Multi-proxy records of Holocene fluvio-lacustrine sediments in the southern Liaodong Peninsula, China

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Abstract. The Liaodong Peninsula is located in the present Asian summer monsoon (ASM) area and has frequent land-sea interactions that make it sensitive to climate change. Terrestrial sediments can continuously record climate change with high resolution. The range and time of the East Asian summer monsoon (EASM), the main Holocene climate change driver, can be better explained by the change in the sedimentary environment in the region. This paper presents the chronology, sedimentology and geochemistry of the Holocene fluvio-lacustrine sediments in the Paozi basin south of Liaodong Peninsula, China. The multi-agent records show that the temperature and humidity are slightly higher from before 5.2ka.cal.BP to warm / wet stage, and the relative transition time from the warmest / wet stage to cold / dry stage is from 5.2ka.cal.BP to 3.5ka.cal.BP. Then, the regional climate shifted to relatively drier and colder conditions after 3.5 ka.cal.BP. Compared with other records near our site, the climate and variations in the water level change of this palaeolake were controlled by the change in the Holocene EASM precipitation, and the insolation-driven temperature co-determined the dynamics. Furthermore, the formation and disappearance of the palaeolake was due to the strengthening and decline in the EASM, respectively.

1 Introduction

The Holocene is the most recent period in the geological history of our planet, and it witnessed a series of changes to the terrestrial landscape worldwide[1, 2]. After the last glacial period, the sea level was -40 m below the present mean sea level (MSL) before the Holocene[3-6]. Since then, our planet has not remained warm/humid but rather has experienced a series of environmental events, such as the Younger Dryas[7-9], 9.2 ka event[10, 11], 8.2 ka event[12], 5.5/5.2/4.2 ka event[13-15], and the Little Ice Age[16, 17]. Thus, the Holocene has become a very popular period for studying the processes and mechanisms of palaeoclimatic conditions via multi-proxy records from different geological settings[18-21]. Among these terrestrial records, fluvial and lake sediments have been widely studied for palaeoclimatic and palaeoecological reconstructions[22-24]. Variable changes in the lithology, particle grain size, mineralogy and geochemistry of sediments with the geomorphic evolution of lake catchments are closely correlated with climatic systems. Hence, these proxies have been extensively used to infer the palaeoenvironmental conditions during the Quaternary period[25-29].

The Liaodong Peninsula, located in southeastern China, has been regarded as a standard area for studying changes in the East Asian summer monsoon (EASM) and sea-land interactions. The Holocene climate change in northeastern (NE) China has long been a problem[30]. Because of its special geographical position, it is dominated by two main atmospheric circulations: the Asian monsoon system (ASM), which plays a dominant

role, and the westerlies. A series of Holocene climatic records have been obtained from lakes and peats in the area adjacent to our study site[30-36]. However, the problem of “wet early/middle Holocene and dry late Holocene” or “dry early Holocene and wet late Holocene”[30] is still ambiguous[37-44]. Various proxy records from different regions reflect the different Holocene environmental changes among northern, northeastern and southern China, although additional research is required to address the mechanisms underlying such changes. Few studies have focused on the Holocene climate at the point area on the Liaodong Peninsula, and our knowledge of the structural characteristics, sedimentary mechanisms and associated regional climate change information based on this fluvio-lacustrine sediment is limited. Under the influence of Neotectonic uplift, the Quaternary sediments are scarce and discontinuous. The Jinzhou fault zone is one of the largest active fault zones on the Liaodong Peninsula. The Paozi basin is the largest basin to the east of the Jinzhou fault zone; it is 22 km wide and 4 to 8 km long and presents Holocene lacustrine-swampy sediments[45]. We selected the Paozi basin located in the southern Liaodong Peninsula as our present study area to determine whether it recorded important information about the regional climate change. We analyse information on the lithology, grain size and major geochemical elements from the sample core PLDXP18 to generate high-resolution climate records from the palaeolake in our site (Fig 1b) and infer regional-scale climate change dynamics. In addition, the results offer new data and perspectives on the climate changes in

northeast China during the Holocene.

