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The Holocene history of Lop Nur and its palaeoclimate implications

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The Holocene hydrological history of Lop Nur in northwestern China's Tarim Basin and its response to climate conditions are inferred from a relatively well-dated multi-proxy record including grain-size, pollen and spores, and soluble salt data. A dated pit section (YKD0301) with a depth of 570 cm in the center of the dry Lop Nur Basin was investigated. The sediments contain a total of twenty fining-upward cycles as a result of strong discharge from the catchment to the lake during relatively wet conditions. The fluvial sediments were probably widely dispersed by wind-driven waves and currents in the large and shallow basin of Lop Nur. Higher runoff and dilution of lake waters are also indicated by lower contents of soluble salt in the sediments and recorded ostracod shells of brackish and oligohaline to freshwater species. In contrast, sediment sections with smaller mean grain size and fewer flood layers are dominated by aeolian sediments which were accumulated during drier periods. Ostracod shells are mostly lacking from these sections, suggesting a higher salinity in the lake. Lop Nur experienced six stages during the last 9 ka. Relatively wet conditions existed between 9.0–8.9, 8.7–5.1 and 2.4–1.8 ka, with periods of increased aridity in between and after 1.8 ka. The lowest salinity was recorded between 8.7 and 5.1 ka which represents the wettest phase during the last 9 ka and probably the regional Holocene Optimum. Relatively wet climate conditions between 2.4 and 1.8 ka and dry conditions afterwards possibly first fostered and later on caused the devastation of the ancient Loulan Kingdom in the region. The uppermost sediments of the section represent a massive salt crust formed during the final desiccation of the lake in the last century. The effective moisture change pattern of the Lop Nur region is roughly consistent with synthesized Holocene moisture records for western China dominated by the westerlies.

1. Introduction

The spatial pattern of the Holocene moisture variations in central Asia is a matter of intensive debate. Based on synthesized moisture index curves from 75 palaeoclimate records, Herzschuh (2006) argued that the Holocene effective moisture history of the westerlies-dominated central Asia is similar to that of the regions dominated by the Indian and East Asian Summer Monsoons. In contrast, Chen et al. (2008, 2010) evaluated 28 records from arid central Asia and concluded that the effective moisture variation in arid central Asia is out-of-phase with that in the monsoon-dominated regions. Furthermore, the Holocene Optimum (the warmest and wettest period) was apparently asynchronous across China (Shi et al., 1993; An et al., 2000; He et al., 2004; Li et al., 2012). Studies by Harrison et al. (1996) and Tarasov et al. (2000) suggest that the Asian summer monsoon reached northwestern Mongolia in the early Holocene implying that monsoonal moisture possibly penetrated generally further west to arid central Asia than it does today. So far, it remains open whether regions in Xinjiang received precipitation with monsoonal sources during possibly wetter periods in the Holocene due to the scarcity of well dated Holocene records with sufficient sample resolution and the difficulty to determine and disentangle different moisture sources from palaeorecords. Geological and geomorphological research in the eastern part of the Tarim Basin and the Lop Nur region since more than a century especially addressed the mystery of the "Wandering Lake"

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Lop Nur, i.e. its appearance at different places at different times (Hedin, 1905; Hörner, 1932; Zhao and Xia, 1984; Fig. 1a). The Holocene history of the lake has been investigated in several studies but low sample resolution and poor dating control impeded robust palaeoenvironmental and palaeoclimate reconstructions (Zhao and Xia, 1984; Yan et al., 1998; Liu et al., 2003, 2006; Xia et al., 2007; Ma et al., 2008; Dong et al., 2012a). Well-dated Holocene climate records from Xinjiang are generally limited compared to the large number of published data from monsoonal China (Herzschuh, 2006; Wang et al., 2010; Zhang et al., 2012a; Wang and Feng, 2013). An exception is Bosten Lake (Fig. 1a, d) near the northeastern margin of the Tarim Basin which provided a number of Holocene climate records with reliable chronologies (Xu, 1998; Zhong and Xiong, 1998; Wünnemann et al., 2003, 2006; Chen et al., 2006; Mischke and Wünnemann, 2006; Huang et al., 2009; Zhang et al., 2010). In this study, we conducted a high-resolution multi-proxy analyses using materials from a well-dated pit section in the center of Lop Nur to (1) reconstruct the hydrological history of the lake basin, and (2) improve the understanding of the spatial variability of the Holocene moisture conditions in arid central Asia.

2. Study area

Lop Nur (Lop Nor, Lop Nuer, Luobupo) in Tarim Basin is a playa lake surrounded by a barren desert in the heart of Asia (Fig. 1a, d). The Tarim Basin is one of the largest inland basins of the world with an area of ~560,000 km^2. The basin is bounded by the Tianshan Mountains in the north, the Pamir Mountains in the west, the Kunlun Mountains in the south, and the Altun (Altyn Tagh) Mountains in the southeast. These mountains have average elevations >4000 m above sea level (asl) and partly glaciated peaks. The elevation of the basin varies from 800 to 1300 m asl, and progressively decreases from south to north and from west to east. The eastern corner of the basin is its lowest part occupied by Lop Nur (39°40′–41°20′N, 90°00′–91°30′E, 780–795 m asl). The basin receives sediments from glaciofluvial runoff from the mountains. The maximum thickness of Quaternary deposits in the basin exceeds 1000 m (Zhu et al., 1981). Its central part is occupied by the Taklamakan (also: Taklimakan) Sand Sea, the largest sand desert in China and the second largest on Earth with an area of ~337,000 km^2.

