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Changes in palaeoproductivity of Genggahai Lake over the past 16 ka in the Gonghe Basin, northeastern Qinghai-Tibetan Plateau

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Sequential samples of a 7.82-m sediment core from Genggahai Lake in the central Gonghe Basin, controlled with 12 accelerator mass spectrometry (AMS) ^{14}C dates, have been analysed for total organic carbon (TOC) and total nitrogen (TN) contents, carbon isotope of bulk organic matter ($\delta^{13}C_{org}$), and carbonate content. Plant macrofossils and stem encrustations, derived mainly from the species of *P. pectinatus*, *M. spicatum* and *Chara* spp., were identified, and they dominated the aquatic plant community of the lake. Alternations of plant macrofossils of *Chara* spp. and the vascular species reflect the changing productivity of the lake over time. In such a shallow lake, the carbonate content is highly related to photosynthesis of aquatic macrophytes and thus indirectly indicates variations in productivity, consistent with a quantitative estimate of palaeoproductivity. Based on these results, the palaeoproductivity history was reconstructed over the past ca. 16 ka. The lake was formed or recharged at 15.3 cal ka BP, as indicated by aeolian sand deposits at the core base. A marked increase in palaeoproductivity occurred from 15.3 to 11.6 cal ka BP. Between 11.6 and 9.2 cal ka BP, a sharply increased water-level, modulated probably by the enhanced Asian summer monsoon, might have exceeded the optimum water depth for macrophyte vegetation, causing a marked decline in coverage of aquatic macrophytes and low palaeoproductivity. The palaeoproductivity appeared to be high in the early stage of the period from 9.2 to 7.4 cal ka BP, and then decreased at approximately 8.6 cal ka BP. The palaeoproductivity sustained an overall high level between 7.4 and 2.1 cal ka BP, and decreased gradually since 2.1 cal ka BP. Our results suggest that the variability of Genggahai Lake palaeoproductivity may be associated with fluctuations of the lake level controlled by the strength of the Asian summer monsoon, probably indicating changes in the Asian summer monsoon.

palaeoproductivity, lake sediments, plant macrofossils, Asian summer monsoon, Qinghai-Tibetan Plateau

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Lake productivity is a function of the aquatic biocoenose status, physical and chemical properties of the water body and climatic and environmental changes. Thus, lake palaeoproductivity has been widely utilised to reconstruct changes in the palaeoenvironment and palaeoclimate [1–3]. Lake palaeoproductivity plays a significant role in understanding in-lake processes of aquatic plant successions and biogeochemical cycles as well as environmental changes in response to the global change. Recently, based on multi-proxies of total organic carbon (TOC) contents, carbon isotope of organic matter ($\delta^{13}C_{org}$) and organic compounds, many researchers have focused on variations in lake palaeoproductivity [4–7]. An equation developed by Müller and Suess [8], depicting the oceanic productivity, was employed to estimate the primary productivity of lakes [9–12]. However, it seems to not be practicable for lakes because the organic matter in lake sediments is from various sources. Shallow grass-type lakes are characterised by a relatively explicit provenance of sedimentary organic matter and have a great potential for research on palaeoproductivity [13]. There are a number of lakes on the Qinghai-Tibetan Plateau and its adjacent areas. Many studies on environmental

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changes have been carried out using the lake sediments, but those related to the palaeoproductivity of lakes are relatively scarce. The changes in palaeoproductivity of lakes can not only provide important information on the evolution of the ecosystem structure within lakes, but are also helpful to further understand regional environmental changes. Therefore, it is necessary to conduct palaeoproductivity research in these areas.

Genggahai Lake, a small and shallow lake, is located in the Gonghe Basin and occupied by abundant aquatic plants. The simple hydrological pattern of the lake makes it sensitive to environmental changes. The lake has been productive both in the present and in the past, inferred by the presence of submerged vegetation mats and the abundant biologic macrofossils preserved in the sediment cores. Therefore, it is an ideal site to investigate changes in palaeoproductivity.

1 Materials and methods

The Gonghe Basin is situated in the northeastern Qinghai-Tibetan Plateau. The basin has an area of approximately 13800 km^2, with an elevation of 3000 m a.s.l. (Figure 1(a), (b)). According to the meteorological data from the Gonghe station, between 1953 and 2000, the mean annual precipitation is ca. 310 mm, occurring mainly from May to September, mean annual temperature is ca. 3.7°C, and potential evaporation varies between 1528 and 1937 mm. Genggahai Lake (36°11′N, 100°06′E), is situated in the central Gonghe Basin. The lake contains two separate parts, namely the Up Genggahai Lake and the Down Genggahai Lake (Figure 1(c)). The latter has currently nearly dried up. Genggahai Lake (UP) has a maximum depth of 1.8 m, a surface area of ca. 2 km^2, a salinity of ca. 1.3 g L^{-1} and a mean pH value of 9.1. Genggahai Lake is fed mainly by groundwater. A few streams derived from springs in the north and northwest of the catchments drain directly into the lake. Human activity is relatively weak, except for some grazing by Tibetans around the lake. Submerged plants in the lake are composed of *Potamogeton pectinatus*, *Myriophyllum spicatum* and *Chara* spp. There is a patch of emergent *Phragmites australis* in the southeastern area of the lake.

In January 2008, two cores, GGH-A (782 cm in length) and GGH-B (750 cm in length), were recovered from the central Genggahai Lake at a water depth of 170 cm with a piston corer (Figure 1(d)). The inner diameter of the corer was 5.3 cm. The lengths of cores GGH-A and GGH-B were 659 and 646 cm, respectively. The measured length of the cores was different from the true depth below the lake bed due to compaction or stretch as a result of coring. To obtain a continuous sediment sequence, profiles of grain-size and magnetic susceptibility of the two cores were compared to each other. The missing sediments of core GGH-A were supplemented from the corresponding layers of core GGH-B. Two parts of the missing sediments were 8 and

