

# Chapter 7

## Rapid Environmental Change of Jingpo Lake in Mid-Holocene: Inferred from Fluvial/Lacustrine Sedimentary Facies Transition

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**Abstract** The Jingpo Lake is the China's largest lava-dammed lake, however, the formation age of Jingpo Lake and associated volcanic eruption events are poorly understood and still under controversy. In this study, we obtained a 12.72-m-long sediment core (JP-C) from Jingpo Lake in south Heilongjiang Province, northeast China, and used AMS radiocarbon dating of terrestrial plant macrofossils to provide a robust chronology. This study will focus on the sediments below 954 cm depth. Lithology, multi-proxy analyses and microbiological fossils data reveal rapid transition from fluvial to lacustrine sedimentary environment related to volcanic eruption events. Three stages of sedimentary environment change are documented: (i) Unite 1, fluvial sedimentary facies (below 1,232 cm, prior to ~5,120 cal. yr BP); (ii) Unite 2, transition sedimentary facies (between 1,232 and 1,154 cm, from ~5,120 to 5,060 cal. yr BP); (iii) Unite 3, lacustrine sedimentary facies (above 1,154 cm, after ~5,060 cal. yr BP). Our results suggest that Unite 1 represents fluvial sedimentary facies, while the lacustrine sedimentary facies developed afterwards. Between 1,250 and 1,240 cm intervals, the highest MS values and high amounts of charcoal could be the result of the Jingpo volcanoes eruption at ~5,135 cal. yr BP. During and after the volcanic eruptions, the lava flows descending along lowland areas and valleys may block many river valleys and eventually dammed the Mudanjiang River and created Jingpo Lake. Therefore, the core JP-C provides clear evidence that the Jingpo Lake was gradually formed

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after the Holocene volcanic eruption of Jingpo volcanoes (after  $\sim 5,135$  cal. yr BP). The stabilization of the lacustrine sedimentary environment had formed after  $\sim 5,065$  cal. yr BP.

**Keywords** Jingpo Lake • Lava-dammed lakes • Volcanic eruptions • Sedimentary facies transition

## 7.1 Introduction

Lakes are normally formed under various geological and geographical backgrounds. As an important component of the terrestrial hydrosphere, lakes have close links with the atmosphere, biosphere and lithosphere. Lake evolutionary processes usually involve geological, physical, chemical and biological processes, and these processes are all documented by lacustrine sediment archives (Shen 2013). Therefore, lacustrine sediment generally possesses a continuous record with high-resolutions that provides abundant information can be used to track past climatic and environmental changes (Last and Smol 2001). Volcanic eruptions are among the most effective agents of geomorphic change on Earth in terms of geologically instantaneous debris production (Korup and Clague 2009). During and after the volcanic eruptions, magma can erupt to the surface and form lava flows. The lava flows rapidly descending along lowland areas and valleys may dammed the confluences of tributary streams, and form lava-dammed lakes (Rodolfo and Umbal 2008). The sudden drainage of naturally lava-dammed lakes has caused some of the largest floods on Earth, potentially resulting in severe loss of lives and property (O'Connor and Costa 2004). Therefore, systematic study of the lava-dammed lakes histories, particularly the formation age and evolutionary processes, is essential to understanding the occurrence of natural disasters, and consequently, in developing and applying adequate strategies for prevention and mitigation of natural disasters and loss of life and property (Alcántara-Ayala 2002).

