A 7.3–1.6 Ma grain size record of interaction between anticline uplift and climate change in the western Qaidam Basin, NE Tibetan Plateau

Yin Lu, Xiaomin Fang, Erwin Appel, Jiuyi Wang, Christian Herb, Wenxia Han, Fuli Wu, Chunhui Song

ARTICLE INFO

Article history:
Received 3 November 2014
Received in revised form 15 January 2015
Accepted 19 January 2015
Available online 28 January 2015

Editor: J. Knight

Keywords:
Grain size
Lithofacies
Anticline uplift
Climate change
Qaidam Basin

ABSTRACT

How sediment grain size corresponds to both climate change and tectonics is increasingly the focus of debate. The shrinkage and migration of the huge paleo-lake in the western Qaidam Basin (WQB), NE Tibetan Plateau (TP) provide an excellent case study. We present a nearly 6 Ma well-dated high-resolution grain size record from the 723-m-deep drill core SG-1b (located in the Jianshan Anticline in the WQB) to show how sediment grain size responds to anticline growth and climate change. The results show that variations in grain size represent three distinct phases. Phase I (7.3–3.6 Ma) is characterized by fine sediments with good sorting, with a predominance of clay and fine silt. During this phase, the drilling site was in a deep to semi-deep lake environment, the Jianshan Anticline has undergone relatively weak tectonics and the climate was dry, but still much wetter than that in the Quaternary; grain size variation and lacustrine deposition were principally controlled by climate. Phase II (~3.6–3.3 Ma) was a transitional period characterized by a rapid shift toward consistently coarser sediments with increased volumes of medium-coarse silt and sand. During this phase, the drilling site underwent a dramatic shift to a shallow lake environment, the anticline experienced rapid uplift and the climate was in an episode of rapid drying; grain size variation and lacustrine deposition were principally controlled by tectonics in the Jianshan Anticline. Phase III (~3.3–1.9 Ma) was a period exhibiting a long-term fining trend in mean grain size relative to Phase II, but still much coarser than that of Phase I, and with a distinct and prolonged increase in very fine sediments accompanied by poor sorting. During this phase, the drilling site was in a shallow lake environment between 3.3 Ma and 1.9 Ma, and finally became a lakeshore-like environment between 1.9 Ma and 1.6 Ma; the anticline experienced rapid and continuous uplift and the climate was in a long-term stepwise drying and cooling trend. A conceptual model was drawn to show how grain size and lacustrine deposition responded to uplift of the Jianshan Anticline and climate change in the Qaidam Basin.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

The interaction of climate and tectonics has long been thought to control major Earth surface processes such as geomorphological development and sedimentation, and has received greater scrutiny in recent geodynamic research (Molnar and England, 1990; Molnar et al., 1993; Willett, 1999; Beaumont et al., 2001; Montgomery et al., 2001; Burbank et al., 2003; Lamb and Davis, 2003; Whipple, 2009). The conundrum faced by such research is whether it is climate or tectonics that is the major control in geomorphology and sedimentology, and how such factors can be quantified. The Qaidam Basin (QB) in the northeastern Tibetan Plateau (NE TP) provides an ideal study area for understanding how climate and tectonics affect geomorphological development and sedimentation. This is because the QB which has been closed since the Eocene, has experienced the development of significant lake areas and basin tectonics (Métivier et al., 1998; Wang et al., 2006; Fang et al., 2007; Yin et al., 2008a, 2008b), and has undergone great climatic changes (Wu et al., 2011; Miao et al., 2011b, 2013a). In the western Qaidam Basin (WQB), a huge paleo-lake developed until the Quaternary (Wang et al., 2012; Han et al., 2014). Several NW-trending folds were progressively formed basinwards, with faults propagating into the basin. As part of a joint Sino–German project we drilled a 723 m deep core (SG-1b) at the top of the Jianshan Anticline (38°21′9.46″ N, 92°16′24.72″ E), with an average sediment recovery rate of 93%. Detailed paleomagnetic dating of core SG-1b constrains its age at ca. 7.3–1.6 Ma (Zhang et al., 2014). In this paper we use high-resolution grain size records, combined with information from a detailed examination of
lithofacies and seismostratigraphy, to detect how sedimentation has responded to climate change and tectonic folding in the WQB.