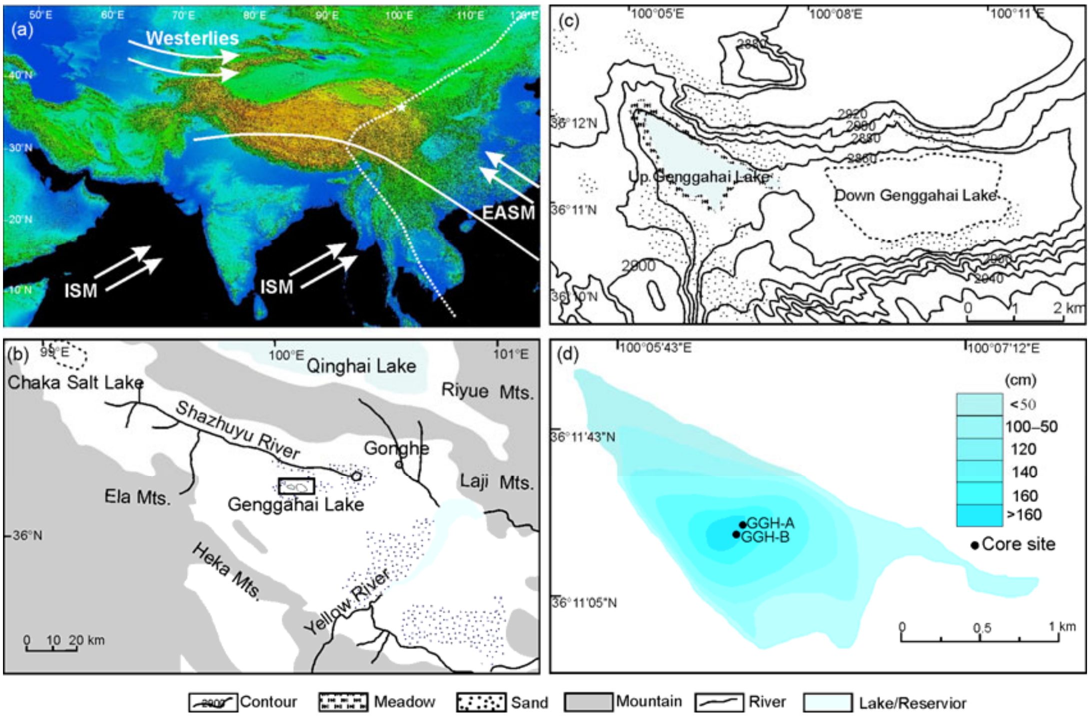

Figure 1 Settings and location. (a) Circulation systems influencing the study area. Dashed and solid lines indicate the modern extent of the East Asian summer monsoon (EASM) and Indian Ocean summer monsoon (ISM), respectively [14]. The red five-pointed star shows the location of the study area. (b) Physical environment of the Gonghe Basin. (c) Topography of Genggahai Lake, the contour interval is 20 m. (d) Bathymetric chart with contours in centimetres and coring sites in Genggahai Lake.

19 cm in length, respectively. The sediments were mostly composed of silty clay, clayey silt and sand silt. Well-sorted eolian sands were present at the base of the core (Figure 2(a)). There were abundant biological macrofossils in the sediments, primarily the remains of macrophytes, gyrogonites, stem encrustations and mollusc shells.

Subsamples were sectioned continuously at intervals of 1 cm. A total of 659 and 646 subsamples were obtained for cores GGH-A and GGH-B, respectively. The depth of each sub-sample was corrected to the true depth below the lake bed, in the light of the ratio of the measured core length relative to the true depth below the lakebed. For the wet weight of each sample, all subsamples were weighed prior to drying with a vacuum freeze dryer. After drying, they were weighed again to calculate water content. Dry bulk density was expressed as

$$\rho_s = m/(\pi r^2 \times h), \quad (1)$$

where ρ_s is the dry bulk density of the sample (g cm^{-3}), m is the dry weight of the sample (g), π is 3.14, r is the radius of the sediment core (cm), and h is the corrected depth of each sub-sample (cm).

Twenty samples of aquatic plant remains (e.g. leaves, stems or seeds) were selected from core GGH-A for accelerator mass spectrometry (AMS) ^{14}C dating. Two seed samples were analysed at the Australian Nuclear Science and Technology Organization and the others at the Archaeological Chronology Laboratory of Peking University.

Macrofossils were picked out from the freeze dried samples, washed with distilled water, identified, and counted. The carbonate content of bulk sediments was measured using a modified Calcimeter at the Key Laboratory of Western China's Environmental Systems, Lanzhou University. Mollusc shells and encrustations were picked out prior to the measurements of carbonate content. Total organic carbon (TOC) and total nitrogen (TN) contents of the samples were determined using a CarloErba NC2500 elemental analyser at the GFZ Germen Research Center for Geoscience (Potsdam). For analysis of carbon isotopic composition of bulk organic matter ($\delta^{13}C_{org}$), the samples were acid-washed with 5% HCl to remove carbonate, rinsed with de-ionised water and oven dried at 60°C for 32 h. The dried samples were ground in an agate mortar to pass through a 120-mesh sieve. The $\delta^{13}C_{org}$ were analysed using an on-line Conflo Ⅲ-Delta Plus isotope ratio mass spectrometry combined with a Flash EA1112 elemental analyser at Lanzhou University. The results are reported in ‰ relative to PDB. The analytical precision is ±0.1‰.

2 Results

2.1 Chronology

Due to the lack of terrestrial plant remains in the core sediments, aquatic plant (*P. pectinatus*) remains were used for dating. Macrophytes assimilate carbon from lake water for growth through photosynthesis. In doing so, old carbon is incorporated into the samples. Therefore, a "reservoir effect" to bias dating results is expected [15]. The measurement of organic debris from the lake surface deposit (0–1.16 cm) yielded an age of 1010±35 years, an apparent "reservoir effect". The sample ages of BA091367, BA091369, LAMS08–72, LAMS08–73, and OZL038 appear to be younger than adjacent ages (Table 1). This could be attributed to uncertainty in the measurements or a changing "reservoir effect" during the different depositional periods. Seven samples from 391.97 to 575.74 cm were dated in the range of 5100–5975 ^{14}C a BP. The occurrence of the high sedimentation rate during this period was indicated by the large median grain size of the lake sediments (Figure 2(d)). There are no obvious hiatuses found in the sediment sequence, and it is difficult to determine the amplitude of the "reservoir effect" at that time based on available data. Therefore, the chronology of core GGH-A was established using the ages in chronological order. Furthermore, the dating results appeared to be characterised by three distinct slopes, i.e. 782–570, 570–400, and 400–0 cm, suggesting three distinct sedimentary stages over the history of the lake. The ages of samples LAMS08–66, BA091367, BA091371, and LAMS08–74 deviated from their assumed linear trends. Thus, we created an age model using the remaining 12 ages (Figure 2(b)).

