Aridification recorded by lithofacies and grain size in a continuous Pliocene-Quaternary lacustrine sediment record in the western Qaidam Basin, NE Tibetan Plateau

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\begin{abstract}
The Pliocene-Quaternary aridification of the Asian interior is key to understanding the impacts of global cooling and Tibetan Plateau uplift and the potential linkage to North Pacific Ocean biochemical processes and global changes. However, there is a lack of detailed continuous Pliocene-Quaternary paleoclimatic records from the Asian interior because most climatic records have been obtained from discontinuous coarse sediment outcrops around the rims of inland basins. Here, we provide a continuous, high-resolution 3.1 Myr record of grain size from the well-dated SG-3 borehole in the western Qaidam Basin on the northeastern Tibetan Plateau, NW China. The results reveal a long-term upward coarsening trend in grain-size that can be divided into three phases: (i) 3.1–1.1 Ma, laminated fine sediments (fine to medium silts) containing scattered gypsum crystals and interbedded by thin beds of marl; (ii) 1.1–0.15 Ma, massive medium to coarse silts interbedded by beds of mirabilite; (iii) 0.15–0 Ma, coarse silts containing thin layers of mirabilite, halite, bloedite, and polyhalite. This pattern reflects the upward shallowing and shrinking of the lake from a brackish lake to a salt lake, and then to a playa, suggesting a long-term stepwise drying of the Asian interior since the Late Pliocene, probably forced by global cooling and uplift of the Tibetan Plateau.
\end{abstract}

1. Introduction

The vast arid region in the Asian interior in the mid-latitudes, extending to an approximate latitude of 55°N, is one of the most striking geographical landscapes on Earth and has long attracted the attention of scientists worldwide. It has been generally thought that the onset of aridification in the Asian interior occurred in the Miocene (Guo et al., 2002; Miao et al., 2011; Sun et al., 2015) or earlier in the Eocene and Oligocene (Fang et al., 2015; Wang et al., 2019). This aridification has been variously attributed to multiple phases of uplift of the Tibetan Plateau (Kutzbach et al., 1989; Manabe and Broccoli, 1996; Li and Fang, 1999; Li et al., 2014, 2015; Fang et al., 2015), global cooling (Ruddiman and Kutzbach, 1989; Felzer et al., 1995; Ding et al., 2005; Lu et al., 2008; Fang et al., 2019), retreat of the Para-Tethys sea (Ramstein et al., 1997; Zhang et al., 2014a; Fang et al., 2015; Wang et al., 2019; Sun et al., 2015), and the combined effect of the Tibetan Plateau uplift and global cooling (Raymo and Ruddiman, 1992; Kutzbach et al., 1993; Liu et al., 2001; Guo et al., 2004; An et al., 2006; Lu et al., 2014; Lu et al., 2020). However, the primary driving factor, especially of the Pliocene-Quaternary aridification, remains debated. This is mainly due to a lack of direct evidence from the Asian interior. The existing records in the Asian interior from the Oligocene–Pliocene are either in low resolution or discontinuous (Wang et al., 1999; Sun and Liu, 2006; Miao et al., 2011; Lu et al., 2015) because they have all been obtained from outcrops in basins of the rims of Asian inland where the sediments are very coarse (mostly conglomerates and sandstones) or discontinuous (thrusted, folded, covered, and eroded). The lack of continuous high-resolution paleoclimatic records since the Pliocene hinders our understanding of Asian interior aridification.

