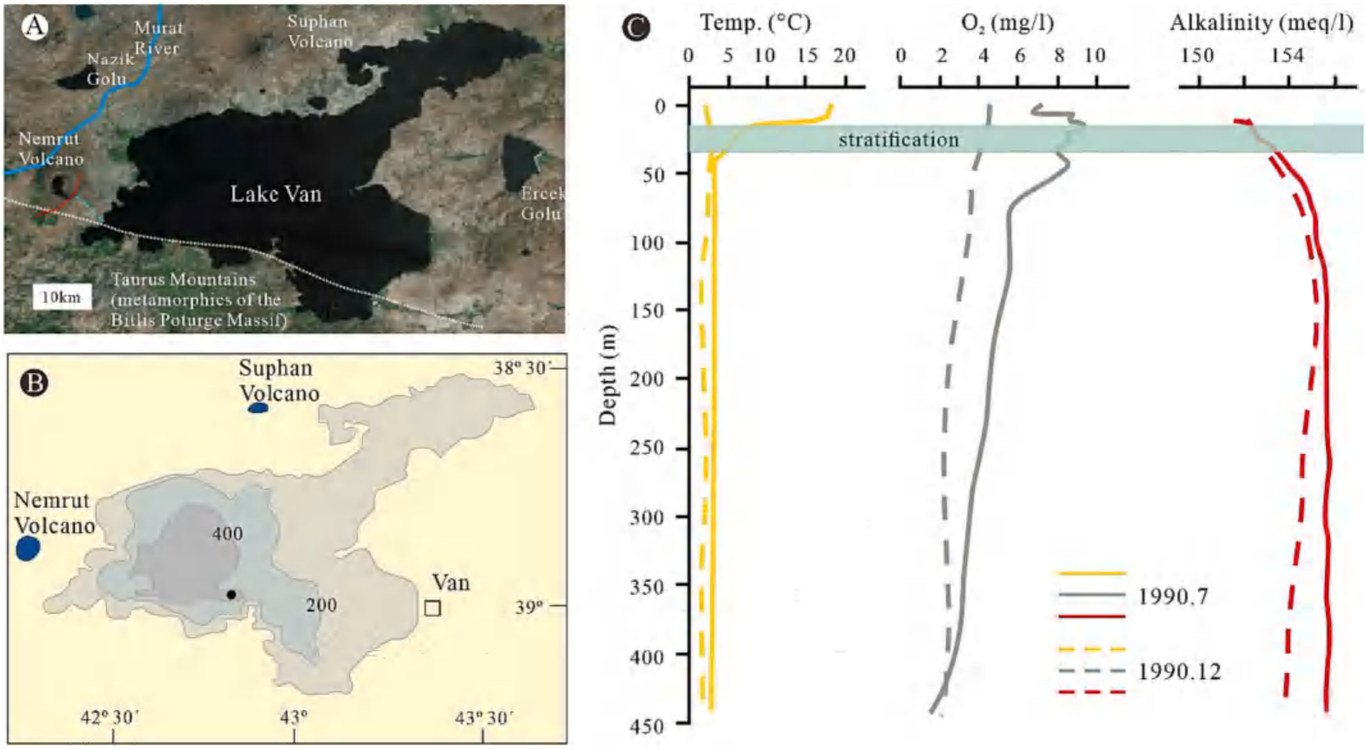

Fig. 15. Location, depth and characteristics of Lake Van. (a) Satellite image of Lake Van; (b) Location diagram of Lake Van; (c) Temperature, O_2 and alkalinity change with depth in Lake Van (modified after Thiel et al., 1997).

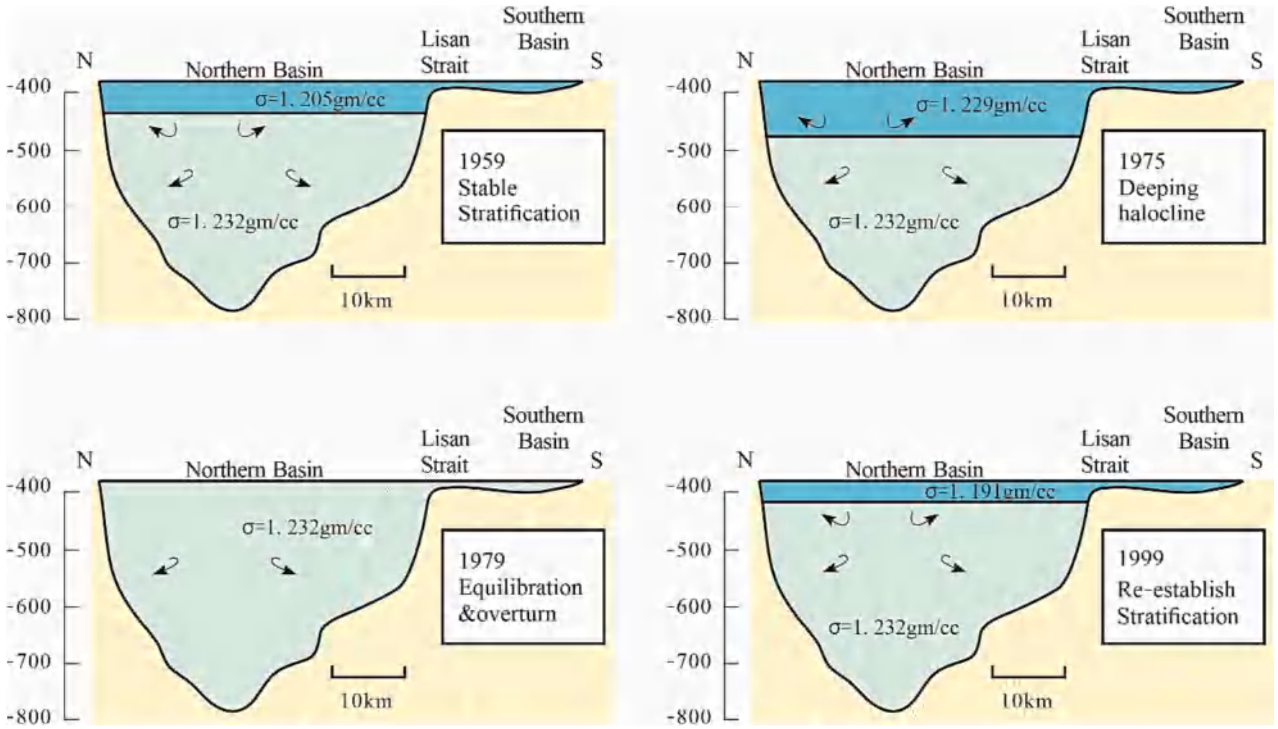

Fig. 16. Evolution of the Dead Sea Stratification (modified after Warren, 2016).