Fig 1. Location of the Paozi basin. (A) Map of Liaoning Province and digital elevation model of the Liaodong Peninsula. (B) Digital elevation model of the study area and location of the sample core

2 Study area and core collection

The Paozi basin (also known as “Lianhua Pao”, 39°25′33.28″N, 121°59′51.11″E; 20 msl) belongs to the hilly area east of Pulandian Bay and is a palaeolake located in the southern Liaodong Peninsula, China (Fig 1). The Liaodong Peninsula is the second largest peninsula southeast of Liaoning Province, China. The whole peninsula runs from northeast to southwest; it is 340 kilometres long and 150 kilometres wide in the north and covers an area of 294 thousand square kilometres. The Tianshan Mountains run across the Liaodong Peninsula from the north to the south. The highest point is above 1000 metres.

Located in the southern Liaodong Peninsula, the Paozi basin has a temperate continental monsoon climate during summer months, where a warm/humid monsoon climate contributes approximately 80-90% of the annual precipitation, while during winter months, a cold/dry monsoon climate brings continuous dust storms from late autumn to early spring. The current mean annual temperature is 10.5°C, with the highest temperature of 37.8°C in August and the lowest temperature of -19.13°C in January. The annual precipitation is 550-950 mm.

During August 2018, we collected one core (122°00′42.53″E, 39°42′57.74″N) from Xipao Village using a Xy-2 drill produced by the Chongqing drilling geological machinery factory with the assistance of the Liaoning Hydrogeology Engineering Geological Survey Institute. The core used in our study reached 330 cm deep. A total of eight core sections were wrapped and transported to the laboratory. We first described the stratigraphy before subsampling at 2 cm intervals, and we took care to remove potentially contaminated sections. The samples were then air dried before sieving at 2 mm, and we ultimately obtained 165 subsamples for subsequent analyses.

3 Methods

3.1 Dating

AMS analyses were measured by the BETA Analyses

Company, USA (instrument: NECSSAMS). All ages presented were calibrated to calendar years. Calib 7.10 calibration software was used (Table 1). Four bulk samples were used for radiocarbon dating.

3.2 Grain size analysis

A grain size analysis was conducted using a Beckman Coulter Laser Diffraction Particle Size Analyser (Model: LS13 320) at the experimental centre of Liaoning Normal University. We set the time of measurement of this analyser to 90 s with a measurement range of 0.04–2000 μm . Before measuring the sample, we performed a control analysis (the control standard: Coulter LS control GB 500, Beckman Coulter, Inc.) by using a standard operating method and ensuring that the measurement result was within the following limits: mean: $582 \pm 34.5 \mu\text{m}$; and SD: $45.4 \pm 22.5 \mu\text{m}$.

We chose a total of 165 sub-samples along the core at intervals of 2 cm. The sample pretreatment steps are as follows: Samples were first naturally dried at room temperature, and then 0.25-0.28 g per sample was weighed in a 100 ml beaker. Next, 10 ml of 10% H_2O_2 was added to remove organic matter, and 10 ml of 10% HCl was added to eliminate carbonate. The samples were then washed, and 10 ml 0.01 mol/L $\text{Na}(\text{PO}_3)_6$ was added to disperse the samples before testing. We classified the clay (0.04–4 μm), silt (4–63 μm), and sand (63–2000 μm) fractions, the mean grain size (Mz) and the median diameter (Md) of each sample. The distributions of these 3 fractions from all subsamples are shown using the curve of depth changes and a ternary diagram (Fig 3c).

3.3 Geochemistry

The major elements were measured in a Rigaku ZSX primus II wavelength-dispersive X-ray fluorescence (XRF) spectrometer. The test range was 0-100%. After the sample is placed in the tester, the elements are subjected to a laser beam that generates a unique X-ray. The X-ray detector in the instrument will receive the ray signal sent by the elements and record it in the form of spectral lines. The spectral lines are then converted into atomic characteristics through software analysis, and the content of the corresponding elements can be calculated. The XRF measurement precision is < 0.5%.

The test sample preparation method involved weighing 10 g of the 105°C dried sample, grinding it for at least 30 s to a nanoscale powder, and then mixing the ground samples. Then, 4 g of the samples was weighed and placed into a mould with a polyethylene powder edge at the bottom, which was followed by pressing the sample into the outer diameter of 40 mm and inner diameter of 32 mm; the sample number was written on the back of the sample, and then it was placed in the machine for analysis. The tests were carried out at a resolution of 2 cm.