The Qaidam Basin, located in the northeastern Tibetan Plateau, has been closed since the Eocene, resulting in the deposition of thick and continuous fluvial-lacustrine sediment that can provide high-quality sedimentary records for the study of paleoclimate (Wang et al., 1999; Zhou et al., 2006; Fang et al., 2008, 2016; Miao et al., 2011; Wu et al.,...
2011; Zhuang et al., 2011; Heermance et al., 2013; Nie et al., 2017; Zhang et al., 2018; Zhang et al., 2019; Kaboth-Bahr et al., 2020; Lu et al., 2020). In the western Qaidam Basin, a closed paleo-lake has existed since the Eocene (Xia et al., 2001; Wang et al., 2006; Yin et al., 2008; Han et al., 2014). We carried out deep drilling in the western Qaidam Basin (38°22′N, 91°43′E) and obtained a continuous 600 m core containing a high-quality sedimentary record covering the Late Pliocene and Quaternary. Detailed paleomagnetic analyses and organic 14C dating have precisely constrained the age of the core to approximately 3.1–0 Ma (Cai et al., 2012). We use a high-resolution grain size proxy, combined with lithofacies analysis, to reconstruct the paleoenvironment history and investigate the aridification of the Asian interior since the Pliocene and discuss its possible driving mechanisms.

2. Geological settings

The Qaidam Basin, which located in the eastern part of the arid centre of the Asian interior, is the largest intermontane basin on the NE Tibetan Plateau and has an area of ~120,000 km² (Fig. 1a). It is bordered by the Qilian Mountains to the north, the Kunlun Mountains to the south, the Altyn Tagh to the west and the Ela Mountains to the east, with elevations ranging from 4000 to over 5000 m, standing over 1000–2000 m above the Qaidam Basin (Fang et al., 2007). Early exploration for petroleum indicated that the sedimentary
depocentre in the Early Cenozoic was located in the western Qaidam Basin (Xia et al., 2001; Fang et al., 2007; Wang et al., 2006; Yin et al., 2008). With the uplift of the Altyn Tagh, the depocentre began to shift eastward between the Oligocene and Early Miocene (Xia et al., 2001; Zhou et al., 2006; Wang et al., 2006; Zhang et al., 2013; Zhang et al., 2014b). Later, the western Qaidam Basin was shortened and uplifted in thrust-fold belts along the margins of the surrounding mountains by thrusting and folding, separating the former uniform basin centre into several closed sub-basins. Dalangtan is one of the largest sub-basins and remains a lake at present (Fig. 1b). Seismic stratigraphy, borehole data and sedimentary facies analyses demonstrate that this sub-basin has received continuous lacustrine sediment deposition since the Oligocene (Shen et al., 1993; Xia et al., 2001; Wang et al., 2006), but since the Late Pliocene evaporites started to deposit in the basin (Shen et al., 1993; Cai et al., 2012).

The East Asian summer monsoon extends only to the southeast part of the basin, while the western part is mainly impacted by the westerlies (An et al., 2012) and East Asian Winter Monsoon (Lu et al., 2015). Consequently, the mean annual precipitation is very low (20–50 mm) in the western basin but slightly higher (170 mm) in the eastern basin, and the mean annual evaporation is as high as 3700 mm (Qiang et al., 2006; Cai et al., 2012). Since this area is located in the centre of the Asian interior and there is little moisture from the ocean, a typical continental desert climate has formed in the western Qaidam Basin (Kapp and Rohrmann, 2011).

3. Lithofacies and grain size records of paleoenvironment

In the eastern Dalangtan sub-basin, which was drained with the youngest depositional age of about 0.01 Ma according to organic $^{14}$C dating (Cai et al., 2012), we carried out scientific deep drilling (SG-3) and obtained 600 m of core sediments with an average recovery rate of 90%. Detailed paleomagnetic analyses determined that the depth intervals of 600–532 m, 532–269 m, and 269–0 m correspond to the upper Gauss Normal Chron (3.1–2.58 Ma), the Matsuyama Reversed Chron (2.58–0.78 Ma), and the Brunhes Normal Chron (0.78–0 Ma), respectively (Fig. 2g) (Cai et al., 2012). The sediments in core SG-3 are mainly composed of silts, calcareous muds and marl with gypsum and halite layers (Fig. 2a).

3.1. Lithofacies record

The characteristics of sediments such as colour, texture and structure reflect specific sedimentary environments (Allen and Collinson, 1986; Reading, 2010; Wang et al., 2012; Lu et al., 2015; Lu et al., 2020). We performed detail core description and microscopic identification of the core sediments (Fig. 3). According to the petrological and sedimentological characteristics, the sedimentary sequence of the SG-3 borehole can be divided into three phases delineated by boundaries at 1.1 Ma and 0.15 Ma (Fig. 2).

