



Detailed Processes and Potential Mechanisms of Pliocene Salty Lake Evolution in the Western Qaidam Basin

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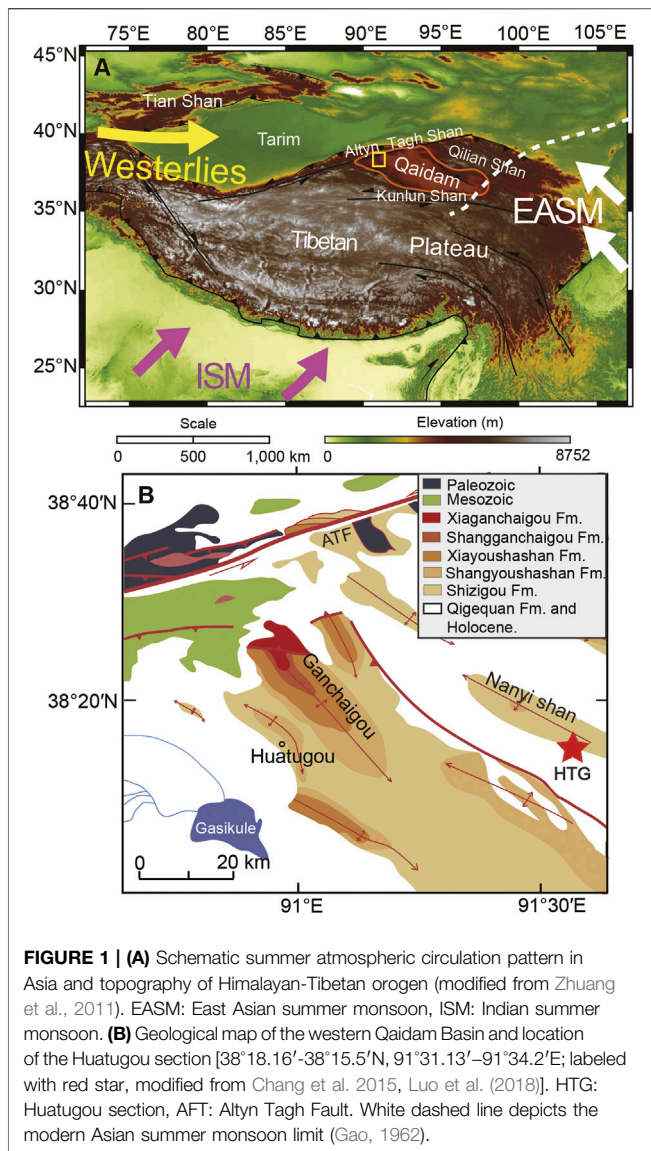
Hyperarid climate and salty lakes prevail in the current Qaidam Basin, but this basin was once a large paleolake until the early Quaternary. However, its evolution history and relationship with climate and tectonics are still elusive. Here we present detailed stratigraphic descriptions combined with total organic carbon content and weight ratio of organic carbon to total nitrogen records from fluvio-lacustrine sediments in the western Qaidam Basin to infer how the lake evolved during the late Pliocene-early Pleistocene. These data reveal a drying trend since 3.3 Ma, which we attribute to low latitude forcing and/or local tectonic activities. However, this trend was interrupted during 2.84–2.48 Ma, in which climate wetting was observed. We attribute the climate wetting during 2.84–2.48 Ma to intensified East Asian summer monsoon as is documented by the Chinese Loess Plateau records. Halite and gypsum content increased dramatically after 2.5 Ma, indicating the formation of salty lake in the western Qaidam Basin. These data improve our understanding of the detailed processes of Qaidam aridification and its potential forcing mechanisms.