We assumed a constant ^{14}C "reservoir effect" over the dated span. The age of the surface sample (1010±35 a BP) was deemed the "reservoir effect". All of the selected ages were calibrated to calendar ages after a subtraction of 1010 years (Calib 5.0.1 [16], Table 1). Then, the chronology was obtained by interpolating between two controlling ages. The absolute age at the base of core GGH-A (782 cm) was 16.7 cal ka BP. The maximum sedimentation rate was 1.18 cm a^{-1} between the depth of 492 and 390 cm. Samples of the core represented a temporal resolution of 1–50 a.

2.2 Plant macrofossils and submerged plant encrustations

Plant macrofossils preserved in the Genggahai Lake sediments mainly include (1) *Chara* gyrogonites (Figure 3(a)), and (2) leaves, stems and seeds of aquatic macrophytes (Figure 3(b)). The *Chara* gyrogonites and seeds were represented by individuals per 10 cm^3 of dry sediment. The plant remains (leaf and stem fragments) were expressed as mass (mg) per 10 cm^3 of dry sediment. Two types of submerged plant encrustations, namely *Chara* spp. (Figure 3(c)) and vascular submerged plants (*P. pectinatus* or *M. spicatum*) (Figure 3(d)), were difficult to quantify due to the friable feature of the encrustations. The marked zones with different encrustation were delineated (Figure 4(a)).

The profile of submerged plant encrustations was remarkably characterised by alternating appearances of *Chara* spp. and vascular submerged plants (*P. pectinatus* or *M.*

Table 1 AMS ^{14}C dating results for core GGH–A

Lab No.	Depth (cm)	Material	δ^{13}C (‰)	^{14}C age (a BP)	Corrected ^{14}C age (a BP)	Calibrated age (2σ cal a BP) (average value)
LAMS08–64	0–1.16	plant remains	−15.24	1010±35	0	33–73(53)
LAMS08–65	35.86–37.02	plant remains	−13.71	1125±35	115	11–271(141)
LAMS08–66[a)]	106.42–107.58	plant remains	−15.45	2915±35	1905	1736–1926(1831)
OZL037	107.58–108.74	seeds	−12.40	2545±35	1535	1352–1520(1436)
LAMS08–67	200.12–201.28	plant remains	−13.63	3545±35	2535	2489–2748(2618)
BA091366	235.98–237.14	plant remains	−10.39	4255±35	3245	3391–3558(3475)
BA091367[a)]	273.00–273.97	plant remains	−13.57	3740±35	2730	2758–2920(2839)
BA091368	325.23–326.20	plant remains	−14.43	4975±35	3965	4348–4523(4436)
LAMS08–70	391.97–392.93	plant remains	−17.14	5700±35	4690	5319–5577(5448)
BA091369[a)]	483.68–484.80	seeds	−11.96	5655±35	4590	5060–5450(5255)
LAMS08–71	497.15–498.28	plant remains	−20.78	5820±35	4810	5470–5604(5537)
BA091370	569.01–570.13	seeds	−11.04	5975±35	4965	5604–5844(5727)
LAMS08–72[a)]	572.37–573.50	plant remains	−17.78	5100±35	4090	4444–4812(4628)
LAMS08–73[a)]	572.37–573.50	seeds	−15.80	5540±35	4530	5050–5311(5181)
OZL038[a)]	574.62–575.74	seeds	−12.40	5520±60	4510	4965–5320(5143)
BA091371[a)]	597.07–598.20	plant remains	−10.51	8890±35	7880	8587–8780(8684)
LAMS08–74[a)]	633.00–634.13	plant remains	−15.92	4735±35	3725	3974–4223(4099)
BA091372	657.83–658.96	plant remains	−16.85	10300±40	9290	10370–10586(10478)
LAMS08–75	701.86–702.98	plant remains	−18.07	12365±40	11355	13136–13304(13220)
BA091373	780.87–782.00	plant remains	−10.14	14995±50	13985	16282–17028(16655)

a) Rejected ages.

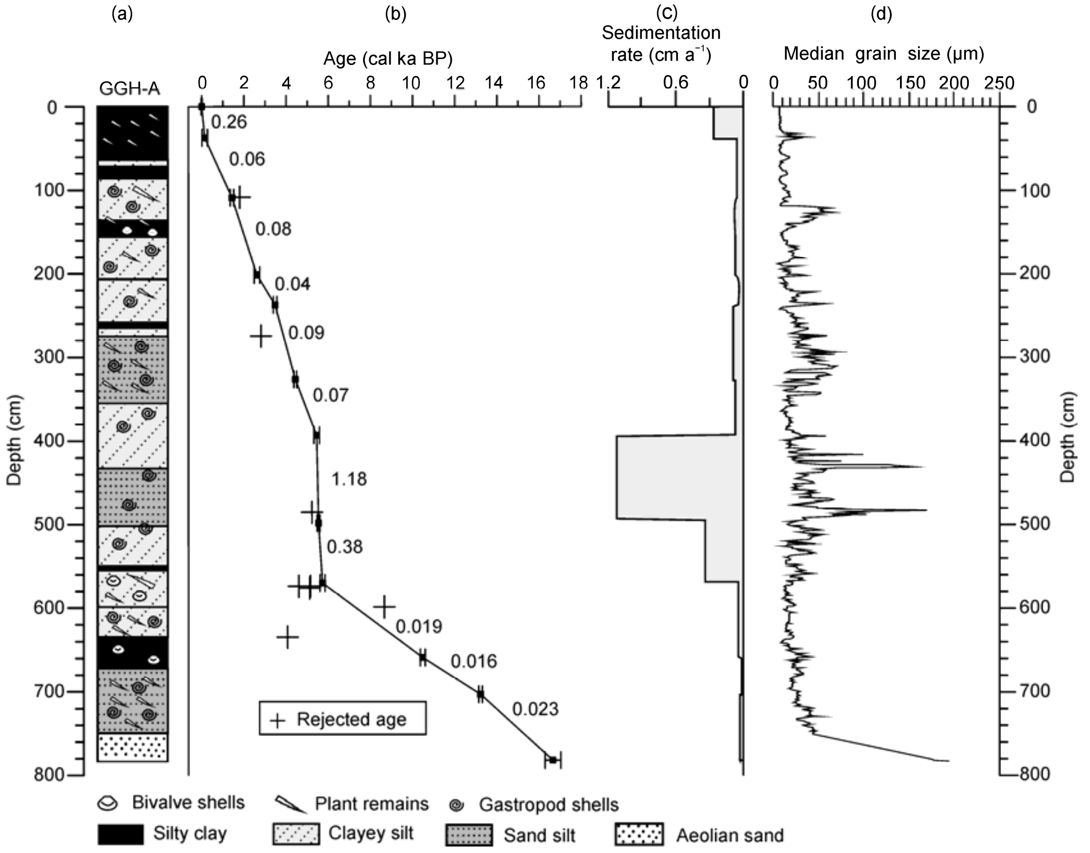

Figure 2 Lithostratigraphic units (a), age-depth model (b), sedimentation rate (c) and median grain size (d) for core GGH–A.