4 Results

4.1 Chronology

We created a chronology for the palaeolake sample core PLDXP-18 using four acquired calibrated radiocarbon dates (Table 1, Fig 2). We used the Calib 7.10 program (<http://calib.org/calib/calib.html>) IntCal13 calibration curve to calibrate four ages, which are in chronological order. The other corresponding strata ages are determined by interpolation and extrapolation. The age-depth model was established using the Bacon model[46] (Fig 2c).

The 330-cm core represents an age of approximately 6830 cal BP, and this date generally represents the early age of lake formation. The four radiocarbon dates measured at 20–270 cm from XP10, XP32, XP51, and XP135 are 2156-2267 cal BP, 3326-3414 cal BP, 5053-5190 cal BP and 6742-6905 cal BP, respectively. Compared with previous dating results, the age of an ancient lotus extracted from the black mud sediment (approximately 20 cm from the surface) from a profile of the Paozi basin near our core was approximately 1040±210 or 2000 BP[47, 48]. Thus, we can infer that a limited carbon reservoir effect likely occurred. Although the dates based on organic sediment are not very robust, we considered that our chronological framework is reliable on centennial scales (Fig 2) and that these organic dates can be used to constrain some millennium climate change events. In addition, the nearby strata without carbonate lithology so old carbon pollution is rare or not exist. Under the impacts of regional tectonic uplift or human activities, the sediment rate in different periods of this core is low, especially after 2156-2267 cal BP.

Fig 2. Lithology, ages and sedimentation rates of core PLDXP-18: (a) Description of lithology; (b) Sedimentation rates along the core. (c) Age-depth model of the core.

Tab 1. Results of AMS radiocarbon dates.

Sample data	Laboratory code	Depth (cm)	Dated material	δ ¹³ C (‰)	Measured age (BP)	2-Sigma range	Calibrated age (cal BP)(Median)
XP10	Beta - 501944	20	Organic sediment	-24	2250±30	2156-2267	2232
XP32	Beta - 521400	64	Organic sediment	-27	3140±30	3326-3414	3367
XP51	Beta - 501945	102	Organic sediment	-22	4530±30	5053-5190	5156
XP135	Beta - 501942	270	Organic sediment	-22.3	5990±30	6742-6905	6829

Calibrated using the IntCal13 calibration curve (Calib 7.10)

4.2 Grain size

The mean grain size (Mz) (Fig.3) is low and stable above a depth of 208 cm, with an average value of 217 μm and

an abrupt increase at a depth of 208 cm. In addition, the Mz of the lacustrine sediment above a depth of 105 cm is 79 μm, which is much finer than that of the sediment below. The median grain size (Md) shows the same trend as the mean grain size, with an average value of 189 μm. The content of clay and silt decreases with depth, while the sand content increases with depth. Three distinct points of change are observed: 64 cm, 108 cm and 208 cm. We divide the sedimentary units according to the lithology and grain particle size below. In addition, changes in the grain size parameters occurred at 108-120 cm and 180-208 cm, with decreases in the percentage of sand and clay and increases in silt. Fig. 4a shows the typical particle size frequency curves. We chose 11 samples from different depths. The curves are mainly characterized by unimodal modes, with bimodal modes showing the combination of different force mode types.

Fig. 3. Plots of grain size proxies: mean grain size (μm), median grain size (μm) and content of clay (%), silt (%) and sand (%) from the core PLDXP-18.

Fig. 4. (A) Typical particle size frequency curves of representative samples from the core PLDXP-18. (B) Grain size distribution ternary diagram of samples from the cores.