The sediments deposited during Phase I (3.1–1.1 Ma) are mainly composed of grey-green or grey-black fine to medium silts with some thin beds of marl. The fine sediments are characterized by dark colours and laminations (Fig. 3a, b). Additionally, there are some small scattered gypsum crystals within the fine sediments, indicating a brackish lake (Wang et al., 2012). The sediments deposited during Phase II (1.1–0.15 Ma) are mainly composed of massive blue-grey to greyish-yellow medium to coarse silts with interbedded evaporites such as...
sulfates and halite (Fig. 3c, d), indicating that the sedimentary environment had transitioned into a brackish to salt lake (Fig. 2b) (Wang et al., 2012). The lack of laminations in these sediments most likely reflects a rapidly depositing environment disturbed by turbulent flows (Allen and Collinson, 1986; Reading, 2010; Wang et al., 2012; Lu et al., 2015). The grey sediments are associated with high contents of carbonates, sulfates and halite. The sediments deposited after 0.15 Ma (Phase III) are dominated by coarse silts and chemical deposits, such as grey-white halite, blödite, and polyhalite (Fig. 3e, f), indicating that the sedimentary environment had transitioned into a playa (Fig. 2b) (Wang et al., 2012).

3.2. Grain size record

3.2.1. Sampling and methods

A total of 1597 samples were collected at an interval of 25 cm for grain size analysis. The grain sizes are measured using an American Microtrac S3500 laser grain sizer at the Institute of Tibetan Plateau.
Research, Chinese Academy of Sciences. The test range of the instrument is 0.02–2000 μm, and its repeat error is less than 3%. First, 0.1–0.3 g of sediment from each specimen was pre-treated with 10 ml of 10% H2O2 to remove organic matter (Lu et al., 2015). Second, 10 ml of 10% HCl was applied to remove carbonate. Third, distilled water was used to neutralize the pH of the sediments, and the mixture was left for 24 h. After removing the supernatant, 10 ml of 3.6% (NaPO3)6 was applied to disperse the sample. The measurement was performed after oscillation in an ultrasonic bath for 10 min. GRADISTAT version 6.0 was used to calculate the grain size (Blott and Pye, 2001), and the following grain size thresholds were adopted: clay (< 4 μm), silt (4–63 μm, including fine silt (4–16 μm), medium silt (16–32 μm) and coarse silt (32–63 μm)) and sand (> 63 μm). We also used the logarithmic Folk and Ward graphical measures (Folk and Ward, 1957) to calculate the mean grain size and mode.

3.2.2. Grain-size distribution and environmental implications

Lakes are divided into exorheic lakes and closed lakes according to whether there is an outflow of lake water. The grain size of sediment in modern exorheic lake shows that the coarse grain corresponds to a humid climate with stronger precipitation while the fine grain reflects an arid climate with weaker precipitation (Lerman, 1978; Campbell, 1998; Chen et al., 2004). As for closed modern lakes, detail grain-size distribution analyses based on log-normal distribution function fitting reveal that sediments increase in grain size from deep lake centre to lakeshore (Lu et al., 2018). As for closed paleo-lakes, larger grain size in lake center represents the dry climate period with lake shrinkage while smaller grain size indicates the wet climate with lake expansion (Menking, 1997; Xiao et al., 2013; Lu et al., 2020). Due to the long-term influence of the neotectonic movement in the western Qaidam Basin, Dalangtan becomes an important sub-closed lake since the Late Pliocene (Shen et al., 1993; Xia et al., 2001). Under arid climate with no strong precipitation in the western Qaidam Basin, precipitation was not the main external factor driving the grain size changes in the central lake zone. Moreover, the change of evaporites from carbonate via sulfate of halide from bottom to top in the SG-3 borehole reflects a typical process of drying up and shrinking of the closed lake.