Keywords: total organic carbon, Pliocene, salty lake, Qaidam Basin, Tibetan Plateau

INTRODUCTION

The Qaidam Basin (QB), with an area of ~80,000 km² and an average elevation of ~2.7 km above sea level, is the largest internally drained basin on the northeastern Tibetan Plateau (Fang et al., 2007). A hyperarid climate prevails with mean annual precipitation <50 mm and evaporation >1,000 mm in this basin (Wu et al., 2011; Cai et al., 2012; Wang et al., 2013). The basin is largely covered by dry salt playas, with only minor desert vegetation and hypersaline lakes (Wang et al., 2012). However, previous studies suggest that a huge Qaidam paleolake might have existed during the Eocene (Wang et al., 2006; Yin et al., 2008a, Yin et al., 2008b; Zhang et al., 2018; Liang et al., 2021), which expanded from the Oligocene to the Miocene (Yang, 1986; Wu and Xue, 1993), and broke into several small lakes likely during the Quaternary (Han et al., 2014; Lu et al., 2015). However, due to the scarcity of continuously dated sediment records (Lu et al., 2015; Fang et al., 2016), how the Qaidam paleolake evolved into its hyperarid condition remains relatively unknown. Furthermore, lack of such records prevents understanding the underlying forcing mechanisms for Qaidam drying and central Asian aridification.

Here we report lithofacies, total organic carbon (TOC), and weight ratio of organic carbon to total nitrogen (C/N) data for the Huatugou (HTG) section in the western Qaidam Basin in order to clarify



the above question. TOC coupled with C/N ratio in fluvio-lacustrine sediments is sensitive to lake shrinkage and expansion and has been widely used to reflect variations of terrestrial input relative to lake productivity (Liu et al., 2013; Fan et al., 2017). Normally, >20 C/N ratio indicate terrestrial organic matter in lacustrine setting (Talbot and Lærdal, 2000), therefore a higher TOC coupled with a higher than 20 C/N ratio points toward terrestrial organic matter dominating TOC in lake sediments, indicating more terrestrial input relative to lake productivity (Talbot and Lærdal, 2000).

MATERIALS AND METHODS

Geological Setting

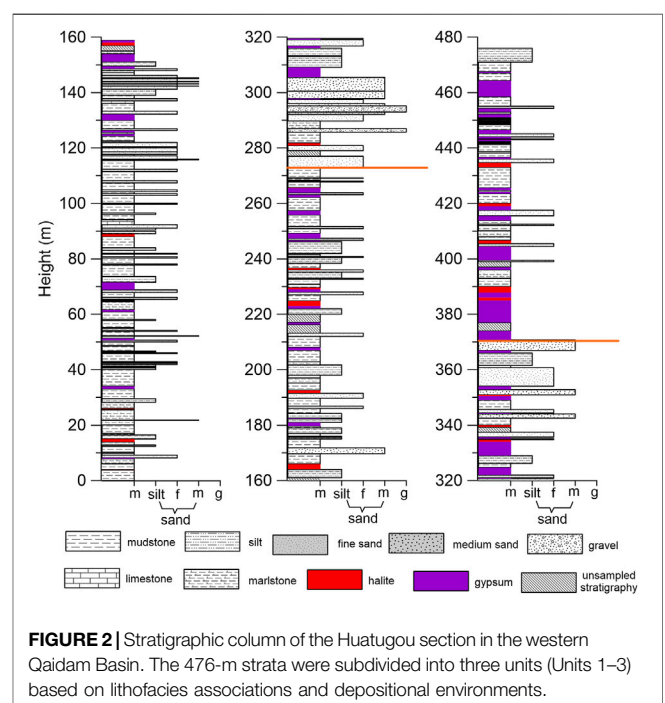
The Qaidam Basin is located at the northeastern Tibetan Plateau, surrounded by the Altyn Shan to the northwest, the Qilian Shan