basins (Xingouzui Formation in Jiangling Depression, Wenchang Formation in Pearl River Mouth Basin, Lake Kinneret (Sea of Galilee), and Puntudo Formation in the Cuyo Basin) all have or had open environments (Stiller and Kaufman, 1985; Wang et al., 2013; Benavente et al., 2015). The carbon and oxygen isotope data of all salinized lake basins point to closed or semi-closed lake environments (Fig. 18). Furthermore, saline lakes in geological history often developed good source rocks. This indicates that closed or semi-closed lake environments lead to the salinization of lake basins and the enrichment of organic matter (Fig. 18).

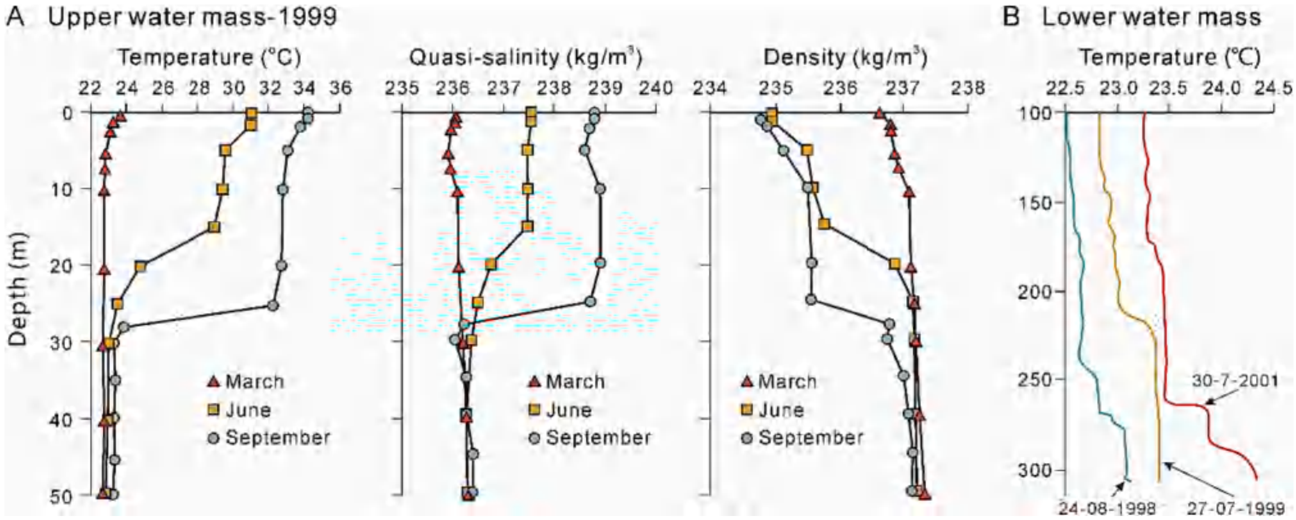

Fig. 17. Temperature, salinity and density stratification of the Dead Sea (Gertman and Hecht, 2002). (A) Stratification of upper water mass in different months in 1999; (B) Stratification of lower water mass in different years.