4.3 Major element geochemistry and the molecular weathering ratios

The major element data are shown as weight percentages of oxides, and the content changes with depth are presented in Fig. 4. The bulk core sediment samples mainly consist of SiO₂ (54.70–80.05%, averaging 67.87%), Al₂O₃ (7.92–18.73%, averaging 13.17%), Fe₂O₃ (1.98–10.62%, averaging 4.50%), MgO (0.11–1.57%, averaging 4.50%), K₂O (2.69–4.57%, averaging 3.23%), and Na₂O (0.80–1.94%, averaging 1.24%), and CaO (0.40–5.23%, averaging 1.02%), with low concentrations of TiO₂ (0.20–1.01%, averaging 0.66%), MnO (0.01–0.49%, averaging 0.07%) and P₂O₅ (0.02–0.17%, averaging 0.06%). SiO₂ and Al₂O₃ are the most abundant elements. SiO₂, TiO₂, Na₂O and K₂O generally increase with depth. The other six major elements tend to slowly decrease with depth. In addition, SiO₂ is positively correlated with Na₂O and K₂O but negatively correlated with Al₂O₃, Fe₂O₃, MgO, CaO, MgO, TiO₂, P₂O₅ and MnO. All of the major elements have an abrupt change in age at 5.2ka cal BP, meaning that the sedimentary environment and the grain size data suddenly changed.

The molecular weathering ratios (chemical index of alteration (CIA), salinization, calcification) are shown in Fig. 5. The CIA value is between 40.97 and 66.59, with an average of 58.48, which indicates slightly low to moderate alterations. The salinization value decreases with depth, and the highest value is at the bottom of the core, which indicates a moderate to low saline environment. The provenance decreases towards the top and then increases, and the top value along the core is 0.21 at 180 cm. The clayeyness shows a similar trend as the provenance in stage A, and the values between 0.05 and 0.08 in stage B indicate normal conditions.

Fig. 5. Plots of the content of ten major elements: SiO₂ (%), Al₂O₃ (%), Fe₂O₃ (%), MgO (%), CaO (%), MgO (%), TiO₂ (%), Na₂O (%), K₂O (%), and MnO (%)

Tab 2. Formulas of the molecular weathering ratios and indicators

Process	Formula	Indicator
CIA	$100 \times \text{Al} / (\text{Al} + \text{Ca} + \text{K} + \text{Na})$	Alteration
Salinization	$(\text{K} + \text{Na}) / \text{Al}$	Hydrolysis
Provenance	Ti / Al	Parent material input

The ratio refers to [49, 50].

Fig. 6. Plots of molecular weathering ratios: CIA, salinization, calcification and clayeyness

5 Discussion

5.1 Proxy interpretation

The grain size distribution, which is one of the basic physical properties of sediment, can reflect the dynamics of the source material as well as the transportation and deposition of the sediment, and it has been widely used for palaeoclimatic reconstructions [37–44]. Coarse clastic materials, such as sand, usually indicate an abundance of sediment sources and high transport energy, and vice versa. In general, regional precipitation, a drier climate and stronger aeolian activity can strengthen regional external agents and lead to more coarse grain size fractions in lake sediment. In our study site, an intermountain basin, high precipitation would enhance the soil erosion of the surrounding hills, and then flood currents and rivers would transfer more coarse clastic materials and deposits into lakes [48]. However, aeolian activity may have had a less dramatic effect. Hydrological cycles mainly related to precipitation and lake mechanical sedimentation are the major factors controlling the grain size distribution.

We typically use major geochemical elements, especially terrestrial sediments, as effective proxies to demonstrate the intensity of chemical weathering, climate changes and precipitation variations [51]. Changes in the major elements usually closely correspond with changes in sedimentary environments. Thus, studying changes in the content of major elements in sediments can reflect the source of origin and can be used to interpret the evolutionary characteristics of the regional palaeoenvironment via combinations with other indexes, such as grain size.

Molecular weathering ratios can be useful tools for identifying the origin of sediments that reflect the environmental conditions of the parent rocks [49]. In addition, we usually use elemental ratios to provide information on the sedimentary process, which may be influenced by various factors, such as grain size sorting during the transportation of sediments, changes in the source area, and variations in the chemical weathering strength of the source area [50]. The CIA ($\text{CIA} = [\text{Al} \times 100 / (\text{Al} + \text{Ca} + \text{Na} + \text{K})]$) can be used to assess the degree of weathering of siliciclastic sediments in sediment source areas and is shown in Table 3. Generally, warmer and wetter climates have a higher weathering degree (assuming that the sediment is not

disturbed after deposition) and vice versa. Fresh rock has CIA values below 50. We defined CIA values below 60 as low chemical weathering, values from 60-80 as moderate chemical weathering and values more than 80 as extreme chemical weathering. Salinization is the value used to evaluate soluble mobile elements, mainly K and Na, that accumulate in the sediment. The salinization ratio has been widely used to indicate the mean annual temperature. When using this ratio, we should combine it with other aridity indicators to reconstruct the climate[52]. Ti is easily removed by physical weathering, while Al contents are relatively constant. Therefore, the Ti/Al ratio is widely applied as a provenance indicator of the parent material input, such as quartz and zircon[26, 53], into the sedimentary system[54]. In addition, the ratios can be indicators of clastic input by various sedimentary forces, such as aeolian processes or fluvial transportation. If the provenance value is higher, then the strength input of the parent material is clastic, while lower values of Ti/Al usually suggest a different provenance of sediments into the basin from higher quartz and feldspars to felsic.