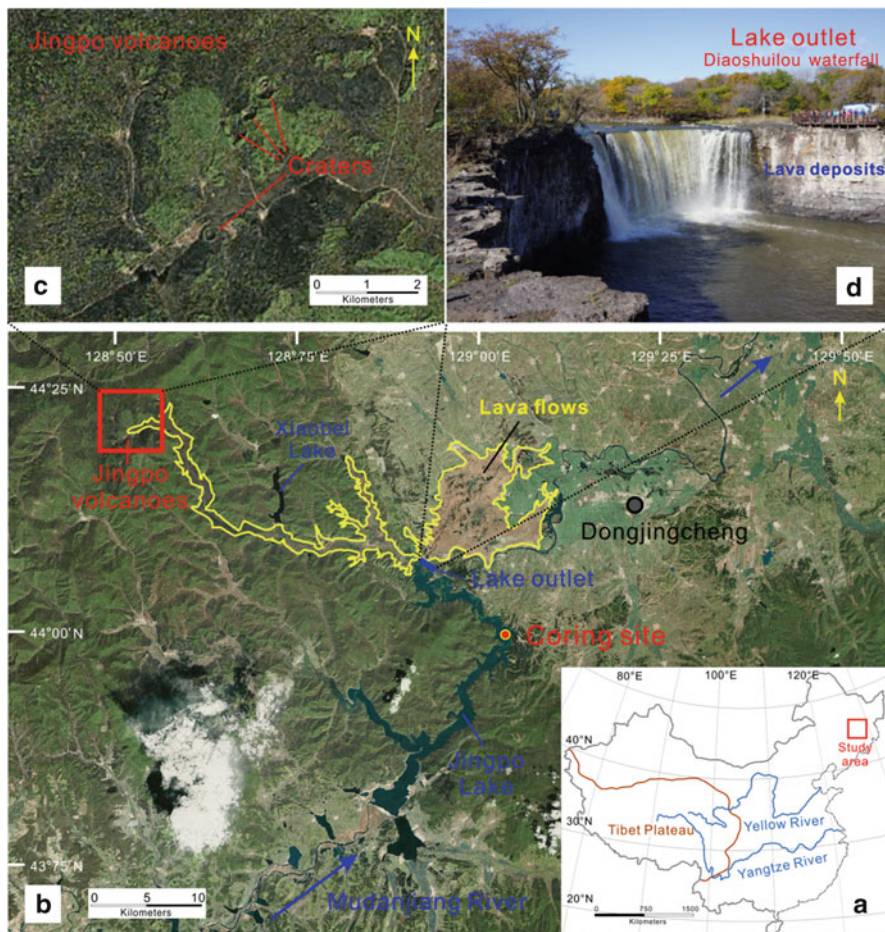
The Jingpo volcanoes ( $44^{\circ}08' - 44^{\circ}14'N$ ,  $128^{\circ}29' - 128^{\circ}34'E$ ,  $\sim 1,000$  m above sea level) is located in the Zhanguangcai Mountains, Southeastern Heilongjiang Province, NE China, which is an important component of the circum-Pacific volcanic belt. The Jingpo volcanoes is situated in the eastern part of the east-west trending Central Asian Orogenic Belt (CAOB) and in the western part of the Dunhua-Mishan Fault (Davis and Marc 2001; Buchan et al. 2002; Yan and Zhao 2008). The Jingpo volcanoes are in front of the currently active Pacific slab, which is subducted beneath Eurasia (Chuvashova et al. 2007). According to K-Ar analysis,  $^{14}C$  dating and thermoluminescence dating results, volcanic activity in this area occurred in four stages: Paleocene-Eocene; Late Miocene; Pleistocene; and Holocene. More than ten craters were created during a series of fissure eruptions between 5,500 and 5,200 yr BP when basaltic glass was formed on the surface of the lava (Fan et al. 2003, 2005; Chuvashova et al. 2007; Jia et al. 2013). During this time lava flowed over  $300 \text{ km}^2$  forming an extensive basaltic plain (Fig. 7.1) (Jia et al. 2013). This large amount of lava flows filled many small river valleys and

formed numerous long distance lava tubes. The lava flows eventually blocked the Mudanjiang River and created Jingpo Lake (Fan et al. 2003; Yan and Zhao 2008; Jia et al. 2013). However, the formation age of Jingpo Lake and associated volcanic eruption events are poorly understood and still under controversy, and clues regarding them are urgently needed. Based on volcanic activity, a number of studies have suggested that Jingpo Lake formed about 10 ka BP (Wang and Dou 1998; Li et al. 2011). According to  $^{14}\text{C}$  dating of carbonized wood and charcoal samples, however, some other scholars suggested that Jingpo Lake formed about 5,500–4,400 yr BP (Zhang et al. 2002; Fan et al. 2003, 2005; Chuvashova et al. 2007; Jia et al. 2013). According to fluvial/lacustrine sedimentary facies transition, we can conclude that the formation age of Jingpo Lake. Therefore, in this study, we present a multi-proxy analyses results with robust chronologies (AMS  $^{14}\text{C}$  ages obtained from terrestrial plant leaves and charcoal) of a sedimentary sequence derived from Jingpo Lake. Lithology, grain size, magnetic susceptibility, geochemistry, pollen concentration, and diatom concentration were studied for their ability to explore the formation age of Jingpo Lake and the directly related to the timing of volcanic events.