2. Geological setting

The QB (area ~120,000 km²) in the NE TP is surrounded by the East Kunlun Shan, the Altun Shan, the Qilian Shan and the Erlang Shan to the south, west, north, and east, respectively, with average elevations of ca. 4000–5000 m, and over 1000–2000 m above the QB (Fig. 1a). This topographical configuration and its location determine the basin's inland hyper-arid climate, with a mean annual temperature (MAT) of 0–5 °C, a mean annual precipitation (MAP) of 100 mm in the east to ~20 mm in the west, and strong winds in winter and spring (Cai et al., 2012a). Meteorological data for the years 1957–2000 from the Lenghu Meteorological Station in the northwestern QB (103 km NE of the drilling site) show that strong winds (≥17 m/s at 10 m above ground level) average 55 days per annum in the QB (Qiang et al., 2007). In the WQB, large river systems develop mainly from the NW Kunlun Shan (e.g., the Ataatek and Bayingele rivers) and the SW Altun Shan (e.g., the Yousupualeike and Tiemulike rivers), transporting most clasts into the Gasikule Depression located between the Kunlun Shan and the Xianshuqian–Yousunzi–Mangai Anticline Zone (Fig. 1).

The QB has a maximum thickness of ~12,000 m of Cenozoic sediments derived from the surrounding mountains (Xia et al., 2001; Fang et al., 2007). This Cenozoic stratigraphy has been divided into seven formations (Fms.) throughout the Basin: the Lulehe Fm. (E1+2); Shangyoushashan Fm. (N2); Xiayoushashan Fm. (N1); upper Xiaganchaigou Fm. (E3); Shangganchaigou Fm. (N1); Xiayoushashan Fm. (N1); and Qigequan Fm. (Q1). The Qigequan Fm. (Q1) is a distinctively thick gray conglomerate intercalated with sandstone and sandy siltstone–mudstone covering most of the QB. Only in the depocenter at the middle to eastern part of the QB does it change to dark-gray mudstone intercalated with siltstone and muddy sandstone. The Shizigou Fm. (N2) is mostly conglomerate to sandstone intercalated with siltstone in the basin margins, and yellow-gray calcareous sandy mudstone intercalated with blue-gray sandstone and gravely sandstone. It is conformable with the underlying Shangganchaigou Fm. (N2) at the basin center but unconformable at the basin margins (Fang et al., 2007).

The QB is composed of three first-order tectonic units: the West Depression Region (WDR); the North Block-faulted Belt (NBB); and the East Down-warping Region (EDWR) (Fig. 1a). The SG-1b core was drilled at the top of the Jianshan Anticline, located in WDR (Fig. 1a–c). The WDR contains several rows of progressively formed NW-trending folds which young NE via propagation faults rooted in the Kunlun Fault (Fang et al., 2007). The Jianshan Anticline Zone is the row of folds farthest away from the Kunlun Shan, but only ca. 30 km away from the Altun Shan to the NW (Fig. 1b). The Altun Shan therefore provided the majority of clasts to the Jianshan Anticline area after the folds closer to the Kunlun Shan were uplifted. The seismic profile across the SG-1b core indicates that the deformation of the Jianshan Anticline began during the deposition of the upper Xiaganchaigou Fm. (E3), and the strongest deformation occurred after the deposition of the Shizigou Fm. (N2), expressed as a growing thrust fault–fold unit, and resulting in the development of two phases of growth strata sequences (GS-1 and GS-2) (Fig. 1c).

The extensive closed Qaidam paleo-lake in the WQB formed at the latest during the Oligocene, and expanded from the late Oligocene to the Miocene (Yang, 1986; Wu and Xue, 1993). However, after formation of the Xianshuqian–Yousunzi–Huanggumiao Anticline and the Nanyishan–Youdunzi Anticline in the late Miocene (Fig. 1b), this paleo-Qaidam lake began to break up and the depocenter of the lake shifted markedly from the QB to the SE (Meyer et al., 1998; Yin et al., 2002; Fang et al., 2007). Thus, the rivers originating from the SW of the Altun Shan were not able to supply further sediments to our drilling position in the paleo-lake, but those from the NW Altun Shan, the central and eastern East Kunlun Shan and the Qilian Shan could still do so. The Qaidam paleo-lake underwent dramatic shrinkage after the Pliocene and then completely disintegrated into several smaller, separate lakes in the late Pleistocene, subsequent to the strong uplift of the WQB and block subsidence in the eastern QB (Xia et al., 2001; Yin et al., 2002; Fang et al., 2007).

3. Material, methods and chronology

A total of 617 samples were collected from core SG-1b for grain size analysis. Sample grain size was determined using an American Microtrac S3300 laser particle sizer at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (ITPAS). About 0.1 g of sediment from each bulk sample was pre-treated with ca. 20 ml of 30% H2O2 to remove organic matter, then with 10 ml of 10% HCl boiled to remove carbonates, and finally washed in distilled H2O; the sample was then dispersed with 10 ml of 0.05 M (NaPO3)6 using an ultrasonic bath for 10 min before the measurements were taken (Lu and An, 1997). GRADISTAT Version 6.0 was used for grain size statistics (Blott and Pye, 2001), whereby the fractions <3.9 μm (5c) and >63 μm (4c) are regarded as clay and sand, respectively; in between, the fractions <10 μm and >32 μm (5c) indicate clay to very fine silt and coarse silt to sand, respectively. We calculated mean grain size and standard deviation values (MSD, used for sorting) using the logarithmic Folk and Ward Graphical Measures (Folk and Ward, 1957).