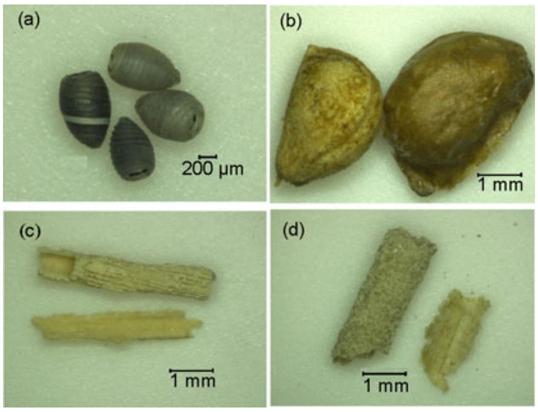

Figure 3 Plant macrofossils and submerged plant encrustations. (a) *Chara* gyrogonites; (b) *P. pectinatus* seeds; (c) *Chara* encrustations; (d) vascular submerged plant encrustations.

spicatum), except at a depth of 674–634 and 180–160 cm in which they were both absent (Figure 4(a)). The *Chara* spp. gyrogonites occurred abundantly in the layers dominated by the encrustations of *Chara* spp. (Figure 4(b)). In contrast, the high abundance of plant remains was generally consistent with the presence of the vascular submerged plant encrustations (Figure 4(c)), accompanied by seeds of *P. pectinatus* in some layers.

2.3 Carbonate content

The carbonate content of bulk sediment varied from 13.53% to 85.94%, with an average value of 55.01%. XRD analyses of bulk sediment demonstrated that the carbonates were mainly composed of calcite and aragonite. This suggested that the carbonate minerals precipitated directly in lake water and were of authigenic origin. However, 20% and 3.7% dolomite were present in samples GGHA01–01–069 and GGHA04–01–059, respectively (Table 2).

2.4 TOC, TN, C/N and $\delta^{13}C_{org}$

TOC values varied from 0.37% to 8.06%, with an average value of 2.93%. The TOC contents were much lower at depths of 750–680 and 100–0 cm (approximately 1%) than those in other intervals (Figure 4(h)). The TN contents were generally low, with an average value of 0.27%, and highly correlated with TOC (Figure 5(a)). The C/N ratios varied between 6.5 and 19.0, with the maximum and minimum value at depths between 680 and 640 cm and above 100 cm, respectively (Figure 4(j)). During the other stages, the C/N ratios fluctuated around 12. The C/N ratios displayed a positive correlation with the TOC (Figure 5(b)) but they seemed to very weakly correlate with the TN (Figure 5(c)). These relationships suggested that the TOC content may mainly affect the changes in C/N ratios. The $\delta^{13}C_{org}$ values varied from –16.37‰ to –29.53‰, with an average value of –21.39‰ and a slightly increasing trend in the profile (Figure 4(g)). The correlation between TOC and $\delta^{13}C_{org}$ was more positive above a depth of 100 cm than below it (Figure 5(d)). This was also reflected in the other proxies.

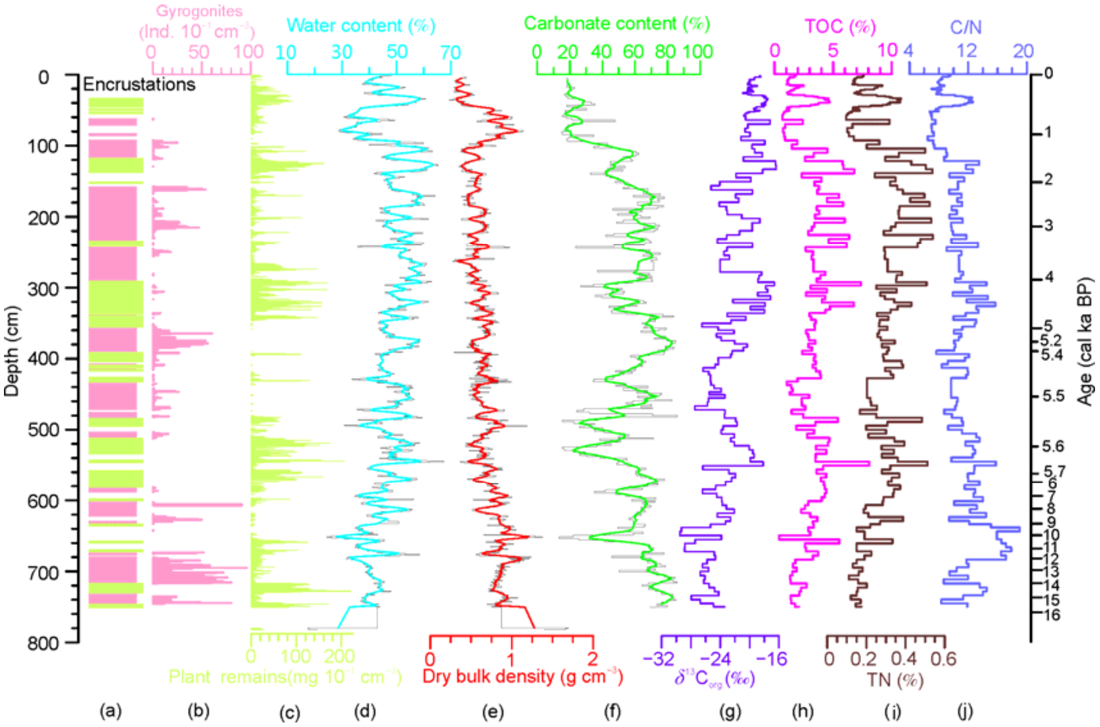

Figure 4 Multi-proxies of sediments from Genggahai Lake. Green and pink bars in (a) show the vascular submerged plant and *Chara* spp. encrustations, respectively. The coloured lines in (d), (e), and (f) indicate five-point moving averages.