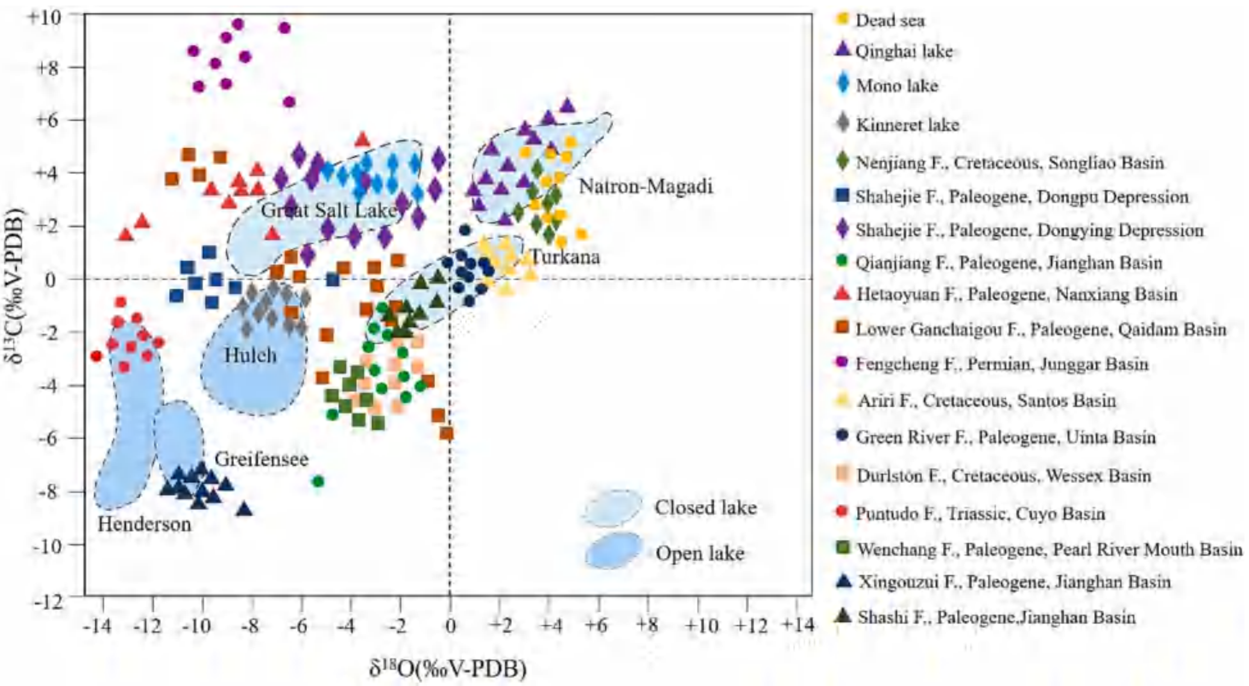

Fig. 18. Distribution of carbon and oxygen isotopes in multiple lake basins.

Data source: Dead Sea (Janssen et al., 2007); Qinghai Lake (Liu et al., 2018); Mono Lake (Della Porta, 2015); Kinneret Lake (Stiller and Kaufman, 1985); Songliao Basin (Ding et al., 2021); Dongpu Depression (Ma, 2020); Dongying Depression (Cai et al., 2009); Qianjiang Formation, Jianghan Basin (Xu, 2018); Nanxiang Basin (Su, 2020); Qaidam Basin (Guo et al., 2017); Junggar Basin (Yu et al., 2018a); Santos Basin (Felipe et al., 2019); Uinta Basin (Davis et al., 2008); Wessex Basin (Gallois et al., 2018); Cuyo Basin (Benavente et al., 2015); Pearl River Mouth Basin (Liu et al., 2001); Xingouzui and Shashi Formation, Jianghan Basin (Wang et al., 2013).

6. Sediment characteristics

According to the Kurnakov–Valyashko classification method, saline lakes can be divided into carbonate, sulfate, and chloride types (Fig. 19). The environments of each type of salinized lake are quite different. Consequently, the sediments they produce have varying characteristics. Carbonate saline lakes are mainly created by volcanic activity or mantle-derived hydrothermal fluids and are characterized by the development of Na-carbonate minerals. An example is the Lower Permian Fengcheng Formation in the Junggar Basin, China. Sulfate saline lakes are formed mainly by seawater intrusion. They are characterized by the deposition of large volumes of sulfate minerals, such as gypsum and mirabilite, with the evaporite sequence dominated by thick layers of gypsum, glauberite, and halite. Chloride saline lakes often develop in rift lakes, which may be due to inputs of $CaCl_2$ hydrothermal fluids from faults, and are characterized by carnallite-bischofite-halite and carnallite-halite, such as the Shahejie Formation in the Dongpu Depression and the Qianjiang Formation in the Qianjiang Depression in China, where a large number of thick layers of halite developed.

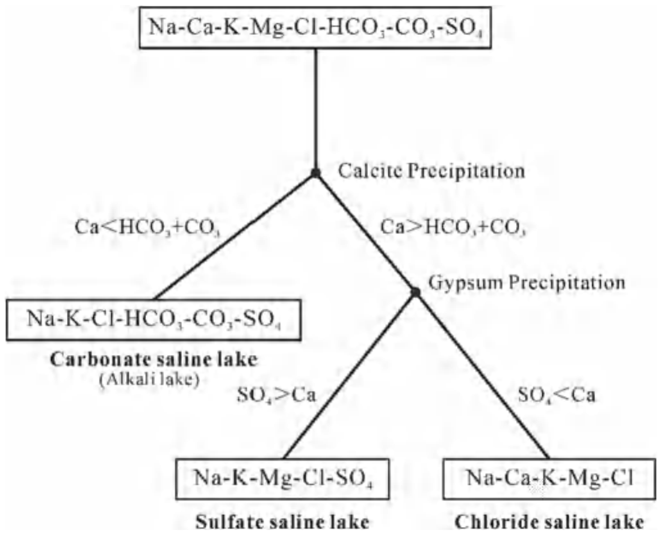

Fig. 19. Evolution of different types of brine in saline lakes (modified after Lowenstein et al., 2017).

6.1. Minerals and assemblages

Salinized lake minerals include evaporites deposited by evaporation and clay minerals.

(1) Saline minerals

There are >100 types of evaporites from saline lakes. China has many widely distributed saline lakes, which produce approximately 60 types of saline minerals. The most common are gypsum, rock salt, trona, and glauberite (Table S3). Evaporite-saline minerals can be divided into five categories: carbonates, sulfates, borates, nitrates, and chloride salts. Warren (2016) summarized previous studies on marine and continental evaporation sequences and proposed the following evaporation sequence: carbonate minerals → sulfate minerals → halite → potassium chloride → bischofite.

(2) Clay minerals

Clay minerals are a vital component of clastic sediments of saline lakes and are the product of high water mineral content in brine environments. The types of clay mineral assemblage and changes to clay minerals serve, to an extent, as a reference for the depositional environment. It is widely believed that clay minerals in saline lakes come from terrigenous clasts. Among salinized lake sediments, clays are dominated by illite, followed by chlorite (Sun et al., 1997). It also has high Al_2O_3. The relative contents of illite and chlorite are generally 80%–90% and 10%, respectively, in the non-salt-forming stage, with the relative content of illite decreasing to 70%–80%, while that of chlorite increasing to 15%–20% (Gonçalves et al., 2006). Most of the chlorite in the non-salt-forming stage is Fe-chlorite, which becomes Mg, and Fe-chlorite in the salt-forming stage (Xu, 1983).