6 Palaeoenvironmental reconstruction

The lithologic changes in core PLDXP18 suggest that palaeolakes experienced several environmental stages during the Holocene. Based on transitions of the lithology, grain size and geochemical proxies, we mainly distinguished four main palaeoenvironmental stages, as indicated below.

Stage A (330-208 cm, prior to 6.0 ka cal BP)

This stage is characterized by the deposition of pure light-yellow coarse sand, and we also found very little boulder clay at the bottom. The light-yellow coarse sand is alluvium, while the mixed little boulder clay is intermittent diluvium; thus, we infer that they are the products of flood alluviation. The sedimental environment may have been a river or shallow lake that flooded intermittently. The Mz values of the sand range from 163 to 615 μm , with a mean of 451 μm . The coarse grain size indicates strong hydrodynamics in the lake watershed, which led to a high SiO_2 content. At the same time, the CIA value is low but higher than that of the late Holocene, especially the value of 58.29 from 2000-0 cal BP, which indicated low chemical weathering. The provenance and clayeyness has the same trend as the CIA, indicating a strong input of quartz clastic material. The soluble element index (salinization) decreases in this period, which indicates abundant water injection and low weathering. These results reveal a wet climate with abundant surface runoff. The sudden change in the sedimentary environment shows that a transition to lacustrine facies may have occurred under the combined effect of the EASM, which lead to continuous precipitation, and the Holocene high sea level, which led to an elevation of the base level of erosion.

A small peat deposit occurs above the boulder clay or bedrock near our site [47, 48], and it is defined as an early Holocene peat deposit; however, we cannot find

this deposit in our sample core, which is mainly because our site is at a slightly higher elevation that is not conducive to peat deposition. The peat deposit also indicates an earlier wetter climate. Then, with the cold/dry climate in the late-glacial period, the EASM was significantly enhanced and rainfall increased concurrently in the early-middle Holocene. We think that stage A in our study site is dominated by a slightly warm climate with enhanced precipitation.

Stage B (208-108 cm, 6.0-5.2 ka cal BP)

Sediments accumulated during the time interval 6.0-5.2 ka cal BP have a mean Mz value of 101 μm , which is smaller than the mean Mz for the previous interval. The decreased grain size coupled with the higher mean CIA of 69.96 indicates low erosion and a warmer period. Fluvial facies (Stage A) show a transformation into lacustrine facies throughout the core lithology. The major ratio has a similar trend compared to that of stage A. The indicators show transitional characteristics in the two periods from 108-120 cm and 180-208 cm, and the interpolated ages are 5053-5452 cal BP and 5068-6475 cal BP, respectively. We think that these two short periods may correspond to the 5.5 ka and 5.2 ka cooling events[14]. All proxies indicate a relatively warm and wet climate in the area during this stage

Stage C (108-64 cm, 5.2-3.4 ka cal BP)

A slight decrease in Mz (62 μm), clay and sand and an increase in silt compared with stage B suggests a reduction in regional runoff or that the large aquatic and terrestrial plants prevented coarse particles from entering the lake[40]. The lower CIA (65.19) means that the weathering is low indicating a drier regional climate compared to the previous two stages. Salinization has the lowest value (0.24) in the middle stage and has an opposite trend to CIA, while the other two major element ratios mainly remain stable, indicating that the climate becomes slightly colder and drier. It is a transition period from warmest and wet to colder and dry. The 4500 cal BP is an obvious global drought event in the late-middle Holocene[30], but it did not have an obvious response compared with the 5.5 or 5.2 ka cool event in our region. Precisely, the Holocene optimum in our site ended during this period, and the lake gradually became a shallow lake or marsh.