Table 2 Carbonate mineral compositions of core GGH–A

Samples No.	Depth (cm)	Calcite (%)	Aragonite (%)	Dolomite (%)	Carbonate content (%)
GGHA01–01–003	3.47	100	0	0	18.50
GGHA01–01–069	79.82	80	0	20	15.34
GGHA01–01–139	106.79	38.7	61.3	0	67.84
GGHA01–01–209	241.77	100	0	0	40.15
GGHA02–01–039	310.72	100	0	0	37.68
GGHA02–01–109	378.43	47.8	52.2	0	82.10
GGHA03–01–023	472.88	100	0	0	51.47
GGHA03–01–093	542.49	48.4	51.6	0	65.18
GGHA03–02–001	612.11	30.2	69.8	0	66.21
GGHA04–01–059	699.60	63	33.3	3.7	62.00

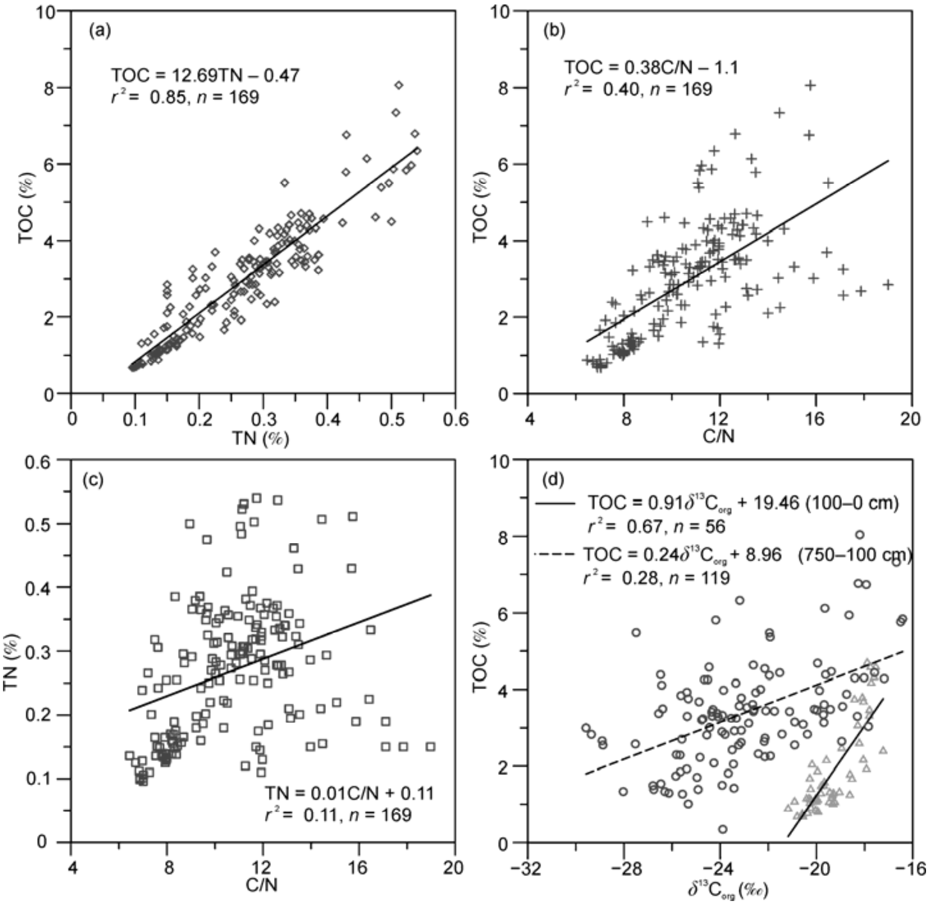

Figure 5 Correlations between TOC contents, TN contents, C/N ratios and $\delta^{13}C_{org}$.

3 Discussion

3.1 Sources of organic matter in lake sediments

The origins of organic matter (OM) in lacustrine sediments have been suggested to be aquatic algae, aquatic macrophytes and terrestrial plants. The contributions of different OM provenances are affected by the regional climates and environments [17]. For shallow lakes with high productivity, the autochthonous source is a major contribution to OM in lake sediments [18]. The plant community of Genggahai Lake mainly consists of *Chara* spp., *P. pectinatus* and *M. spicatum* at present. The plant macrofossils are also dominated by the remains of three species of aquatic macrophytes, suggesting that the aquatic vegetation in Genggahai Lake appears not to have changed significantly over the lake's history. This observation further suggested a significant contribution of an autochthonous source to the sedimentary OM in Genggahai Lake. In addition, vegetation in the lake catchment is dominated by semiarid desert grasslands. Genggahai Lake is fed mainly by groundwater. The physical features of the study area, to a certain extent, restrict terrestrial inputs to the lacustrine OM. The C/N ratio has been thought of as an effective indicator for the sources of OM in lake sediment [19–21]. Generally, the C/N ratios of terrestrial OM vary between 20 and 30, the algae, between 4 and 10, and the aquatic macrophytes, between 10 and 20 [17]. For the sediments of Genggahai Lake, the C/N ratios are lower than 20, suggesting that the aquatic macrophytes are a major contribution of OM to the lake sediments and the terrestrial input is negligible. It is noteworthy that the C/N ratios increase dramatically from 680 to 640 cm, and the abundances of plant remains decline gradually and stem encrustations disappear. It is inferred that in this stage, the contributions of terrestrial OM to the lake sediments increase remarkably relative to the aquatic macrophytes.