6.2. Rocks and assemblages

The sedimentary structures of saline lakes consist of detrital (silt) deposits, clay deposits, and evaporite deposits: (1) Detrital (silt) deposits are less widespread and located in the middle and lower parts of sediments, usually mixed with clay or halite. (2) Clay deposits are found in lacustrine deposits' middle and lower parts. They are sediments formed after the deposition of coarse clastic rocks and before the chemical deposition of salts in the middle stage of salinized lake or salinized lake basin formation. Regarding lithology, some of the most common clay minerals are illite, chlorite, and kaolinite. (3) Evaporite deposits are distributed in the upper sediment and are a product of the late stage of lake development. Saline lakes can have long formation and evolution processes and varying salt formation processes, forming distinct salt sedimentary structures with obvious layering, thick deposits, and large-scale salt deposits.

Mineral assemblages of evaporite deposits can be divided into the following four categories. (1) Glauberite and dolomite-mudstone. This is more common type in salinized lake deposits, occurring in large quantities in sulfate, chloride, and carbonate saline lakes (Fig. 20A). (2) Gypsum and dolomite-mudstone (silt). This develops more commonly in sulfate saline lakes. Gypsum is produced in layers or blocks in dolomite mudstone, mostly in a sedimentary rhythm interbedded with dark mudstone (Fig. 20B and D). (3) Halite and carbonate rock. This assemblage is commonly found in chloride saline lakes, such as the Qianjiang Depression, Dongpu Depression in China, and Salta Basin in Argentina. The third member of the Shahejie Formation (Es3) in the Dongpu Depression is the primary layer of halite development, and halite, carbonate rock, and shale have a notable vertical sedimentary sequence (Fig. 20C and E). The saline rhythm composed of halite and carbonate rock in the Qianjiang Depression is abnormally developed, with 193 saline rhythms. Each rhythm comprises salt rock and intrasalt deposits, mainly halite (Fig. 20F). (4) Alkaline-rich mineral carbonate rock and dolomite mudstone. This assemblage is commonly found in carbonate saline lakes (alkaline lakes). For example, the Green River Formation in the Uinta Basin developed large volumes of nahcolite nodules, trona, and clastic rocks (Vanden Berg and Birgenheier, 2017). Generally speaking, it has the depositional rhythm of alkaline-rich mineral carbonate rocks (nahcolite and trona) and dolomite mudstone (Fig. 20G).

A-Dolomitic mudstone and glauberite layer combination, Qianjiang Formation, Qianjiang Depression, Jianghan Basin, Well BYY2, 2818.7–2818.8 m (Chen et al., 2021); B-Mudstone with gypsum layer, Upper Ganchaigou Formation of Oligocene in Xichagou Section of Qaidam Basin (Guo et al., 2017); C-Marl filled with halite, Shahejie Formation, Dongpu Depression, Bohai Bay Basin, Well W200–6, 3285.7 m (Li, 2018); D-Macroscopic gypsum(G) layer and mudstone(M) layer, Arbolí formation, Catalan basin (Ortí et al., 2018); *E*-Halite layer and surrounding carbonate rock association, Yacoraite Formation, Salta Basin, Argentina (Deschamps et al., 2020); F-Layered halite and marl, Qianjiang Formation, Qianjiang Depression, Jianghan Basin, Well W99, 1672.9 m (Li, 2018); G-Alkaline mineral nodule in dolomitic mudstone, Green River Formation, Uinta basin, Well 42 × 36, 591.0 m (Vanden Berg and Birgenheier, 2017).

Salinized lake basin formation is closely connected to sediment characteristics. Seawater-derived lakes usually become sulfate salinized lake basins that develop glauberite/gypsum and dolomite-mudstone assemblages, such as Sivrihisar Basin, Ebro Basin, and the Central Iran Basin. Salinized lake basins formed by inland evaporation usually have high salinity. The high salinity of the evaporite sequence precipitates halite, leading to a more developed assemblage of halite and intrasalt carbonate rocks, such as the lower sub-member of the third member of the Shahejie Formation in the Dongpu Depression, and a rich alkaline mineral carbonate rock and dolomite-mudstone assemblages, such as Unita Basin, Lorca Basin, and Newark Basin. Lakes formed by deep hydrothermal fluids usually form carbonate (alkaline) saline lakes or chloride saline lakes, so rich alkaline mineral carbonate rock and dolomite-mudstone or halite and intrasalt carbonate rock assemblages develop, such as Mahu Depression, Dongpu Depression, and Lake Albert Basin. Finally, lakes formed from a combination of mechanisms have varying rock assemblages based on salinization factors in different evolutionary stages.

In contrast to freshwater lakes, saline lakes, apart from the mechanical deposition at the margins of the lake basin, have more chemical deposition (crystallisation of salts) and biochemical deposition (microbial induction, etc.) in the interior of the lake basin. In the final stages of development of some salt lakes, there is a complete lack of mechanical