Stage D (64-0 cm, after 3367 cal BP)

The lithology consists mainly of black hard clay with rich organic matter and some reworked material, such as cultivated silt-sand soil, on the surface. This layer is also called "the ancient lotus seed layer" because it contains ancient lotus seeds from nearly a thousand years ago[47]. We infer that this part of the sediment was a marshy deposit. The lowest Mz and CIA values and irregular grain size variations mean that the water supply is discontinuous and tapers off to a stop under the combined effect of a dry climate, river diversion and autogenic basin infilling processes that may have occurred at this time. The CIA and salinization values are lower, while the CaO content rapidly accumulates, showing that a cold and dry climate began. Because farming activities disturbed the surface deposit over the last thousand years, we are not able to interpret the

proxies of the surface sediments here.

7 Comparison with other regional records and Holocene climate change drivers

This history of palaeoenvironmental variations is consistent with the results of the profile of Northeast China north of our study site, with a warmer and wetter climate occurring in the early- to mid-Holocene that ended with a cold/dry climate to the present day. During that time, some short cool events, such as 10.5 ka, 9.2 ka, 8.2 ka, 7.2 ka, 6.2 ka, 5.5 ka and 4.2 ka, were recorded. Hani peatland indicated an expansion of broadleaf deciduous trees from 9.3 ka to 4.5 ka[55], which was accompanied by alternating cooling and warming climate conditions from 8.8–4.8 cal. ka BP; moreover, a rapid decline of the EASM occurred from 5.5 to 4.5 cal BP based on peat evidence in the Sanjiang Plain[56]. The key period of climate change in Northeast China is from 5.5–4.5 cal ka BP, which means that the end of the Holocene optimum started from 9.0 ka BP[27]. A rapid dry event occurred at 3600 cal yr BP[33]. Our results showed the same trend during the 5.2–3.4 ka cal BP period. In addition, sediments of the Horqin sand land became coarser and indicated a dry/cold climate from 3.8 ka to 1.7 cal kyr BP[37], which is consistent with the stage 4 after 3.4 ka cal BP in our study.

Fig. 7. Comparison of climate change-related parameters with other regions. Extra-terrestrial insolation (EXI) [W/m²] in the mid-month insolation 65N for July (orange line)[57]; $\delta^{18}\text{O}$ records from Dongge Cave[58] and Sanbao Cave (SB26 dark green curve; SB10 light green curve[59]).

The climate change parameters (Fig. 7.) showed that strong Northern Hemisphere insolation and higher temperatures resulted in an enhanced EASM intensity, which is also reflected by the speleothem $\delta^{18}\text{O}$ records. The isolation decreased from 8.0 ka cal BP, and our study area experienced a warm to colder climate. The EASM precipitation recorded by speleothems shows fluctuations. Our study area did not show the climate during the early Holocene however, while a warm/wet climate was observed before 6.0 ka cal BP. At Sanbao Cave (core SB26, core SB10), an abrupt climatic change is documented at approximately 4.0–4.5 ka cal BP, which is consistent with the stage 3 climate transition in our core. The wet period was consistent with the general

wetter to wettest to drier pattern during the Holocene, which suggested that the monsoon precipitation and insolation-driven temperature co-determined the dynamics[60] at our site.

8 Conclusions

We analysed Holocene palaeoenvironmental changes based on fluvio-lacustrine sediments in the Liaodong Peninsula, China, to determine its Holocene climate history and significance of the EASM evolution. We extracted the core pldxp18 with a length of 330cm and carried out high-resolution stratigraphic analysis. The core mainly contained three facies: lacustrine mud at the middle, fluvio-sediments at the bottom, and black organic mud at the top above a sharp boundary. Our analysis indicates that before 6.0 ka cal BP, fluvial sediments were deposited at the study site, implying a warm humid climate, and then lacustrine sediments were deposited because of the continuous runoff and precipitation from the EASM. Subsequently, a drying interval occurred and caused a major drop in the water level, which converted the paleolake to a marsh at approximately 3.4 ka cal BP. In addition to the gradual lake-infilling process, we attribute the transition to the influence of the sudden decline of the EASM during the middle-late Holocene, which was initially controlled by the ocean–atmosphere interactions in low-latitude regions. We conclude that our area had a wet middle Holocene and a dry late Holocene.

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