3.2 Influence of plant community succession on $\delta^{13}C_{org}$

Variations in $\delta^{13}C_{org}$ are closely related to the sources of OM in lake sediments [22]. The C3 and C4 land plants have $\delta^{13}C_{org}$ values that range from –24‰ to –37‰ and –9‰ to –19‰, with an average value of –27‰ and –14‰, respectively [23]. The CAM plants have a broad range of $\delta^{13}C_{org}$ values. The $\delta^{13}C_{org}$ composition of aquatic macrophytes is complex and has a broad range. For submerged plants, the $\delta^{13}C_{org}$ values vary between –12‰ and –20‰. These plants take up carbon from the HCO_3^- (DIC) of lake water for photosynthesis, yielding the higher $\delta^{13}C_{org}$ values than emergent plants (–24‰ to –30‰) [24]. The $\delta^{13}C_{org}$ values of the Genggahai Lake sediments range from –29.53‰ to –16.37‰, indicating a possible mixture of OM from different sources. As mentioned above, the C/N ratios indicate the major contributions of aquatic macrophytes to OM in the sediments. It is inferred that such large fluctuations in $\delta^{13}C_{org}$ values could reflect the internal differentiations of OM sources resulting from successive deposition of aquatic vegetation. Stratigraphic macrofossils have been used as a direct indicator for the successions of aquatic vegetation [25]. The records of plant macrofossils in the sediments from Genggahai Lake demonstrate that the submerged plants were characterised by the alternation between *Chara* spp. and the vascular plants of *P. pectinatus* and *M. spicatum* (Figure 4(a)–(c)). The $\delta^{13}C_{org}$ values seem to be strongly associated with the aquatic vegetation successions. When the vascular submerged plants dominated the plant community, the $\delta^{13}C_{org}$ values were much higher than those in the layers in which *Chara* spp. were present. Furthermore, when the aquatic macrophytes disappeared from the lake, the $\delta^{13}C_{org}$ values decreased to a very low level, suggesting a significant terrestrial input of OM inferred from the changes in C/N ratios (Figure 4). This observation is supported by the carbon isotope compositions of living aquatic macrophytes. *P. pectinatus* and *M. spicatum* have similar $\delta^{13}C$ values, varying between –12.19‰ and –14.49‰, that are higher than those of *Chara* spp. (–15.56‰ to –21.02‰). The emergent plant *P. australis* has a more negative value of –27.17‰ (Table 3). The $^{13}C_{org}$ is slightly depleted in the lake sediments compared to that of the coexisting plant remains, suggesting that some carbon components from the emergent plants and/or the C3 land plants were incorporated into the bulk OM (Table 3). Nonetheless, the successions of aquatic vegetation are still an important factor influencing changes in the $\delta^{13}C_{org}$ values. Therefore, to a certain extent, the $\delta^{13}C_{org}$ in Genggahai Lake sediments can be used as a proxy for the successions of plant communities.

3.3 Lake palaeoproductivity

Biological productivity is defined as the amount of organic matter for a certain time per unit area and is expressed as

Table 3 $\delta^{13}C$ values of living aquatic plants from Genggahai Lake and bulk OM and coexisting plant macrofossils of core GGH–A

Samples No.	Location	Water depth (cm)	Species	$\delta^{13}C$ (‰)
Site01	36°11.427′N, 100°06.384′E	130	*P. pectinatus*	–12.19
Site02–01	36°11.409′N, 100°06.461′E	90	*Chara* spp.	–15.56
Site02–02		90	*P. pectinatus*	–14.49
Site03	36°11.372′N, 100°06.832′E	79	*M. spicatum*	–13.21
Site04	36°11.298′N, 100°06.376′E	113	*M. spicatum*	–13.23
Site05–01	36°11.558′N, 100°05.759′E	60	*Chara* spp.	–18.36
Site05–02		60	*P. pectinatus*	–13.02
Site06	36°11.650′N, 100°05.777′E	65	*Chara* spp.	–21.02
Site07	36°11.214′N, 100°06.556′E	40	*P. australis*	–27.17
A01–01–110	127.25–128.40 cm	—	Plant remains	–13.66
A01–01–110		—	Plant remains	–13.89
A01–01–110		—	Bulk OM	–16.37
A02–01–030	302.02–302.98 cm	—	Plant remains	–15.43
A02–01–030		—	Plant remains	–15.63
A02–01–030		—	Bulk OM	–17.54

g TOC m^{-2} a^{-1} [26]. The organic matter content in sediments is mainly related to biological productivity within lakes. Given the same conditions, a higher primary productivity of a lake will result in more organic matter in lake sediments and thus a higher TOC content. Previous studies suggest that the TOC content of sediments from closed lakes is an effective indicator of lake primary productivity in the semi-arid and arid areas [27]. However, several factors have to be considered about preservation of organic carbon in lake sediments: (1) lake primary productivity, (2) sedimentation rate, (3) rate of organic matter degradation, (4) oxidation and reduction statuses at lake bottom, and (5) dilution effects of inorganic materials. Therefore, the TOC content may not be a direct indicator reflecting lake palaeoproductivity [28].

Carbonate precipitated in Genggahai Lake was detected as authigenic in origin (Table 2). In the semiarid and arid areas, authigenic carbonate in closed lakes generally contributes to variations in the ratio of precipitation relative to evaporation (P/E) and/or changes in regional effective moisture. However, for lakes with high productivity, the photosynthesis of aquatic macrophytes consumes CO_2 and suppresses the level of CO_2 pressure in lake water, causing intense precipitation of carbonate. The enhanced productivity in lakes, therefore, might be closely related to an increase in carbonate contents [29,30]. Morrill et al. [31] stated that there was a negative correlation between the abundance of *P. pectinatus* remains and the carbonate content for the sediments from Ahung Co. This correlation also exists in Genggahai Lake sediments, except for the sediments above a depth of 100 cm, suggesting that the precipitation of carbonate minerals within the lake may be affected by the growth of aquatic macrophytes (Figure 4(c),(f)). Compared to the vascular submerged vegetation (*P. pectinatus* and *M. spicatum*), *Chara* spp. seems to be much more effective for forming carbonate because the species exhibits a higher photosynthesis rate and a lower respiration rate [32]. This makes it more competitive to use HCO_3^- and results in intense carbonate precipitation. Carbonate encrustations (calcite) attached to the stems of *Chara* spp. account for more than 60% of its dry weight [33,34]. This ability of *Chara* spp. can produce more carbonate deposition relative to the vascular submerged plants due to its higher primary productivity. In fact, the layers of *Chara* spp. macrofossils always correspond to high carbonate contents in Genggahai Lake sediments, and the vascular submerged plants have relatively low carbonate contents. In addition, the carbonate content was lowest when the aquatic macrophytes disappeared from the coring site. Thus, the variations in carbonate content can be used to indicate changes in lake productivity [35].