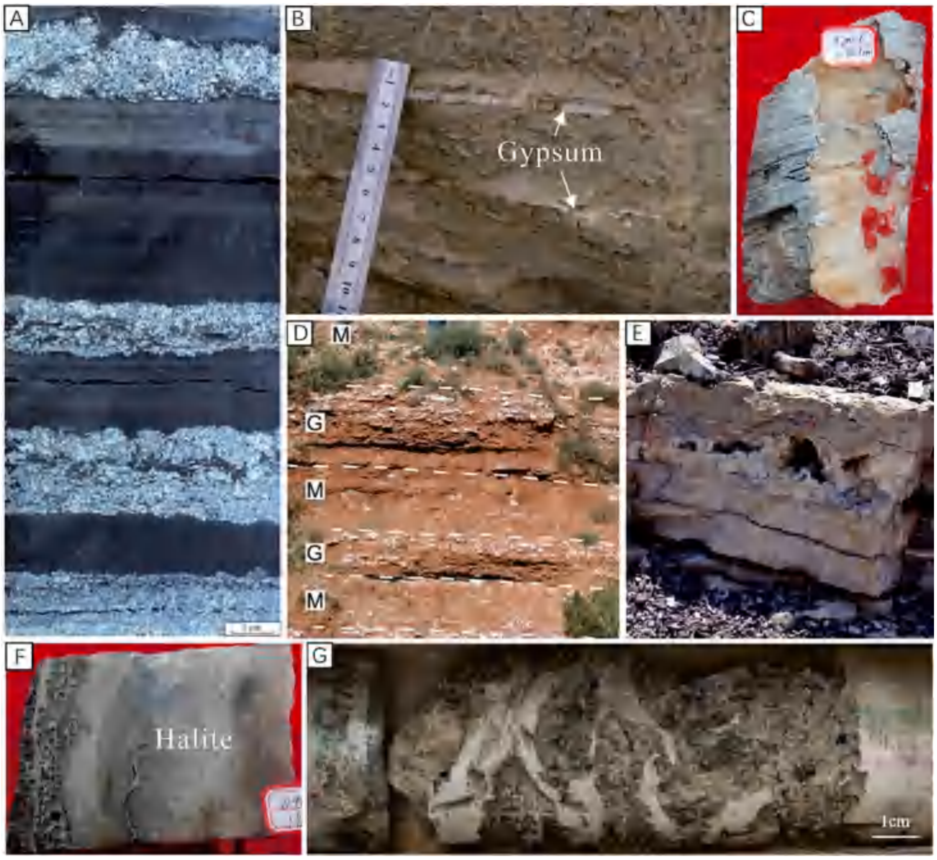

Fig. 20. Sedimentary rocks and assemblage types of different saline lake basins.

deposition. The type of sedimentation is strongly related to lake ecology and changes with salinity. In the bottom sediments of Qinghai Lake, sands and silts are deposited at the margins, which sequentially transitioned to calcium carbonate and dolomite sediments towards the centre of the lake (Wu et al., 2022a), and the deposited sediments have a correspondence with the lake salinity (Fig. 12). In the lacustrine shales of the Jiyang Depression (saline lake in Paleocene), studies suggested that algae induced calcium carbonate precipitation through photosynthesis to form micritic calcite, which is the main source of carbonates in shales (Liang et al., 2018). In the shale of Mahu Depression (alkaline lake in Permian), microorganisms are well developed, and series of biochemical processes of Cyanobacteria and Chlorophyta accelerate the mineralisation of organic matter (Cao et al., 2020; Xia et al., 2020).

In addition, the stratification of the saline lake water column has a clear control on sediments distribution. In the mixolimnion above the chemocline, where salinity is low, oxygen content is high, and hydrodynamics are strong, massive sediments are formed. While, In the monimolimnion below chemocline, where salinity is high, oxygen content is low, and the water circulation is restricted, laminated sediments tend to be formed (Tylmann et al., 2012), e.g., in the Dead Sea, where organic matter-clay laminae and aragonite laminae are formed (Neugebauer et al., 2014). Thus the location of the chemocline controls the distribution of laminae sediments (Liang et al., 2023). Furtherly, organic matter-rich sediments formed at the bottom of the saline lake, and organic matter degradation under the action of microorganisms such as sulphate-reducing bacteria and methanogenic bacteria and the production of authigenic minerals such as pyrite and calcite (Irwin et al., 1977), hydrogen sulphide and methane, exacerbate the redox of the saline water (Treude et al., 2005).

7. Organic matter enrichment

7.1. Organisms characteristics

Due to the organisms varying tolerance to salinity, lakes have varying biological evolution sequences depending on their salinity (Couch, 1971; Zheng, 2010; Warren, 2016). When salinity changes from 0 to 5‰, the number of freshwater species decreases significantly, and marine, estuarine, and euryhaline species, appear (Fig. 21A). When salinity goes from 5 to 10‰, freshwater species almost disappear, but the number of other species, including marine and euryhaline organisms, remain stable (Warren, 2016). When salinity changes from 10 to 35‰, the number of marine species continue to increase and peak, becoming the dominant type of organisms. When salinity exceeds 35‰, the number of all types of species decrease (Whitfield et al., 2012).

In water with a salinity of 60–200‰, many halotolerant eukaryotic algae develop under aerobic conditions (Fig. 21B). Many sulfur-oxidizing bacteria, sulfate-reducing bacteria, acetic acid bacteria, methane bacteria, and halotolerant archaea can also survive in anaerobic conditions. When salinity increased to 240–320‰, halophilic archaea and bacteria began to dominate, and the only eukaryotes that survived were brine shrimp and some algae (Barbé et al., 1990; Ghai et al., 2011). Although halophilic archaea and eubacteria can survive in hypersaline (>320‰) conditions, their numbers are small and cannot produce organic matter (Barbé et al., 1990) (Fig. 21B).

Studies have shown that in a high-salinity environment (>35‰), organisms species decrease as salinity increases, but total biomass does not decrease (Fig. 21B). Even at a salinity of 100‰, biomass remains high. Furthermore, a high-salinity environment prevents the growth of parasites but is conducive to algae blooms, leading to greater productivity (Amils et al., 2007).