Seismic profiles across core SG-1b at the Jianshan Anticline clearly show the development of growth strata accompanying growth folding of the anticline (Fig. 1c). Growth strata are sets of syntectonic depositional stratigraphy developed at the limit top and at the fronts of a growing fold, and thus directly record the details of tectonic deformation (Suppe et al., 1992; Ford et al., 1997; Raffi and Mercier, 2002; Verges et al., 2002; Li et al., 2014). The tectonic uplift of the Jianshan Anticline accelerated the development of growth strata, thus decreasing the angle of corresponding strata dip (α). The uplift history of the Jianshan Anticline since late Miocene was recovered by measuring the dip angle of major strata in the front limb of the anticline.

Dating of the deep borehole SG-1b is mainly based on the detailed paleomagnetic work of Zhang et al. (2014). The ages of the samples between identified magnetic polarity chrons were calculated by linear interpolation, assuming a constant sediment accumulation rate within polarity chrons. A set of interpreted seismic profiles across the SG-1b core was used to trace the growth strata and deformation of the Jianshan Anticline (provided by PetroChina Qinghai Branch) (Fig. 1c).

Fig. 1. (a) Map showing the distribution of the QB’s tectonic sedimentary units (modified from Zhang, 2006). Inset gives the outline of the TP and location of the QB. (b) Geological map of the study area (modified from Cai et al., 2012a). Location of core SG-1b and a seismic profile (line A–B) across the core are indicated. (c) Interpreted seismic profile along line A–B across the Jianshan Anticline showing the drilling site is also plotted to provide an overview. T0 to T4 are basin-wide major correlative seismic reflection layers; T5 is the bottom of the so-called Quaternary Qigequan Fm. (Q1) and is located at a depth of 221 m in core SG-1b, which is now paleomagnetically dated to 3.4 Ma; T1 is the bottom of the Pliocene Shizigou Fm. (N2) and is found at a depth of 679 m in the core and is now dated to 7.2 Ma; T2, T3, T4, and T5 are the bases of the Shangganchaigou Fm. (N1), Xiayoushashan Fm. (N1), upper Xiaganchaigou Fm. (E3), and lower Xiaganchaigou Fm. (E3), respectively; GS-1 and GS-2 are the two growth-strata sequences. TWTT indicates two-way travel time.
4. Results

4.1. Lithofacies of core SG-1b

The lithofacies provides useful information on the sedimentary environment and thus aids grain size interpretation. The lower part of the core (723–245 m, ca. 7.3–3.6 Ma) presents gray to dark-gray fine siltstones with striking horizontal millimeter-scale laminae (Fig. 2a). The laminae exist in mudstones and siltstones, often expressed by changes in particle size, mineralogy and differing organic matter contents (Fig. 2a). The middle part of the core (245–200 m, ca. 3.6–3.3 Ma) is characterized by massive bedding and occasionally weak laminations accompanied upwards by increasingly coarse siltstones and thin bands (millimeter to centimeter-scales) of sandstones (Fig. 2b). The upper part of the core (200–0 m, ca. 3.3–1.6 Ma) is characterized by a lack of lamina- tion and the development of massive bedding, but with abundant millimeter- to centimeter-scale interbedded sandstones and scattered gypsum crystals (Fig. 2c). In particular, sediments between 35 m and the top of the core (1.9–1.6 Ma) display markedly alternating colors be- tween dark-gray/gray and grayish-green/gray-yellowish (Fig. 2c). Dis- tinct ooids begin to occur at 81 m (2.6 Ma) and increase upwards (Fig. 3).