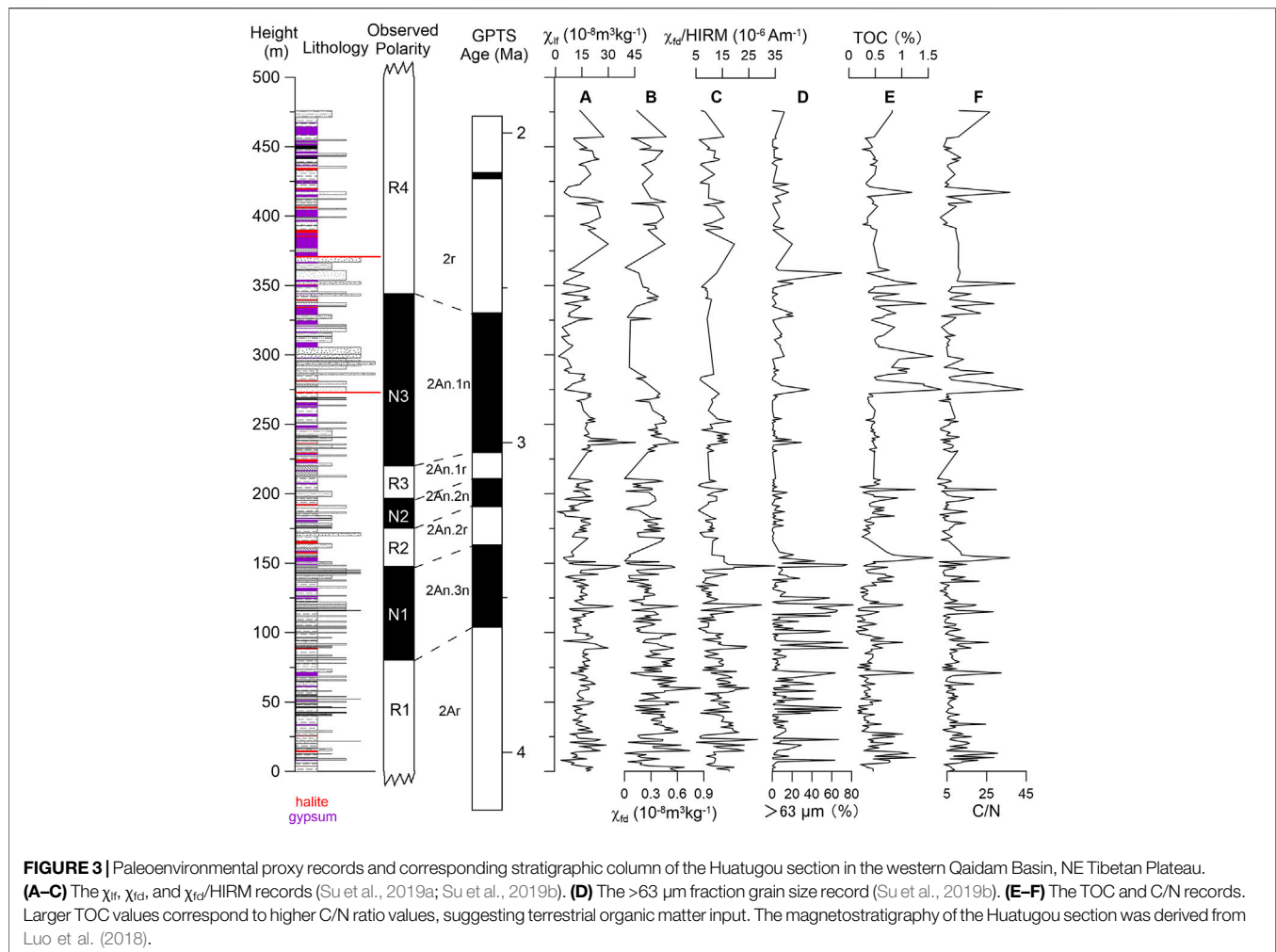
to the northeast, and the Kunlun Shan to the southwest (Figure 1). It is far from any major moisture source and is in the rain shadow zone of the Tibetan Plateau and central Asian mountain ranges (Fang et al., 2007; Heermance et al., 2016). Its climate is cold (mean annual temperature 0–5°C), windy and dry. Hyperarid conditions combined with internal drainage within the basin have resulted in extensive evaporite and playa deposition throughout the Quaternary (Chen and Bowler, 1986; Fang et al., 2008; Heermance et al., 2016; Zhang et al., 2012; Wang et al., 2013). ~12,000 m of sedimentary strata has been deposited in the basin since the early Cenozoic (Huang et al., 1996). These strata are divided into seven formations: the Lulehe Formation (Fm.), Xiaganchaigou Fm., Shangganchaigou Fm., Xiayoushashan Fm., Shangyoushashan Fm., Shizigou Fm., and Qigequan Fm. (Fang et al., 2007; Wang et al., 2007; Lu and Xiong, 2009; Zhuang et al., 2011; Chang et al., 2015; Bush et al., 2016; Wang et al., 2017; Nie et al., 2020).