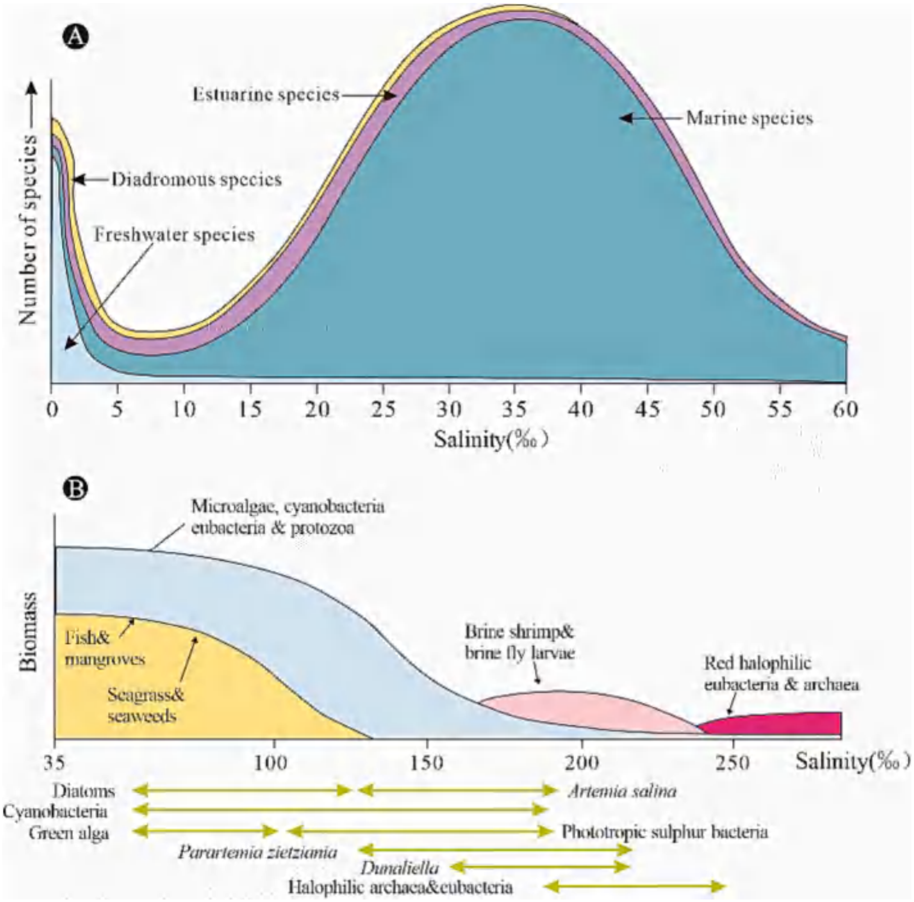

Fig. 21. Biological characteristics of saline lake basin. (A)The relationship between the number of species and salinity (modified after Whitfield et al., 2012); (B) Salinity range of salt-tolerant microorganisms (modified after Barbé et al., 1990), and corresponding biomass of salinity range in modern saline water (modified after Warren, 2016).

7.2. Organic matter enrichment in saline lakes

Organic matter enrichment is primarily influenced by primary productivity, preservation conditions and sedimentation rate.

Primary productivity varies depending on lake salinity and oxygen content (Xia et al., 2017; Wei and Algeo, 2020). Saline lakes tend to have higher productivity than freshwater lakes (Kirkland and Warren, 1986; Warren, 2010). Algae and bacteria in saline water form organic matter with osmotic activity in response to changes in salinity. Lake productivity is closely related to nutrient supply, most notably including phosphate and nitrate supply (David et al., 1994). Bio-organisms settle to the anoxic layer and are dissolved in the water by microbial decomposition, resulting in eutrophication of the bottom water column. Seasonal return of water in saline lakes, where bottom nutrients are brought to the surface for reuse, is an important mechanism for algal blooms (Harris et al., 2004). The contribution of bacteria to productivity in brackish lakes is similarly not negligible. Photosynthetic bacteria (e.g., green sulfur bacteria, purple bacteria) are usually found in the chemotaxis layer where light energy is projected, and utilise light energy to synthesise organic matter. In contrast, chemoenergetic synthesizing bacteria such as hydrogen-oxidizing bacteria, sulfur bacteria, nitrifying bacteria, and iron bacteria synthesise organic matter using energy released from the oxidation of inorganic substances such as H_2, NH_3, and S (Yang et al., 2022; Huang et al., 2023).

Due to the stratification of saline lakes, the living environment suited to organism changes with lake depth, leading to stratification of organism species (Jin et al., 2008; Warren, 2016). Elevated levels of dissolved oxygen in surface water help algae and higher plants flourish, with photosynthesis synthesizing considerable organic matter, resulting in increased productivity. However, the bottom layer exhausts free oxygen through microbial respiration, forming an anoxic environment where only anaerobic bacteria can survive. Productivity derived from autotrophic microbes (both photosynthesis and dark fixation of carbon) is abundant in modern saline lakes, such as Qinghai Lake (Wang et al., 2021; Huang et al., 2023), and ancient saline lakes, such as Permian Mahu Depression (Cao et al., 2020). Thus, stratification often creates a low-salinity, aerobic, and highly productive surface layer and a high-salinity and anoxic bottom layer with abundant autotrophic microbes, which is conducive to the enrichment of organic matter (Wang et al., 2021). In addition, when nutrients (e.g., nitrates and phosphates) increase, it causes an explosion of organisms in the lake basin and increases productivity. An example is Lake Tanganyika in Africa, which has regular inflows of surface eutrophic water and bottom sediment TOC as high as 7%–11% (Cohen, 1989).

Preservation conditions are crucial to OM enrichment, which depends on many complex factors such as dissolved gases, mean temperature, and osmotic pressure (Miller et al., 2005). Total dissolved O_2 and CO_2 in salinized lake water decrease as salinity increases, suggesting high-salinity water creates a reducing environment, which helps to preserve organic matter (Warren, 1986; Allen et al., 2005). Furthermore, lake stratification leads to anoxic environment and increased osmotic pressurein the bottom layer, which will help to prevent the degradation of organic matter leading to the preservation of organic matter. In addition, OM is oxidized during setting, so the lake's depth affects OM enrichment. For example, in Lake Kivu, a deep-water alkaline lake with a maximum depth of 489 m (Degens et al., 1973), organic matter is oxidized during long-distance sedimentation, resulting in low TOC content in the lake bottom. Thus, deep water is not conducive to preserving OM, but saline lakes with a moderate-to-shallow depth is better (Hammer, 1986; Burke and Knott, 1997; Golubkov, 2012). In addition, the oxidation of organic matter by nitrate, metal oxides, and sulphate with the participation of the corresponding microorganisms (bacteria) is prevalent in saline lake environments, and microbial activity and diversity are critical for organic matter preservation (Yang et al., 2020a, 2020b, 2022; Jiang et al., 2022b).