The Lop Nur is a fault basin with an area of ~18,056 km^2 controlled mainly by northeast-striking faults (Liu et al., 2006; Fig. 1b). The depression is characterized by the flat topography with a relative relief of less than 1 m in the central area (Fig. 1c), covered with an extensive and 30–100 cm thick salt crust (Zhao and Xia, 1984). According to historical books and maps, Lop Nur was a large lake during the Han Dynasty (206 BCE–220 AD; Yang et al., 2006a). The lake area decreased after the Han Dynasty, and the lake eventually desiccated in the 1930s and left a distinct series of shorelines visible on satellite images as white concentric rings (Yang et al., 2006a; Li et al., 2008; Fig. 1b). The shape of the rings resembles a human ear, and the area is thus called the “Great Ear” (Zhao and Xia, 1984). The landscape of the Lop Nur region is characterized by yardangs carved from the palaeolake sediments, indicating that aridity and wind erosion has played a significant role in the geomorphological evolution of the region (Xia, 1987; Dong et al., 2012b). The dry climate conditions are also reflected by extensive potash brine deposits found in the Luobei subbasin, a secondary basin of the Lop Nur depression in the northeast of the playa (Wang et al., 2001, 2005). The potash-rich salt accumulation probably results from the long history of low effective moisture in the region.

The Lop Nur playa is the terminal depression of the Tarim River in the Tarim Basin. The 2200-km long Tarim River runs west to east along the northern edge of the Taklamakan Desert where it collects water from the Tianshan Mountains. The 523-km long Konqi (Konche) River is a major tributary of the Tarim River originating from the Bosten Lake to the northwest of Lop Nur and in turn fed by the Kaidu River from the eastern Tianshan Mountains. At present, there is no water flowing into the terminal playa because of human activities such as dam construction and irrigation farming in the upper reaches (Yang et al., 2006b; Hao et al., 2008).

The Tarim Basin is one of the driest places on Earth due to the rain shadow of the Tibetan Plateau to the south and the Pamirs and Tianshan Mountains in the west and north (Sun et al., 2008). The mean annual precipitation at the Yutian Meteorological Station at the southern margin of the basin ranged from 6 to 115 mm between 1956 and 2002 (Yang et al., 2006c). Mean annual precipitation at the Ruoqiang County Meteorological Station (39°1′N, 88°10′E, 890 m asl; period 1960–1996), ~240 km southwest of Lop Nur, is 23 mm and mean annual potential evaporation is 2728 mm (Wang et al., 2001). Rare rainfall mostly occurs in July, August or September. The mean annual air temperature at Ruoqiang is 11.6 °C (−9.4 °C for January and 27.4 °C for July, and minimum and the maximum temperatures of −27.2 °C and 43.6 °C, respectively). The area is also characterized by strong winds (maximum wind velocity 17–25 m/s) and dust storms (115 days per year with significant amounts of dust in the air) (Wang et al., 2001). The harsh climate results in extremely sparse vegetation cover mostly comprising Chenopodiaceae and Compositae (Zhao and Xia, 1984).

The ruins of the ancient city of Loulan (40°30′55″N, 89°54′49″E) were discovered by Sven Hedin at the northwestern bank of Lop Nur (Hedin, 1905; Fig. 1a,b,d), showing that the region was once the political, military, economic and cultural center of west China on the Silk Road connecting China to Europe from c. 77 BCE to 550 AD (Ban, the Eastern Han Dynasty (25–220 AD); Wang, 1996; Xiao, 2006; Xia et al., 2007). Ban Gu (32–92 AD) described the ancient Loulan Kingdom as a flourishing oasis with intensive irrigation farming and grazing (Ban, the Eastern Han Dynasty (25–220 AD); Xia et al., 2007; Qin et al., 2011; Zhang et al., 2013). The once prosperous kingdom completely disappeared about 500 AD and became replaced by a barren yardang region and no man's land due to the lack of water and the intensive wind-erosion (Yang et al., 2006a; Xia et al., 2007; Qin et al., 2011).

3. Materials and methods

3.1. Field work and sampling

In 2003, a pit (40°12′29″N, 90°17′59″E, numbered as YKD0301) with a depth of 570 cm was dug in the center of the Lop Nur depression (Fig. 1b). Large block samples were retrieved from the pit section using PVC tubes of about 100 cm length and 10 cm diameter. The block samples were tightly wrapped with tape and transported to the laboratory in Beijing for high-resolution sampling and analyses. A total of 448, 227, 102 and 225 subsamples were taken from the upper 465 cm for granulometrical, palynological, ostracod and soluble-salt analyses, respectively.

3.2. Age-depth model construction

The section was previously dated using radiocarbon and optically stimulated luminescence (OSL) techniques (Zhang et al., 2012a). The quartz OSL ages were regarded as reliable age data, whilst the radiocarbon ages on bulk sediments were considered to significantly overestimate the ‘true’ ages (Zhang et al., 2012a). Accordingly, only the OSL dates were used to construct an age-depth relationship for the section. Based on the OSL age distribution of dated stratigraphic levels, three linear regressions for the