The studied HTG section lies on the southern flank of the Nanyi Shan (Figure 1B). The 476-m sedimentary strata consist of evaporite, shale, siltstone, sandstone, and rare conglomerate corresponding to the fluvio-lacustrine sediment of the Shizigou Fm., and Qigequan Fm. (Luo et al., 2018). The age model of HTG section is ~3.9–2.1 Ma based on paleomagnetic dating by Luo et al. (2018). Milankovitch cycles are detected in the magnetic susceptibility record (Su et al., 2019a), demonstrating the validity of the paleomagnetic age model.

Methods

For TOC analysis, a total of 298 crushed bulk samples (40–50 mg ea.) were reacted with 3 mol/L HCl to remove carbonates before being wrapped in tin capsules. The wrapped samples were then heated to 1,800°C in a flow of oxygen using a Vario EL Cube





elemental analyser (Elementar Analysensysteme, Germany). The combustion of the sample and absorption of the released CO_2 were performed in the automated mode. The mass content of carbon in the sample was calculated using the proprietary software provided by the device manufacturer. For each set of analyses, calibration was performed against acetanilide.

RESULTS

Lithofacies of the Huatugou Section

The 476-m strata were divided into three units (Units 1–3) based on lithofacies associations and depositional environments (**Figure 2**): Unit 1 (0–273 m; playa-fluvial-lacustrine), Unit 2 (273–371 m; playa-fluvial), and Unit 3 (371–476 m; playa-evaporite).

Unit 1: Playa-Fluvial-Lacustrine (0–273 m)

Unit 1 is characterized by massive mudstone interbedded with fine grained sandstone beds. The evaporite layers started to appear at the base of the section (halite layer at 3.8 m and

gypsum layer at 7.9 m). Evaporite layers in Unit 1 are least frequently observed of the entire sequence. Unit 1 is interpreted as littoral to sublittoral lacustrine sedimentation in an internally drained, playa environment (Pietras and Carroll, 2006). We note that fluvial layers are less frequent for the upper portion of this unit (ca. 150–273 m), and this portion is dominated by playa-lacustrine.

Unit 2: Playa-Fluvial (273–371 m)

Unit 2 is dominated by fine-medium grained sandstone beds with more frequent occurrences of evaporite layers (gypsum and halite) than Unit 1, approximately every 2.4 m. Unit 2 is interpreted as a sand flat and perennial shallow lacustrine environment (Gierlowski-Kordesch and Rust, 1994). The overall increase in grain-size and appearance of medium sandstone beds suggest an increase in sediment-input from fluvial erosion.