4.2. Variations in grain size in core SG-1b

Variations in grain size in core SG-1b are characterized by three dis- tinctive phases, with boundaries at 245 m and 200 m (~3.6 Ma and 3.3 Ma, respectively) (Fig. 4). Phase I: 723–245 m (7.3 Ma–3.6 Ma); fine sediments well-sorted, clay and fine silt predominating; clearest sorting, minimum Mean and highest average contents of <3.9 μm and <10 μm fractions. The sorting (q) is ~1.4 and the Mean is ~9 μm (Fig. 4). The percentages of <3.9 μm, <10 μm, 10–32 μm, >32 μm and >63 μm fractions are ~24%, 58%, 32%, 8% and 3%, respectively (Fig. 4). Phase II: 245–200 m (~3.6 Ma–3.3 Ma); a transitional interval charac- terized by a rapid shift toward consistently coarser sediments accompa- nied by increases in medium-coarse silt and sand. Sediments show a dramatic, persistent coarsening, accompanied by a correspondent breakdown in sorting. The average value of sorting (q) is increasing rap- idly from 1.4 to 1.6 and the Mean coarsening rapidly from 9 μm to 13 μm. The percentages of the <3.9 μm and <10 μm fractions decrease rapidly from 24% to 15% and 58% to 43%, respectively; the percentages of the 10–32 μm, >32 μm and >63 μm fractions increase rapidly from 32% to 35%, 8% to 16% and 3% to 6%, respectively. The persistent coarsening during Phase II is caused principally by dramatic decreases in quanti- ties of fine sediments <10 μm and increases in coarse sediments >32 μm (Fig. 4). Phase III: 200–0 m (~3.3 Ma–1.6 Ma); a long-term fin- ing trend in mean grain size relative to Phase II, though still much coarser than that in Phase I; and distinct and persistent increases in very fine sediments (<10 μm) with weak sorting. The average value of sorting (q) in- creases from 1.6 to 1.7 and the Mean is fining from 13 μm to 10 μm. The percentages of the <3.9 μm and <10 μm fractions increase rapidly from 15% to 28% and 43% to 56%, respectively; the percentage of the 10–32 μm fractions decreases rapidly from 35% to 28%, and the percentages of the >32 μm and >63 μm fractions are 16% and 6%, respectively (Fig. 4).

Most of the core’s samples fall into two representative grain size dis- tribution categories (Supplementary Fig. A1). Type I shows a unimodal distribution with modal values of 5 μm (Fig. 5a) or 20–30 μm (Fig. 5b), almost entirely composed of clay and silt. Type II presents a bimodal distribution with the fine mode ca. 5–10 μm and the coarse one ca. 40–50 μm (Fig. 5e) or 200–300 μm (Fig. 5f). Samples with Type I grain size distribution shown in Fig. 5a, b dominate the SG-1b core, accounting for 54.6% and 30.0% of the total number of samples, respectively. Samples with Type II grain size distribution as shown in Fig. 5e, f account for only 8.3% and 7.1% of the total number of samples, respectively, but they account for 57.9% of the total number of samples in the upper 245 m of the SG-1b core (245–0 m, 3.6–1.6 Ma). In Phase I, Type I-a (Fig. 5a) and I-b (Fig. 5b) are accounting for up to 61.0% and 29.4% of the total, respectively; in Phase II, Type I-b and Type II are accounting for up to 61.8% of the total; in Phase III, Type I-b and Type II are accounting for up to 58.2% of the total.

4.3. Growth strata measurement of the Jianshan Anticline

The dip angle (α) of 23 major strata was measured in the front limb of the Jianshan Anticline (Fig. 6). Dip angles (α) of strata between 1540 msec (TWTT, 8.02 Ma) and 1000 msec (TWTT, 4.60 Ma) show little changes (54° to 57.5°), they also show little changes (52° to 49.5°) between 1000 msec (TWTT, 4.60 Ma) and 810 msec (TWTT, T0, 3.4 Ma); however, the angles decrease rapidly from 52° at 810 msec (TWTT, T0, 3.4 Ma) to 41° at 310 msec (TWTT, 2.29 Ma) (Supplementary Table A1).

5. Discussion

5.1. Lacustrine sedimentary environment in the Jianshan Anticline area since late Miocene

Grain-size distributions of the Type I-a and Type I-b in core SG-1b show a unimodal distribution with modal values at ca. 5 μm and 20–30 μm, respectively (Fig. 5a, b). These are strikingly similar to modern deep lake sediments (Fig. 5c) and shallow lake sediments (Fig. 5d) collected from northern China, respectively (Sun et al., 2002; Xiao et al., 2012, 2013), which is strongly indicative of deep lake and shallow lake deposition environment for the clastic material with Type I-a and I-b grain-size distributions, respectively.

Regional strong wind erosion existed in the QB in modern (Qiang et al., 2007, 2010) and ancient times (Kapp et al., 2011; Pullen et al., 2011; Rohrmann et al., 2013). Therefore, a comparison between the coarse fractions of Type II samples and modern dust in the leeward area of the northwestern QB, Qinghai Lake (Fig. 5g) (An et al., 2012) and dust storm deposition in the dust generating areas, i.e., the northwestern QB (Fig. 5h) (Qiang et al., 2007, 2010) was undertaken. Coarse fractions in grain-size distributions of the Type II in core SG-1b are similar to modern dust (Fig. 5g) and dust storm deposition (Fig. 5h), respectively. Thus, river floods and strong regional wind erosion are the two potential sedimentary dynamics for generating the coarse fractions in grain-size distributions of Type II in core SG-1b. Although these wind and paleo-flow processes allow us to understand the grain size composition and its climatic significance, the low frequency (15.4%) of Type II grain size samples in the SG-1b core inhibits any further discussion of their significance in this paper.