The grain size distribution of sediments is an informative proxy sensitive to the sedimentary environment (Friedman and Sanders, 1978; Sun et al., 2002; Xiao et al., 2012, 2013; Lu et al., 2001; Lu et al., 2015, 2018; Lu et al., 2020). In most cases, one geological dynamic force in the sedimentary process produces only one corresponding Gaussian normal distribution (Friedman and Sanders, 1978; Berger et al., 2011). For example, loess has a typical normal grain size distribution with a peak corresponding to the silt component (silt mode) and smaller sand and clay components; this pattern can thus be interpreted as an indication of the aeolian processes (blowing and transport). An increase or decrease in the mode (peak value) of loess grain size without any changes in the normal grain size distribution reflects an increase or decrease in the strength of the wind. These kinds of grain size changes can also be generally described by the mean grain size. Thus, long-term increases in the mode and mean of the loess grain size are interpreted as increases in the wind strength of the winter monsoon and in aridity (Liu, 2003; Ding et al., 2005; An et al., 2012).

In the lacustrine environment, when sediments are transported into a closed lake, they will be subject to redistribution by dynamic processes within the lake, including wave and shore currents driven by winds, as well as by a combination of river (including turbulence) and lake processes in deltaic areas. The intensities of the wave and shore current processes are chiefly controlled by the strength and direction of the wind, the lake size and depth, and the configurations of lakeshores (Allen and Collinson, 1986; Reading, 2010). A closed lake system in an intermontane basin where the lake bottom is generally the surface of the basin and is usually quite flat, the lake size and depth generally covary positively. Thus, the degree of sediment redistribution depends on the distance from the river mouth and lakeshore, i.e., the size and depth of the lake. In the shallow lake area, e.g., the Huatougou site in the paleo-Qaidam lake (Fig. 1a), the sand content of sediments is usually high (> 10%), which indicating more impact from fluvial processes and thus may imply stronger floods and precipitation (Su et al., 2019). However, in the central lake zone that far from the river mouth and lakeshore, especially in the lake centre where the bottom water is usually below the wave base, finer sediments, mostly clays and silts, are deposited (Reading, 2010; Lu et al., 2018). Thus, the larger (smaller) and deeper (shallower) the lake is, the finer (coarser) the sediments are (Lu et al., 2018).

The overall patterns of the grain size distributions in most samples from the SG-3 borehole are characterized by Gaussian normal distribution (Fig. 4). The major difference among them is the mode. The mode shows a clearly upward increasing trend from Phase I (4–5 μm) to Phase III (30–40 μm) (Figs. 2f, 4).

3.2.3. Variations in grain size in the SG-3 borehole

The grain sizes of sediments in the SG-3 borehole indicate that the dominant components are silts with some clays and sands, forming a Gaussian normal distribution (Fig. 4). In Phase I (3.1–1.1 Ma), the average value of clay contents, medium silt contents, mean grain sizes, and mode are 23%, 13%, 20 μm and 13 μm, respectively (Fig. 2). In Phase II (1.1–0.15 Ma), the average value of clay contents, medium silt contents, mean grain sizes, and mode are 13%, 17%, 24 μm and 18 μm, respectively. While, in Phase III (0.15–0 Ma), the average value of clay contents, medium silt contents, mean grain sizes, and mode are 10%, 17%, 33 μm and 26 μm, respectively. Moreover, during 3.1–0 Ma, the grain sizes of the sediments show a clear stepwise trend of upward coarsening, as reflected by the long-term increases in medium silt, the mean and mode values and the decrease in clay.
4. Plio-Quaternary aridification of the Asian interior and discussion

The upward lithofacies change from a brackish lake at 3.1–1.1 Ma to a brackish-salty lake at 1.1–0.15 Ma, and to a playa salt lake at 0.15–0 Ma and the corresponding upward coarsening in grain size collectively suggest the shrinking and shallowing of the paleo-lake in the western Qaidam Basin and the stepwise aridification of the Asian interior since the Late Pliocene. The occurrence and explosion of evaporites in core SG-3 from bottom to top demonstrates the arid climate in the western Qaidam Basin. More concretely, the upward increase in the content of evaporites and the changes in the types of evaporites (from dominantly carbonates and some gypsum in the lower portion of the core to dominantly gypsum and mirabilite with a small amount of halite to mostly halite, blödite, and carnallite) suggest a clear climatic drying trend (Figs. 2, 3).