As discussed above, for Genggahai Lake, the variations in TOC content, $\delta^{13}C_{org}$ and carbonate content essentially reflect the successions of aquatic plant communities. This change is characterised by the alternating appearances of *Chara* spp. and vascular submerged plants (*P. pectinatus* and *M. spicatum*) and reflects the changes in lake palaeoproductivity. The organic components of *P. pectinatus* and *M. spicatum* are higher than that of *Chara* spp. [36] and may explain the higher TOC and TN contents in the layers with the higher abundance of plant remains and the presence of vascular plant encrustations. However, *P. pectinatus* and *M. spicatum* containing high organic components does not imply higher primary productivity relative to *Chara* spp. The biomass of *Chara* spp. is 455–478 g m^{-2} in dry weight and much higher than those of *P. pectinatus* and *M. spicatum* at 73 and 42 g m^{-2} in dry weight, respectively [34]. The primary productivity of *Chara* spp. may be higher than *P. pectinatus* and *M. spicatum* due to its much higher biomass, despite the lower organic component content. Therefore, for Genggahai Lake, the high productivity corresponds to the dominant species of *Chara* spp. The dominance of *P. pectinatus* or *M. spicatum* in the plant community represents a relatively low level of productivity. The absence of aquatic macrophytes suggests the lowest productivity.

3.4 Quantitative estimate of palaeoproductivity

It is difficult to quantify lake palaeoproductivity because of the multiple sources of OM in lake sediments. However, if the specific source of sedimentary OM could be determined and extraneous sources can be ruled out, the palaeoproductivity of lakes can be estimated according to the equation presented by Müller and Suess [8] as applied at Lake Baikal [11], Lake Biwa [12], and Lake Naukuchiyatal [37]. The equation is described as [8]

$$R = C\times\rho_s\times(1-\varphi)/(0.003\times S^{0.30}), \qquad (2)$$

where R is palaeoproductivity (g C m^{-2} a^{-1}), C is the TOC content in the bulk sediment (%), S is the sedimentation rate (cm ka^{-1}), ρ_s is the dry bulk density (g cm^{-3}), and φ is the porosity of lake sediments (%).

The porosity of lake sediments is calculated as

$$\varphi = (1-\rho_s/d)\times 100\%, \qquad (3)$$

where d is the density of lake sediment, referring to the density of soil (2.65 g cm^{-3}).

Although the C/N ratio is an effective proxy to distinguish the potential sources of sedimentary OM, the significance could be affected, to a certain degree, by the total inorganic nitrogen (TIN) content [38]. TIN can be determined through the linear relationship between TOC and TN [39,40]. The TIN value of Genggahai Lake sediments is 0.037% when the TOC reaches zero according to the linear relationship presented in Figure 5(a). The total organic nitrogen (TON) can be determined by assuming that TIN is constant. Then, the ratios of TOC/TON(C/N_{org}) can be obtained (Figure 6(a)). To determine the contribution of autochthonous OM components to the bulk OM, Ishiwatari et al. [11,12] developed the following equation:

$$C/N_{org} = (C/N)_{auto}\times x+(C/N)_{allo}\times(1-x), \quad (4)$$

where x is the percentage of autochthonous OM in lake sediments (%), $(C/N)_{auto}$ is the C/N ratio of autochthonous OM, and $(C/N)_{allo}$ is the C/N ratio of allochthonous OM. The average values of autochthonous and allochthonous OM have been proposed as 8.57 and 25.7 [41,42], respectively. Ishiwatari et al. [11,12] assumed that the values of $(C/N)_{auto}$ and $(C/N)_{allo}$ were 8 and 25, respectively, and quantified the contributions of autochthonous and allochthonous OM to the bulk OM in the sediments from Baikal Lake and Biwa Lake. Similarly, Colman et al. [43] proposed that the C/N ratios of autochthonous and allochthonous OM were 7.4 and 22, respectively. Hence, eq. (4) can be used to assess the contribution of autochthonous OM to the bulk OM. Here, the values of 8 for $(C/N)_{auto}$ and 25 for $(C/N)_{allo}$ were applied to the calculation. After the contribution of autochthonous OM to the bulk OM is determined using eq. (4), the palaeoproductivity of Genggahai Lake was quantified by eq. (2). The palaeoproductivity varied from 2.0 to 75.6 g C m^{-2} a^{-1} (Figure 6(c)). In this quantitative estimate, four parameters, including the TOC content, sedimentation rate, dry density, and porosity of lake sediment, were considered in eq. (2), while the carbonate content was not included. Nonetheless, the quantified variations of palaeoproductivity are in good agreement with the changes in carbonate content (Figure 6(b),(c)). This consistency between the two independent lines of evidence implies that the carbonate content can represent the level of lake palaeoproductivity and suggests that the quantitative estimate is reliable despite the existence of some uncertainties.

3.5 Variations in the productivity of Genggahai Lake over the past 16 ka

Based on the multi-proxy results of the lake sediments and the quantitative estimate of lake palaeoproductivity, the palaeoproductivity history of Genggahai Lake was reconstructed over the past 16 ka. The well-sorted aeolian sands at the bottom of core GGH-A indicate that the lake basin had been occupied by sandy desert fields from 16.7 to 15.3 cal ka BP. Between 15.3 and 11.6 cal ka BP, the presence of abundant *Chara* spp., corresponding to the high carbonate content (more than 70%), reflects an increase in palaeoproductivity. This period can be associated with the Last Deglaciation. During the period from 11.6 to 9.2 cal ka BP, the C/N ratios indicate that the terrestrial OM became a major input to the lake, suggesting a sharp increase in the water level. The deep water might have suppressed the growth of aquatic macrophytes at that time, thereby reducing