The completely stagnant bottom water (hypolimnion) will lead to restricted benthic life and the preservation of organic matter produced in the near-surface water (epilimnion), and laminated muds rich in or- ganic matter can accumulate if such stratified conditions are maintained for a long time period (Fielding, 1984; Dickman, 1985; Dam and Surlisky, 1992; Einsele, 1992; Talbot and Allen, 1996). Hence, the mudstone facies association occurs as a several hundred meter thick layer with good sorting and is dominated by gray to dark gray, finely laminated mudstones rich in organic matter in Phase I (Type I-a grain size distribution dominated, Fig. 5a) which is interpreted as deep to semi-deep lake deposits in a hydrodynamically quiet environment.

Phase II is characterized by a rapid shift toward consistently coarser sediments with increased volumes of medium-coarse silt and sand (Figs. 2b, 4). There is a basic environmental incompatibility in the close spatial association between the finely laminated mudstone facies association and sandstone facies association (comprises variable proportions of mudstone, siltstone and sandstone). The finely laminated mudstones formed under calm, perhaps anoxic, conditions in a deep, periodically stratified lake, while the coarse sediments were reworked from shallow, marginal areas and testify to turbulent, shallow-water conditions (Dam and Surlisky, 1992; Talbot and Allen, 1996). Dam and Surlisky (1992) suggest that the abrupt transition from mudstone to
Fig. 2. (a) Photographs of selected sliced cores for the intervals between 723 m and 245 m (~7.3–3.6 Ma). Note gray to dark-gray muddy fine siltstones with clear horizontal millimeter-scale lamina which characterize the intervals. (b) Photographs of selected sliced cores for the 245–200 m interval (~3.6–3.3 Ma). Massive coarse siltstones interbedded with very thin layers of sandstones dominate this interval (S: sandstone). (c) Photographs of selected sliced cores for the 200–0 m interval (~3.3–1.6 Ma). Lithofacies of the interval are characterized by a lack of laminations, though with an abundance of millimeter- to centimeter-scale thin interbedded sandstones. The colors vary from dark-gray/gray to grayish-green/gray-yellowish, then back to gray, or alternate between 35 m and the top of the core (~1.9–1.6 Ma).
Sheet sandstone is a result of high amplitude fluctuations in the lake level. The mudstones are deposited during periods of highstand, the sheet sandstones during periods of falling and low lake level, when marginal facies prograded far into the basin, therefore indicating a marked shallowing of the depositional environment. Though the average content of medium to coarse silt and sand is still very low in Phase II, this may be because the top of the Jianshan Anticline area is still far away from the nearest lake shore of the Qaidam paleo-lake, i.e., the Altun Shan area to the NW (Fig. 1b). Thus the thickness of the coarse siltstone and sandstone layers is no more than 1 m. The increasing volumes of coarse sediments and lacking finely laminated mudstones suggest that the sediments become more and more easily disturbed by storms and waves over time. Hence, the lack of finely laminated mudstones and increasing volumes of coarse sediments with rapidly poor sorting in Phase II (Type I-b and Type II grain size distribution dominated) is interpreted as shallow lake deposits in a turbulent environment.

According to the color of the lithofacies, Phase III contains two parts: (Part I) 200–35 m (ca. 3.3–1.9 Ma), characterized by a lack of lamination, and by development of massive bedding with abundant millimeter- to centimeter-scale thin interbedded sandstones (Fig. 2c), and scattered gypsum crystals (Fig. 4, lithological column); (Part II) 35–0 m (ca. 1.9–1.6 Ma), characterized by markedly alternating colors between dark-gray/gray and grayish-green/gray-yellowish (Fig. 2c), and the frequent occurrence of distinct ooids (Fig. 3). Lithofacies characteristics in Part I are very similar to Phase II, but show a long term increase in clay and fine silt fractions while keeping a high content of coarse silt and sand (Fig. 4), therefore still suggesting shallow lake deposits in a turbulent environment.

Ooids were formed on a nearshore, wave-washed bench and deposited on the lakeward-dipping bench slope during periods of seasonally higher wave activity (Talbot and Allen, 1996). The frequent appearance of ooids in core SG-1b indicates a very shallow lake water environment with water depth of possibly only several meters (Davaud and Girardclos, 2001; Folk and Lynch, 2001; Duguid et al., 2010). Consequently, the total lake water body can be turned over and mixed by wave-washed processes and in this case, a stagnant lake water with fully anoxic conditions cannot develop. This led to the alternating colors between dark-gray/gray and grayish-green/gray-yellowish in Part II (Fig. 2c). Therefore sediments of Part II (35–0 m, ca. 1.9–1.6 Ma) in Phase III are interpreted as lakeshore-like (the top of the Jianshan Anticline area is still far away from the nearest and truly lake shore of the Qaidam paleo-lake in the Altun Shan area to the NW (Fig. 1b)) deposits in a turbulent environment. Thus, the age at which the Jianshan Anticline emerged above the lake level and terminating lacustrine deposition was not earlier than the end of Phase III (~1.6 Ma). The long-term gradual decrease in the Mean was caused principally by an increase in fine sediments <10 μm and a reduction in the 10–32 μm silt fractions (Fig. 4).