The sedimentation rate is another critical factor that affects organic matter enrichment. Commonly, the faster the sedimentation rate increases organic matter dilution and reduces TOC content (Hofmann et al., 1993; Cody and Cody, 1988; Tyson, 2001). Taking the Oligocene evaporite sequence of the Mulhouse Basin (Alsace, France) as an example, the TOC content decreases as the sedimentation rate increases (Fig.S5), which means that the TOC of marl that has a slow sedimentation rate, is as high as 7%. In contrast, the TOC of anhydrite, which has a fast sedimentation rate, is 0.08–0.78%, and that of halite, which has a faster sedimentation rate, is lower, ranging from 0.01% to 0.25%.

7.3. Saline lakes and source rocks

A salinized lake environment is conducive to the deposition and preservation of organic matter, which leads to the formation of organic matter-rich source rocks (Fig. 22). A saline water environment helps to preserve H and control H content in kerogen, forming type I and type II sapropelic organic matter (Fig. 23A).Thus, high-quality lacustrine source rocks readily develop in saline water environments, on which lake basin salinization has a strong bearing (Yu et al., 2018b; Zou et al., 2019; Kong et al., 2022). The source rocks in lacustrine basins developed in brackish water or saltwater environments, and generally have high hydrocarbon generation potential.

A saline water environment is conducive to forming source rocks, but higher salinity does not equate to higher quality source rocks. Many high-quality source rocks are found in salinized lake basins with moderate, rather than increased, salinity (20–60‰). In moderate salinity conditions, the biodiversity of the water body peaks. The oxygen content of surface water is relatively high, so blue-green algae thrive and enrich the most organic matter. Bacteria and archaea are common organisms in salinized lake basins that are important for hydrocarbon generation. Firstly, they can be the source of hydrocarbon-generating parent materials, and the most common are purple sulfur bacteria, green sulfur bacteria, sulfur-oxidizing bacteria, sulfate-reducing bacteria, and extremophiles (various archaea, such as Halobacterium, Halococcus, and Alkalibacterium) (Zheng, 2010). Secondly, bacteria and archaea conducive to the transformation and degradation of organic matter, and hydrocarbon generation.

Large saline lake basins often form high-quality hydrocarbon source rocks with huge petroleum resources, e.g., the shale oil reserves of the Paleoproterozoic Green River Formation in the United States are >35.4 billion tons (Dyni, 2003); the hydrocarbon resources in the Lower Permian Fengcheng Formation of the Makuhu Depression in Junggar Basin are 14.3 billion tons (Zhi et al., 2016), and the Paleogene Shahajie Formation in the Bohai Bay Basin, Cretaceous Qingshangkou Formation in the Songliao Basin all have hydrocarbon resources of >100 billion tons (Zheng et al., 2019; Wu et al., 2022b).

Compared with freshwater lake, brackish-water environments favour algal and bacterial blooms, which significantly increase the hydrocarbon potential of source rocks (Platt and Wright, 1991; Horsfield et al., 1994; Tao et al., 2019). As the salinity increases, the slightly halotolerant cyanobacteria are gradually replaced by halotolerant or halophilic green algae (e.g., Dunaliella) (Xia et al., 2020). Related to biological evolution, the composition of OM in brackish lakes is distinctly epochal (Warren, 2016). Before the Cretaceous, organic matters were dominated by cyanobacteria and green algae (Damsté et al., 2004). In contrast, post-Cretaceous salt lakes, including the Eocene Green River Formation, the Shahejie Formation, and typical modern salt lakes, developed diatoms, ditch-flagellates, and stromatolites in addition to cyanobacteria and green algae. The composition of the hydrocarbon parent organisms should be controlled by the relative abundance of cyanobacteria, green algae, diatoms, ditch-flagellates, and stromatolites with the variabilities in salinity (Fig. 21), with little OM from terrestrial plants (Collister et al., 1992; McKirdy and Kantsler, 1980; Cao et al., 2020). And OM types are typically dominated by Type I-II1 (Fig. 23).