Unit 3: Playa-Evaporite (371–476 m)

Unit 3 is dominated by massive mudstone with interbedded halite and gypsum beds. This unit has the highest frequency of evaporite

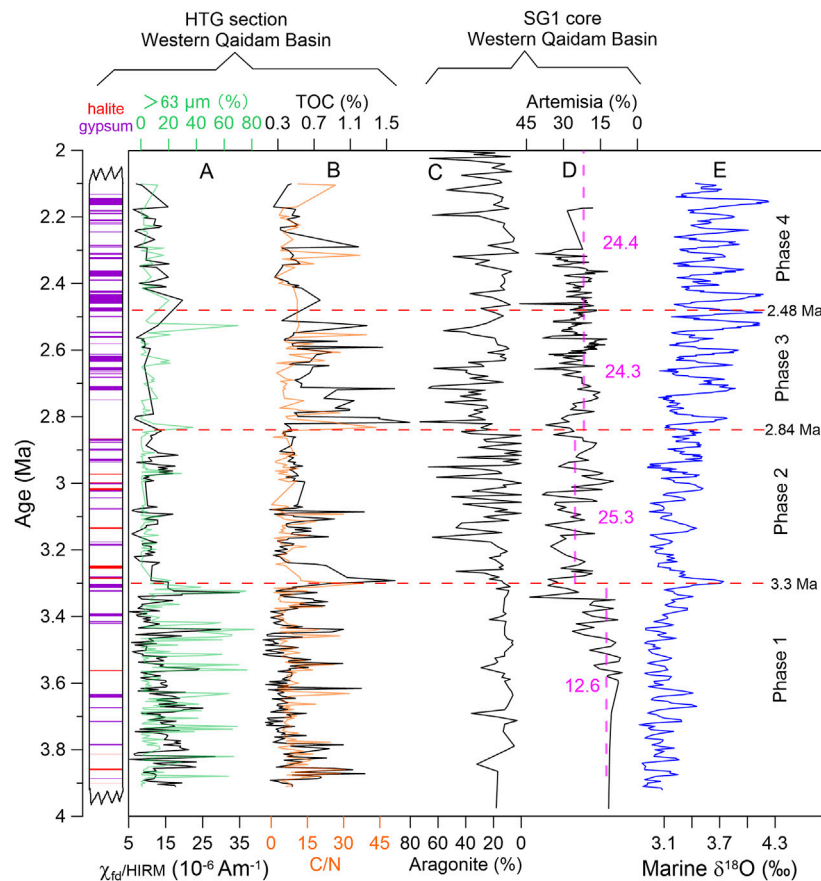


FIGURE 4 | Late Pliocene paleoenvironmental records from the Huatugou section and the SG1 core in the western Qaidam Basin. **(A)** The $>63 \mu\text{m}$ fraction grain size record (green line) and the χ_{fd}/HIRM record (black line, Su et al., 2019b) of the Huatugou section in the western Qaidam Basin. **(B)** The TOC record (black line) and C/N ratio record (yellow line) of the Huatugou section in the western Qaidam Basin. **(C–D)** The aragonite record (Fang et al., 2016) and the artemisia record (Koutsodendris et al., 2019) from the SG1 core in the western Qaidam Basin. **(E)** Marine $\delta^{18}\text{O}$ record (Zachos et al., 2001). Three phase boundaries at ~ 3.3 , ~ 2.84 , and ~ 2.48 Ma are labeled with red dashed lines.

beds, occurring every 2.1 m, which implies either regular times of hyper-concentrated brine within the lake or frequent desiccation.

TOC and C/N Ratio Records

The TOC and C/N ratio records show similar patterns and can be divided into four phases for this set of fluviolacustrine sediments, with boundaries at 158, 273, and 380 m (corresponding to 3.3, 2.84, and 2.48 Ma, respectively, **Figures 3, 4**).

The TOC content record shows high amplitude fluctuations in Phase 1 (0–158 m, corresponding to 3.9–3.3 Ma; **Figure 4**) and Phase 3 (273–380 m, corresponding to 2.84–2.48 Ma; **Figure 4**). The TOC values vary from 0.14–1.59% in Phase 1 and 0.34–1.76% in Phase 3, but almost all the TOC values are below 1% in Phase 2 (158–273 m, corresponding to 3.3–2.84 Ma; **Figure 4**) and Phase 4 (380–476 m, corresponding to 2.48–2.1 Ma; **Figure 4**). Similarly, the C/N ratio values show high amplitude fluctuations in Phase 1 and Phase 3 varying between 1.1 and 43.4, but most of the C/N ratio values are below 10 in Phase 2 and Phase 4.