5.2. Tectonics or climate as major controlling agents of the three grain size phases

5.2.1. Uplift of the Jianshan Anticline and climate change in the QB since the late Miocene

The little change in the strata dip (α) between 1540 msec (TWTT, 8.02 Ma) and 1000 msec (TWTT, 4.60 Ma), also 1000 msec (TWTT, 4.60 Ma), indicates that the Jianshan Anticline was not significantly uplifted throughout the Late Miocene and Pliocene. The lifting of the Jianshan Anticline was followed by the end of lacustrine deposition in Phase III (~1.6 Ma), as the Jianshan Anticline emerged above the lake level and the lakeshore-like deposits in Part II (35–0 m, ca. 1.9–1.6 Ma) were deposited in a turbulent environment. Thus, the age at which the Jianshan Anticline emerged above the lake level and terminating lacustrine deposition was not earlier than the end of Phase III (~1.6 Ma). The long-term gradual decrease in the Mean was caused principally by an increase in fine sediments <10 μm and a reduction in the 10–32 μm silt fractions (Fig. 4).
4.60 Ma) and 810 msec (TWTT, T0, 3.4 Ma) suggest that the Jianshan Anticline has undergone relatively weak tectonic activities before the late Pliocene, while the considerable change and rapid decrease in the strata dip ($\alpha$) from 52° at 810 msec (TWTT, T0, 3.4 Ma) to 41° at 310 msec (TWTT, 2.29 Ma) suggest that the Jianshan Anticline has undergone rapid and continuous uplift since the late Pliocene (Fig. 7i, Supplementary Table A.1). The uplift history of the Jianshan Anticline displays apparent synchronicity with the WQB’s uplift history detailed in other research (Tang and Luo, 1986; Shang, 2001; Zhou et al., 2006; Fang et al., 2007; Heermance et al., 2013).

A synthesis of sporopollen and salinity proxy records from the Yahu section in the central QB (Fang et al., 2008; Wu et al., 2011) and sporopollen records from core SG-3 in the WQB (Cai et al., 2012a; Miao et al., 2013a) (see Fig. 1a, b for locations) demonstrates that the climate had already become relatively dry after 5.3 Ma, in line with a long-term regional drying and cooling trend. There were rapid drying episodes at ~3.6 Ma, 2.6 Ma and 1.8 Ma, as shown by the dominance of and rapid increases in non-arboreal pollens such as dry-tolerant species of *Artemisia* (early stages) and Chenopodiaceae-*Ephedra* (late stages) at those times (Wu et al., 2011; Cai et al., 2012a) (Fig. 7). The deep borehole (ZK402) from the Dalangtan playa in the WQB (Fig. 1b) reveals the first appearance of several meters of thick layers of halite at ca. 3.6 Ma (Huang and Han, 2007), confirming a drying event at that time. The occurrence of evaporate minerals (Li et al., 2010, 2013), ion geochemistry records (Yang et al., 2013a, 2013b), carbonate carbon and oxygen isotope records (Han et al., 2014) and variations in the lithofacies (Wang et al., 2012) of core SG-1 (Fig. 1b) all collectively indicate a long-term stepwise climate drying and lake shrinkage in the WQB after the late Pliocene, with an obvious acceleration in drying at ~2.6 Ma, 1.8–1.6 Ma, 1.2–1.0 Ma and 0.6 Ma (Li et al., 2014).

5.2.2. Tectonics versus climate as controllers of grain size and sedimentary environment variations in core SG-1b

We interpreted the three phases of grain size and sedimentary environments found in core SG-1b vis-à-vis tectonic and/or climatic forcing. The uplift of basin-surrounded mountains such as the Altun Shan and the Kunlun Shan increased the height between the mountains and the QB and thus the erodibility of surface sediments (Molnar, 2004; Molnar et al., 2006), leading to coarser sediments being transported into the paleo-lake. Deformation and uplift of the WQB caused propagation faulting and folding and the depocenter of the paleo-Qaidam lake moved eastward (Yin et al., 2002; Fang et al., 2007; Heermance et al., 2013).

A recent synthesis of major well-dated climatic proxy records for the NE TP confirms our synthetic analysis of QB climatic change and shows that rapid drying began principally from ca. 8 Ma, and then experienced episodic stepwise drying at ca. 3.6 Ma, 2.6 Ma, 1.8 Ma, 1.2–1.0 Ma and 0.6 Ma (Li et al., 2014).

5.2.2.1. Phase I: 7.3–3.6 Ma. Grain sizes and lithofacies suggest that in Phase I the Jianshan Anticline area was in a deep to semi-deep lake environment (Fig. 1a, b). A conceptual model was drawn to demonstrate how grain size and the lacustrine deposition process responded to the uplift of the Jianshan Anticline and lake shrinkage due to climate change (Fig. 8).