The sediments supplied to the basin came mainly via two routes, from Altyn Tagh to the NW of the basin and from the West Kunlun Mountains to the SW of the basin (see Fig. 1a for locations). Both source regions are far from the drilling site of core SG-3, which is located at the centre of the basin (Fig. 1b). The grain size redistribution process in a closed lake, as discussed above, means that increases (decreases) in grain size in the SG-3 borehole indicate shrinking and shallowing (expanding and deepening) of the Paleo-Qaidam Lake in response to an increasingly dry (wet) climate. Thus, the upward coarsening of grain size in the SG-3 borehole suggests an increase in dryness.

This long-term stepwise aridification trend in the Asian interior since ~3.1 Ma reflected by the lithofacies and grain size data presented above is also supported by other climatic records from the Qaidam Basin. The pollen record from the SG-3 borehole shows that the ratio of Artemisia and Chenopodiaceae, a well-known pollen proxy sensitive to climate changes in arid to sub-humid climate regions (Zhao et al., 2010), experienced long-term stepwise decreases from a value of 1.5 at 3.1–1.1 Ma to 1.1 at 1.1–0.15 Ma, and to 0.7 at 0.15–0 Ma, clearly indicating long-term stepwise aridification (Fig. 5b) (Cai et al., 2012). Additionally, the Cl⁻ content, a common lake water paleosalinity index, also records this aridification in the borehole SG-3 in the northern Qaidam Basin (see Fig. 1a for location), where the Cl⁻ content exhibited abrupt increases at ~1.12 Ma and 0.15 Ma, suggesting enhanced aridification at these times (Fig. 5c) (Guo et al., 2018). In addition, the oscillations of the 818O and 813C values of fluid inclusions in primary gypsum crystals, which record lake water conditions, in core SG-1 (Fig. 1b) indicate a long-term and stepwise aridification with two cold and dry events since ~2.2 Ma at ~1 Ma and ~0.6 Ma in the western Qaidam Basin (Li et al., 2017) (Fig. 5d, e). The magnetic susceptibility in the western Qaidam Basin has been demonstrated to be a sensitive proxy for climate change (Zhang et al., 2014; Herb et al., 2015). The persistent decrease in magnetic susceptibility in core SG-1b near the SG-3 borehole (Fig. 1b) also indicates an increasingly arid climate (Fig. 5g) (Zhang et al., 2014).

In summary, our records and other climatic records from the Qaidam Basin all indicate that since the Late Pliocene, the climate has experienced long-term stepwise aridification at approximately 1.1 Ma and 0.15 Ma. Comparison of our grain size record with records of global climate and major phase of NE Tibetan Plateau uplift shows that the obvious increase in global ice volume and cooling at 1.1–0.9 Ma, the so-called Mid-Pleistocene Transition and the rapid Tibetan Plateau uplift during 1.2–0.6 Ma (Kunlun-Huang Movement) (Li et al., 2014) might have contributed to the stepwise and persistent drying of the Qaidam Basin and Asian interior since 1.1 Ma (Fig. 5). However, the rapid drying of the Qaidam Basin does not match the rapid cooling in the global climate record but matches well with the rapid Tibetan Plateau uplift at 0.15 Ma (Gonghe Movement) (Li et al., 2014). This probably indicates that the Late Pleistocene Tibetan Plateau uplift exerted a strong impact on the aridification of the Qaidam Basin (Fig. 5).

5. Conclusions

The grain size parameters and lithofacies of the sediments in the SG-3 borehole suggest that the western Qaidam Basin was a brackish lake between 3.1 Ma and 1.1 Ma, a brackish to salty lake between 1.1 Ma and 0.15 Ma, and a playa salt lake after 0.15 Ma. The shrinking and salinization of the paleo-lake reflect the stepwise aridification of the Asian interior since the Late Pliocene. This trend was probably driven by global cooling and the rapid uplift of the Tibetan Plateau.

Declaration of Competing Interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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Appendix A. Supplementary data

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