DISCUSSION

Environmental Implications of TOC and C/N Ratio Variations

C/N ratio is a useful proxy to distinguish different carbon sources in lacustrine sediments (Talbot and Lærdal, 2000). C/N ratios of aquatic vegetation are generally between 4 and 10, whereas C/N ratios of terrestrial plants are generally greater than 20 (Talbot and Lærdal, 2000). The C/N ratio values in Phase 1 and Phase 3 are frequently greater than 20, suggesting that organic matter in those intervals was mainly derived from terrestrial plants transported by rivers. 83% of C/N ratio values in Phase 2 and Phase 4 are below 10, suggesting a low lake productivity and lack of terrestrial derived organic matter. One may question whether high C/N ratios in the study site are aligned with large grain size and fluvial transport, so that this ratio can not be used to infer terrestrial derived organic matter. However, few large grain size intervals (corresponding to fluvial input) correspond to higher than 20 C/N ratio,

suggesting that higher than 20 C/N ratios correspond to lacustrine setting. Following this observation, we interpret the intervals with higher TOC and C/N ratio during Phases 1 and 3 as climate wetting.

Evolution of Western Qaidam Paleolake During 4–2 Ma

The evolution of Qaidam paleolake is divided into four phases based on TOC and C/N ratios during the Plio-Pleistocene: Phase 1 (3.9–3.3 Ma), Phase 2 (3.3–2.84 Ma), Phase 3 (2.84–2.48 Ma), and Phase 4 (2.48 Ma–2.1 Ma).

The lithofacies, TOC and C/N ratio records from the HTG section suggest an open lake and a regularly wetting climate before 3.3 Ma (Phase 1, **Figure 4**). This inference is consistent with grain size and χ_{fd} /HIRM records from the Qaidam Basin (**Figure 4**, Su et al., 2019b). We interpret that during a wetting climate, terrestrial plants flourished in the surrounding regions, resulting in more terrestrial organic matter being transported to the depositional region.

The TOC and C/N ratio records from HTG section suggest the Qaidam paleolake changed from an open lake to closed, salty lake at ~3.3 Ma (**Figure 4**). Previous studies from the Qaidam Basin consistently suggest a phase of drying at ~3.3 Ma (Heermance et al., 2016; Fang et al., 2016; Su et al., 2019b). For example, in the Northeast Qaidam Basin, a change from wetter fluvial/overbank strata to playa-lacustrine and evaporite strata occurred around 3.3 Ma (Heermance et al., 2016). A drying climate is observed in the western Qaidam Basin as is recorded by mineral composition records suggesting a brackish lake with higher Mg/Ca and higher salinity after 3.3 Ma (Fang et al., 2016). Moreover, our χ_{fd} /HIRM and grain size data from the HTG section in northwestern Qaidam Basin reveal a phase of drying in the Qaidam Basin at ~3.3 Ma (Su et al., 2019b; **Figure 4**). Coupled with previous studies from the western Qaidam Basin, we interpret the hydrological transformation at ~3.3 Ma as a result of intensified aridity (Phase 2; **Figure 4**). Pliocene tectonic uplift in the study region can be one forcing for the observed drying (Lu et al., 2015). Alternatively, closure of the Indonesian Seaway and associated sea surface temperature (SST) decrease of the Indian Ocean is another or additional potential way to explain central Asian drying at ~3.3 Ma (Su et al., 2019b).