[Fig. 4. Variations in Mean, MSD (sorting), and major grain size fractions in the SG-1b core showing three distinctive phases. The magnetostratigraphy of the SG-1b core is derived from Zhang et al. (2014). Heavy black lines represent the five-point running average.]
laminations, suggesting that sediment supplies were weak, distant from river mouths, and that eolian deposition was not strong. Climatic proxy records from the WQB and other parts of the NE TP demonstrate that the climate in the late Miocene and early Pliocene before 3.6 Ma was dry, but much wetter than the Quaternary (Fig. 7e–g). Fossil mammals and their teeth enamel isotopes provide robust support for this (Wang et al., 2007; Zhang et al., 2012). Fossils found in the Huaitoutala section and other nearby sections in the eastern QB show that many large mammals such as rhinoceroses, elephants and giraffes lived there in the late Miocene and early Pliocene, but disappeared in the Quaternary (Wang et al., 2007; Zhang et al., 2012). These large animals need an abundance of plants for their diets, and such plants require relatively wet and warm climates. The enamel tooth carbon and oxygen isotopes confirm that the plants necessary for these diets were produced under much wetter and warmer climatic conditions than the Quaternary in the QB (Zhang et al., 2012). The little change in the dip angles (α) of growth strata suggests that the Jianshan Anticline has undergone relatively weak tectonic activities between 3.6 Ma and 7.3 Ma. Therefore, grain size variation and the deep lake environment in Phase I were principally controlled by climate.

5.2.2. Phase II: 3.6–3.3 Ma. The grain sizes and lithofacies in Phase II suggest that the drilling site underwent a dramatic shift from a deep or semi-deep lake to a shallow turbulent lake environment (Fig. 2b, 4, 5).

![Fig. 5. Diagrams showing two representative grain size frequency distribution types (Type I: a, b; Type II: c, d) for the SG-1b core and their comparison with modern lacustrine (c, d) and eolian sediments (g, h). Modern deep lake sedimentary data were taken from central Daihai Lake (Xiao et al., 2013) and Hulun Lake (Xiao et al., 2012) in Inner Mongolia and the Qinghai Lake in Qinghai Province. Modern shallow lake sedimentary data were taken from Taihei Lake, Qinling, Shaanxi Province (Sun et al., 2002) and the Daihai Lake margins (Xiao et al., 2013). Modern dust samples were collected from the Lenghu Meteorological Station in the northwestern QB (Qiang et al., 2007, 2010) and the Qinghai Lake area to the east of the QB (leeward). An et al. (2012).]
Fig. 7. Comparison of grain size records for the SG-1b core (b, c) with global temperature and ice volume records derived from stacked oxygen isotopes of deep sea sediments (Lisiecki and Raymo, 2005) (d), the climate drying and cooling histories of the WQB recorded by sporopollen records from the Yahu section (Wu et al., 2011) (e, f) and the SG-3 core (Cai et al., 2012a) (g, h) in the WQB (see Fig. 1a, b for locations), and the tectonic uplift history of the Jianshan Anticline quantified by measuring dips in growth strata (i). Logarithm ratio of non-arboreal pollen (NAP) to arboreal pollen (AP). Arid: Artemisia + Chenopodiaceae + Ephedra + Nitraria. Thermophilic taxa: Betula + Quercus + Castanea + Juglans (%). Heavy black lines in grain size and pollen data from the Yahu section: five-point running average. T0 is located at a depth of 221 m in core SG-1b, which is now paleomagnetically dated to 3.4 Ma; T1 is found at a depth of 679 m in the core and is now dated to 7.2 Ma (ages of the secondary seismic reflection layers were calculated using linear interpolation, assuming a constant reflection rate within major correlative seismic reflection layers).
Fig. 8. Schematic model showing how core SG-1b grain sizes record the response of sedimentary processes to the rapid uplift of the Jianshan Anticline and long-term climate drying in the WQB. See the text for a detailed interpretation.
8b). The relatively weak uplift before 3.6 Ma and rapid uplift during 3.6 Ma to 3.3 Ma of the Jianshan Anticline (Fig. 7i) promote that the relative height between the anticline top and the average lake level reach a certain threshold. After reaching the threshold, the top of the anticline emerged above the normal wave or storm wave base level of the lake, thus the sediments became easily disturbed by the storms, waves or water currents, preventing the formation of horizontal laminations, which facilitated their replacement by massive bedding, and allowed the deposition of coarser sediments (Fig. 2b, 4).