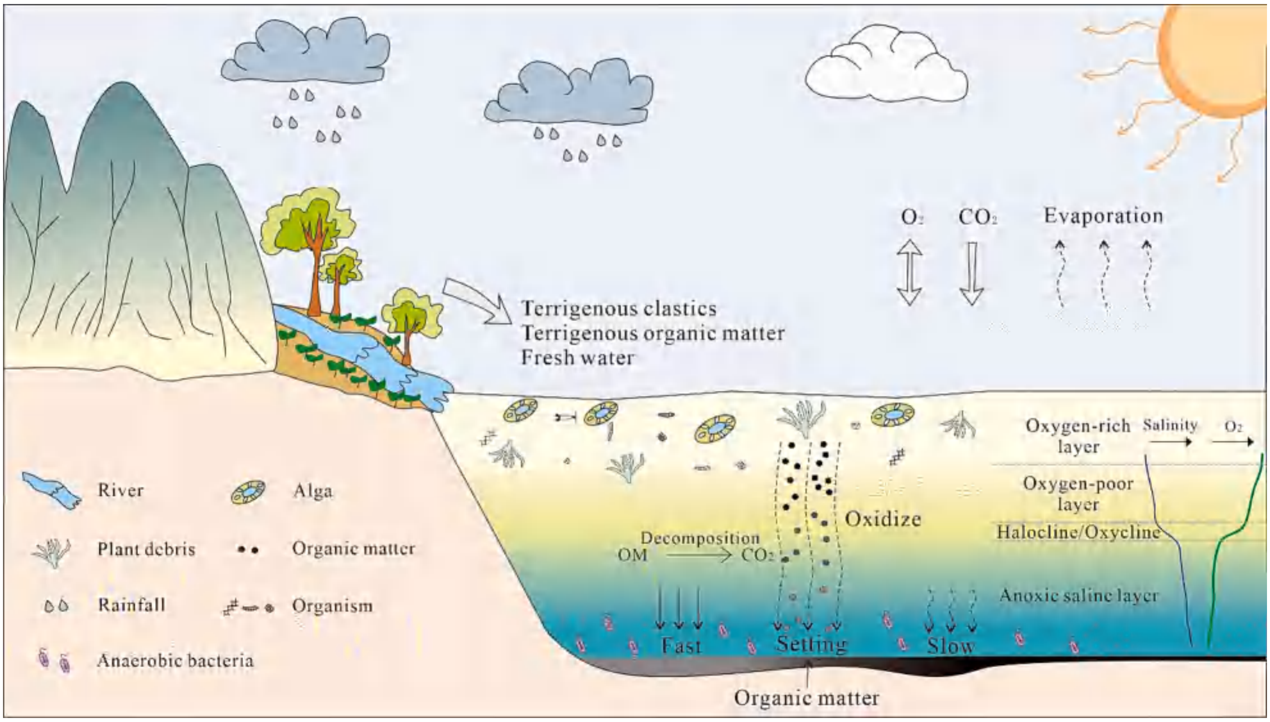

Fig. 22. Organic matter enrichment model of saline lake basin (Modified form Wu et al., 2022a).

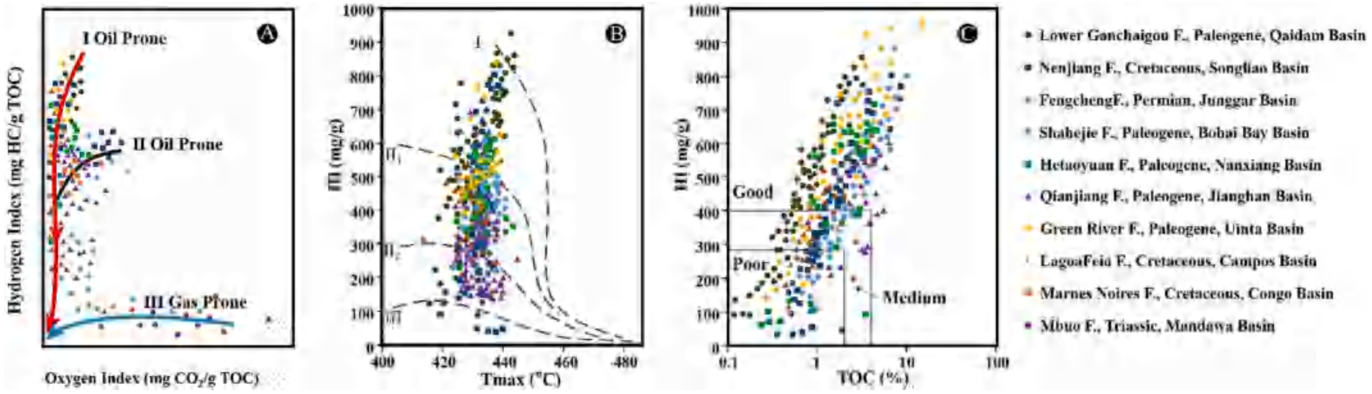

Fig. 23. Geochemical characteristics of source rocks in typical saline lake basin.

8. Closing remarks and prospects

Saline lakes have developed worldwide throughout geological history and continue to develop, is important for understanding deep-time climate evolution, lake evolution and extinction, terrestrial ecosystem evolution, and organic carbon burial processes. There are four modes of lakes salinization: (1) Seawater-derived salinized lake, salt ions are provided by seawater; (2) Inland evaporative saline lakes, the land is the source of salt substances following strong evaporation; (3) Deep hydrothermal fluids-based saline lakes, high-salinity hydrothermal fluids enter the basin through faults; and (4) Any combination of the above mechanisms. During the evolution of saline lake basins, one or more paths can be the main salinization mechanism, and the primary mechanism may change with the evolution of salinization periods. Different mechanisms of salinization control the physico-chemical properties of lake waters, which in turn result in different mineral and lithological assemblages. Although not all saline lakes are stratified, most of them tend to be. Undoubtedly, stratification (including physical, chemical and ecological stratification) is an important feature of saline lakes. Physical stratification exacerbates chemical stratification, which affects ecological stratification, i.e., different species of organisms in the upper and lower water bodies. Lake stratification is impermanent, changing with short-term seasonal temperature variations and long-term climate conditions. Organic matter enrichment in salinized lake basins is determined by water salinity, reducing conditions, and sedimentation rate. A salinized lake environment is conducive to the formation of organic-rich source rocks. It often forms type I and II sapropelic organic matter with high hydrocarbon generation potential. Still, it is not the case that higher salinity is better, as high-quality source rocks often form in moderate salinity.

The ecology of saline lakes affects the physical, chemical, and ecological characteristics of lake water, controlling chemical and biochemical processes in the lake, resulting in sediment differences and thus having a crucial impact on organic carbon burial. The ecological evolution of lakes is a complex process, with significant differences in macro-geological time scales between the Precambrian, Paleozoic, Mesozoic and Cenozoic lake ecology, influenced by global climate, plate activity and evolution of terrestrial organisms, etc.(Warren, 2010, 2016), in the case of the lake basin salinization itself, by the regional and global tectonic and climatic influences. Microorganism abundance is a key feature of saline lakes and is involved in complex biogeochemical cycles, including C, N, P, S, Fe, etc. Meanwhile, microorganisms play a decisive role in the mineralisation of organic matter (Cao et al., 2020). In addition, with the sediments burial in saline lakes, especially in the early stages, a series of physical, chemical and microbiological actions occur near the water-sediments interface and have a significant impact on lake properties in turn. However, the specific mechanisms are complex and require more attention. Currently, large saline lakes represent 44% of the volume and 23% of the area of all lakes on Earth. Ecological monitoring of saline lakes could provide detailed information on global climate change, support more sustainable use of resources, and ecological protection of saline lakes.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2024.104720.

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