Interestingly, superimposed on the long-term drying trend, a wetting climate in the Qaidam Basin occurred between 2.84 and 2.48 Ma (**Figure 4**). Sedimentological evidence from the same site also indicates regular occurrences of fluvial system and wetter conditions between 2.84 and 2.48 Ma. Previous studies demonstrate a stepwise drying of central Asia since the Pliocene (Fang et al., 2008; Han et al., 2014; Lu et al., 2015). However, superimposed on the long-term drying trend, a phase of undetected climate wetting did occur in the Qaidam Basin during 2.84–2.48 Ma. This wetting is not unique to this site. For example, averaged artemisia content decreased from 25.3% in Phase 2 to 24.3% in Phase 3 (**Figure 4**, Koutsodendri et al., 2019), suggesting climate wetting. Interestingly, aragonite content

increased from Phase 2 to Phase 3 (**Figure 4**, Fang et al., 2016), different from the artemisia content variations. We argue that biological proxies may better reflect regional climate than evaporite mineral content. Therefore, we chose to use the biological data.

Global climate was experiencing a cooling trend since 3.6 Ma (Lisiecki and Raymo, 2005), so it is hard to attribute the observed intensified precipitation in the study site during 2.84–2.48 Ma to global forcing. Previous research suggests that stronger East Asian summer monsoon (EASM) precipitation likely penetrated further inland, which could bring more moisture to this inland basin (Liu and Ding, 1998). The magnetic susceptibility records from the Chinese Loess Plateau indicates an intensified Asian summer monsoon during this interval (An et al., 2001; Nie et al., 2014). Thus, we attribute the late Pliocene wetting of the Qaidam Basin to enhancing EASM. Alternatively, increased moisture input from westerly source is another possibility. However, evidence for westerly moisture input increase at this time interval is lacking.

Halite and gypsum content increased dramatically after 2.5 Ma (**Figures 3, 4**), indicating the formation of salty lake and intensified aridification at ~2.5 Ma in the western Qaidam Basin. Intensified aridification of the Qaidam Basin at the beginning of Quaternary is consistent with adjacent sections in the Qaidam Basin (Wu et al., 2011; Cai et al., 2012; Wang et al., 2012; Yang et al., 2013). The deep-lake black lamination abruptly disappeared and changed to a shallow-lake gray massive structure (Wang et al., 2012) and a shift in the paleolake nutrient status (Yang et al., 2013) from SG-1 in the western Qaidam Basin at ~2.5 Ma, indicating rapid aridification at ~2.6 Ma. Pollen records from SG-3 drill cores and Yahu anticline also support intensified aridity during the Quaternary period (Wu et al., 2011; Cai et al., 2012). The marine benthic $\delta^{18}\text{O}$ record (Lisiecki and Raymo, 2005) suggests intensified Northern Hemisphere glaciations at 2.7 Ma. The intensified aridification of central Asia at the Pliocene-Quaternary boundary may be in response to intensive Northern Hemisphere glaciations and resulting decreased evaporation from the Pacific and Indian Oceans, which could have provided moisture to the Qaidam Basin during the Pliocene (Su et al., 2019b). Decreased sea surface temperatures in many oceans (Herbert et al., 2016) is in line with this interpretation.

CONCLUSION

We report new, multiple-proxy records of the western Qaidam Basin lake evolution. These records reveal four phases evolution of the western Qaidam paleolake, with boundaries at ~3.3, ~2.84, and ~2.48 Ma. The data reveal that the Qaidam paleolake change from an open lake to a closed and salty lake at ~3.3 Ma, likely in response to decreased precipitation from the low latitudes and/or local tectonic uplift. Interestingly, superimposed on the long-term drying trend, a phase of wetting climate was observed in the TOC records in the Qaidam Basin during 2.84–2.48 Ma, which we suggest linked to enhancing East Asian summer monsoon. Halite and gypsum content increased dramatically after 2.5 Ma,

indicating the formation of salty lake in the western Qaidam Basin, which may be in response to intensive Northern Hemisphere glaciation and decreased sea surface evaporation. These data improve our understanding of the detailed processes of Qaidam aridification and its potential forcing mechanisms.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

LG and JN designed the experiment; QS and LG analyzed the data; QS and JN wrote the paper with the help of all authors; HR, LG, and RH participated in the discussion and modification.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feart.2021.736901/full#supplementary-material>

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