After the top of the Jianshan Anticline emerged above the normal wave or storm wave base of the lake, it behaved like a subaqueous barrier island (embryonic barrier island), with its major axis lying in a NW–SE direction (Fig. 1b). This would have created sedimentary differentiation between the SW (also the top area) and NE limbs of the anticline: the coarse clastic material (e.g., coarse silt and sand) suspended in the lake water for much shorter periods would have enriched the NE limb of the anticline; while the fine clastic material (e.g., clay and very fine silt) suspended in the lake water for much longer periods would have remained in the lake water and been transported much more easily across the Jianshan Anticline area, leading to its deposition enriching the top and SW limb of the anticline (Fig. 1b, 8b). The anticline limb enriched by coarse clastic material depends on the direction of its main source. On the one hand, the sedimentary differentiation process enhanced by anticline uplift and water depth shallowing; on the other, it facilitated and expanded the anticline’s NE migration. This implies that the drilling site was not located at the top of the anticline during 7.3–1.6 Ma, but rather on the NE limb of the anticline. During Phase II, rapid water depth shallowing and sedimentary differentiation would both result in a dramatic coarsening and poor sorting of sediments (Fig. 4).

The climate change in the QB during this period would also cause lake shrinkage and a lowering of lake levels. Grain size variation and the rapid change from deep or semi-deep lake environment to shallow lake environment in Phase II were principally controlled by tectonics in the Jianshan Anticline.

5.2.2.3. Phase III: 3.3–1.6 Ma. Variations in grainometric parameters and lithofacies features suggest that the drilling site was in a shallow lake environment during 3.3–1.9 Ma, and a lakeshore-like environment during 1.9–1.6 Ma (Fig. 2c, 3, 4, 8c–1, 8c–2). During this phase, the drilling site may have moved SW relative to the top of the Jianshan Anticline, due to the NE expansion of the Jianshan Anticline (Fig. 8d). The rapid and continuous uplift of the Jianshan Anticline (Fig. 7i) and stepwise drying and cooling of the climate in the QB (Fig. 7e–h) during this phase would both aid a shallowing in water depth, and a strengthening of the Jianshan Anticline area’s hydrodynamic conditions. Thus, the sediments are even coarser and more weakly sorted than those for Phase I (Fig. 4). Moreover, the sedimentary differentiation process was likely strengthened by the uplift and water shallowing of the Jianshan Anticline area, leading to long-term grain size fining and increases in clay and very fine silt (<10 μm) while the drilling site moved SW relative to the top of the Jianshan Anticline (Fig. 4, 8d).

The dramatic coarsening of grain sizes during Phase II, and the long-term increase in clay and very fine silt during Phase III are the results of a sedimentary response to rapid uplift and a NE expansion of the Jianshan Anticline, in addition to climate drying and cooling in the QB. The frequent occurrence of ooids after ~2.6 Ma (81 m) in the Jianshan Anticline area (Fig. 3) far from the nearest lake shore of the Qaidam paleo-lake (in the Altun Shan area to the NW) (Fig. 1b) is a good example of the response of lacustrine sedimentary processes to the uplift and NE expansion of the subaqueous Jianshan Anticline.

6. Conclusions

Grain size parameters, combined with lithofacies, paleoclimate and growth strata analysis, suggest that the drilling site was in a deep to semi-deep lake environment between 7.3 and 3.6 Ma, in a shallow lake environment between 3.6 Ma and 1.9 Ma, and finally in a lakeshore-like environment between 1.9 Ma and 1.6 Ma. It underwent a dramatic shift from deep/semi-deep lake to a shallow lake environment during Phase II (~3.6–3.3 Ma).

Grain size variation and lacustrine deposition were principally controlled by climate change during Phase I (7.3–3.6 Ma), by tectonic of the Jianshan Anticline and a further contribution by climate change during Phase II (~3.6–3.3 Ma), and by a combination of climatic drying and rapid uplift of the Jianshan Anticline during Phase III (~3.3–1.6 Ma).

Acknowledgments

This study was co-supported by the (973) National Basic Research Program of China (2013CB956400, 2011CB403000), the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDB03020400), the NSFC grants (41321061, 41172032, 41272184 and 40702006), the Priority Programme 1372 ‘Tibetan Plateau: Formation, Climate, Ecosystems (TIP)’ of the German Research Foundation (DFG; project AP34/1–2, 3) and the German Ministry for Education and Research (BMBF; project Nos. 03G0705A and 03G0708A, the latter being part of the program ‘CAME: Central Asia: Monsoon Dynamics and Geosystems’). We thank Sihu Hu, Xiangyu Li, Yibo Yang and Xiaohui Fang for the field drilling assistance, Mingrui Quang and Yougii Song for providing grain size data, and Maotang Cai, Liwan Cao, Thomas Aigner, Weilin Zhang, Jinbo Zan, Minhui Li and Yadong Wang for their constructive and helpful comments on our manuscript which improve much the quality of the paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.sedgeo.2015.01.008.

References


Verlag, Berlin.