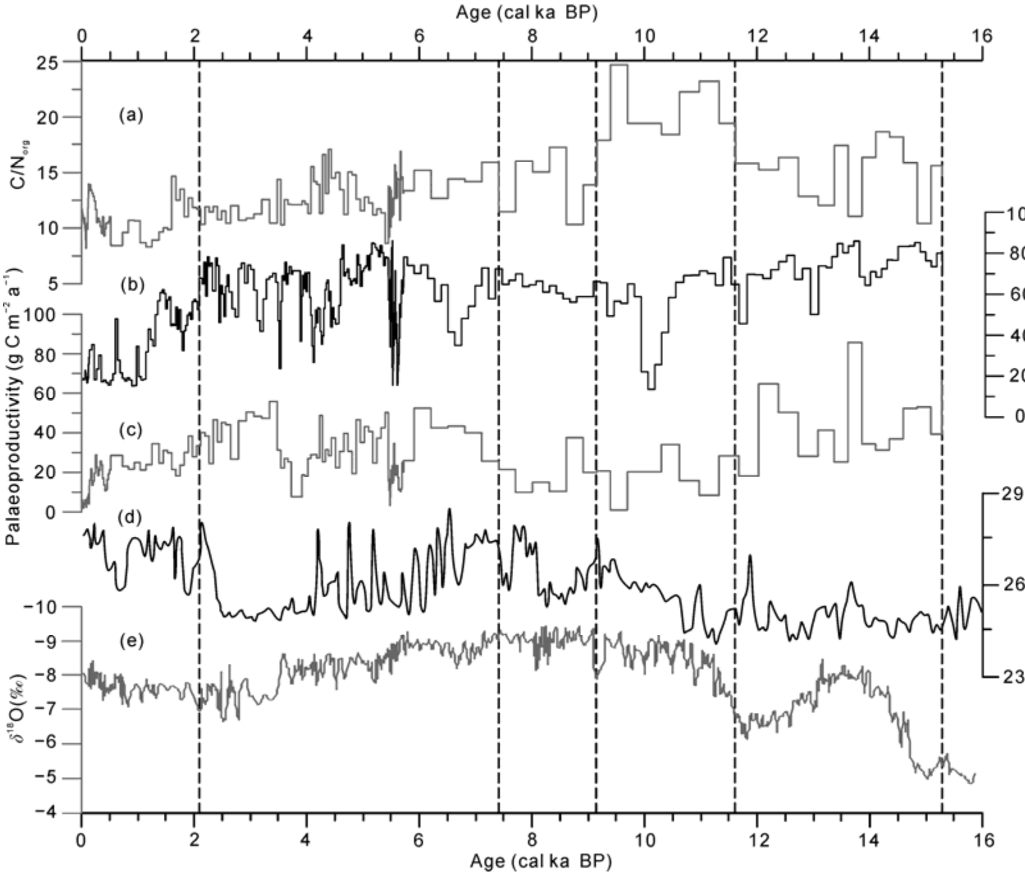

Figure 6 Comparisons of the variations in palaeoproductivity of Genggahai Lake and other records. (a) C/N_{org}; (b) the carbonate content; (c) the quantitative reconstruction of palaeoproductivity using eq. (2); (d) the Redness from Qinghai Lake [46]; (e) the $\delta^{18}O$ of stalagmite from Dongge Cave [47].

the palaeoproductivity. The productivity was high during the early stage between 9.2 and 7.4 cal ka BP and then started to decrease at approximately 8.6 cal ka BP. The palaeoproductivity sustained an overall high level between 7.4 and 2.1 cal ka BP, punctuated by two low-level periods from 5.7 to 5.5 and from 4.0 to 3.5 cal ka BP. The palaeoproductivity decreased gradually since 2.1 cal ka BP.

Lake productivity is a synthesised response to various environment factors and depends mainly on the development of aquatic organisms, especially aquatic macrophytes. Replacements between the specific aquatic species reflect successions of vegetation communities. Therefore, the changes in palaeoproductivity in shallow grass-type lakes most likely indicate successions of plant communities because the primary productivity of specific aquatic plants is distinctly different from one another. The structure and compositions of the plant community are affected by water depth, water chemistry, nutrient status and temperature, of which water depth is the most important factor [44]. A modern survey of the aquatic plant community in Genggahai Lake shows that the distributions of submerged plants are closely related to water depth. *Chara* spp. grow in clear and shallow water near the lake shore, and *P. pectinatus* and *M. spicatum* are present at a similar depth range in deep water. The presence of *Chara* spp., which is related to high productivity, represents a low lake level, while the vascular submerged plants (*P. pectinatus* and *M. spicatum*) indicate an increase in the water level. Genggahai Lake has no water inlets and outlets and is fed primarily by groundwater. The lake level is controlled mainly by local effective moisture or the ratio of precipitation relative to evaporation. The water balance of Ahung Co in the Tibetan Plateau has been attributed to changes in the strength of the Asian summer monsoon [45]. Compared to other records of Asian summer monsoon, the variations in palaeoproductivity of Genggahai Lake are consistent with the redness from Qinghai Lake and the stalagmite δ^{18}O from Dongge Cave (Figure 6(d),(e)) [46,47], strongly suggesting a link between the decreased palaeoproductivity and the strengthened summer monsoon. This connection could be established through the modulation of Genggahai Lake levels on the successions of macrophytes, and the former is in response to the strength of the Asian summer monsoon. In this sense, the changes in palaeoproductivity of Genggahai Lake may also reflect variations in the Asian summer monsoon.

4 Conclusions

Plant macrofossils in lake sediments are indicative of successions of the aquatic plant community, reflecting variations in palaeoproductivity. The plant macrofossil records from Genggahai Lake demonstrate that *Chara* spp. and vascular submerged plants (*P. pectinatus* or *M. spicatum*) alternately dominated the aquatic plant community over the lake history. The TOC and TN contents in the lake sediments are relatively low when *Chara* spp. was present, compared to the periods when vascular submerged plants were dominant in the lake. Many studies have shown that the high TOC content can represent high palaeoproductivity. However, though the organic components of *P. pectinatus* or *M. spicatum* are higher than that of *Chara* spp., the productivity of *Chara* spp. is much higher than the former. Therefore, it is suggested that the palaeoproductivity reconstructed only with the TOC content has to be interpreted cautiously and should be combined with sources of OM, physical and chemical water properties and sedimentary environments on the bottom of the lake.

The precipitation of carbonate in Genggahai Lake is controlled primarily by photosynthesis of the aquatic macrophytes; thus, the carbonate content in lake sediments can used as an indicator of palaeoproductivity of the lake. A good consistency exists between the changes in the carbonate content and the quantitative estimate of palaeoproductivity. The lake basin was covered by desert sands from 16.7 to 15.3 cal ka BP. During the Last Deglaciation from 15.3 to 11.6 cal ka BP, a marked increase in palaeoproductivity was indicated by the great amount of aquatic macrophyte macrofossils. At approximately 11.6 cal ka BP, an increase in the water level with the strengthened Asian summer monsoon was recorded by the disappearance of aquatic macrophytes. The productivity declined rapidly to a very low level until 9.2 cal ka BP. From 9.2 to 7.4 cal ka BP, a high level of palaeoproductivity occurred in the early stage of this period and then decreased at approximately 8.6 cal ka BP. The palaeoproductivity was overall high from 7.4 to 2.1 cal ka BP, but two periods with low productivity occurred from 5.7 to 5.5 and from 4.0 to 3.5 cal ka BP. The palaeoproductivity has declined gradually since 2.1 cal ka BP. Our results suggest that the changes in palaeoproductivity of Genggahai Lake are most likely modulated by the fluctuations of the lake level, which is in response to the strength of the Asian summer monsoon.

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