## 7.2 Regional Setting

The Jingpo Lake ( $43^{\circ}46'-44^{\circ}03'\text{N}$ ,  $128^{\circ}27'-129^{\circ}03'\text{E}$ ,  $\sim 350$  m above sea level) is located in Ning'an County, Southeastern Heilongjiang Province, NE China (Fig. 7.1). It is the China's largest lava-dammed lake and formed by lava damming of the Mudanjiang River. The lake has a surface area of  $\sim 92$  km<sup>2</sup>, with a maximum water depth of 48 m and an average depth of 12.9 m. The length of Jingpo Lake from north to south is  $\sim 45$  km, and the widest distance from east to west is only  $\sim 6$  km (Wang and Dou 1998). Jingpo Lake is mainly fed by surface run-off and precipitation. There are around 30 rivers flowing into the Jingpo Lake; most of these rivers drain into the south part of lake, and the lake water outflows from the northwest to the Mudanjiang River. The south part of the lake is shallow and the deepest part in the northern part of the lake. Jingpo Lake is surrounded by low mountains, topography of the catchment is dominated by hilly plains with a small relative elevation, and with the major rock types include granite, alkali olivine basalts, basanites and tephrites (Zhang et al. 2002).

This region is dominated by the East Asian Monsoon system which shows a strong seasonal variability. The mean annual precipitation (include snowfall) at nearby Ning'an meteorological station is  $\sim 545$  mm for the period 1951–2012. Most of the precipitation falls as rain during the summer and autumn months (May–September), which supplies  $\sim 81$  % of the annual precipitation, and with the peak precipitation of  $\sim 123$  mm in August. The mean annual temperature is  $\sim 4.3$  °C with a maximum monthly mean of  $\sim 22.1$  °C in July and a minimum of  $-17.7$  °C in January. The present-day terrestrial vegetation in the Jingpo Lake catchment belongs to the temperate mixed-forest flora of Changbai Mountain, comprised of evergreen conifers and deciduous broadleaved trees (Qian et al. 2003). The native vegetation is characterized by a *Pinus koraiensis* mixed conifer and broadleaved forest zone, which now deteriorates to secondary broadleaved forest (Li et al. 2011).



**Fig. 7.1** (a) The location of Jingpo Lake within the Heilongjiang Province. The *red square* denotes the location of our study area. (b) Topographic map of Jingpo Lake catchment and the sediment core sampling sites. The *blue arrow* indicate the direction of the Mudanjiang River, the *red square* denotes the Jingpo volcanoes area. (c) Topographic map of Jingpo volcanoes area. (d) A photo of the Diaoshuilou waterfall, outlet of Jingpo Lake

## 7.3 Materials and Methods

### 7.3.1 Coring and Dating Methods

In August 2012, a 1,302-cm-long sediment core (JP-C) was recovered from a water depth of 30.9 m in the northeastern part of Jingpo Lake (43°59'N, 129°02'E) (Fig. 7.1b), using Austria UWITEC™ piston coring system with PVC tubes in 2.0 m length and 60 mm diameter. The sediment cores were placed in polyvinyl

chloride tubes and transported to the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. Overlaps between the core sections were identified using scanned magnetic susceptibility data, resulting in a 1,272 cm continuous sediment record. This study will focus on the sediments below 954 cm depth. Prior to laboratory analysis, the core was sub-sampled at 2 cm intervals, and the samples were freeze-dried and kept in cold storage at 4 °C.

Ten samples of terrestrial plant macrofossils were handpicked for accelerator mass spectrometry (AMS)  $^{14}\text{C}$  dating, which can minimize the carbon reservoir effects (or old carbon effects) that commonly occur in lacustrine sediments. These samples were dated at the Laboratory of Beta Analytic Inc., Florida of the USA. All AMS  $^{14}\text{C}$  dates were calibrated into calendar years before present (0 cal. yr BP = 1950 AD) using the program Calib 6.0 utilizing the IntCal 09 calibration dataset (Reimer et al. 2009).

### 7.3.2 Analytical Methods

For grain size analyses, 0.5 g wet sediment samples were pretreated with 10–20 ml of 30 %  $\text{H}_2\text{O}_2$  to remove organic matter, washed with 10 % HCl to remove carbonate, rinsed with deionized water, and then treated with 20 ml of 0.05 M  $(\text{NaPO}_3)_6$  on an ultrasonic vibrator for 10 min to facilitate dispersion. Grain size distributions between 0.02 and 2,000  $\mu\text{m}$  were determined using a Malvern Mastersizer 2000 analyzer. Magnetic susceptibility was analyzed using a Bartington Ltd MS2 Magnetic Susceptibility Meter linked to an MS2B Dual Frequency Sensor (470 and 4,700 Hz). Total organic carbon content (TOC) and total nitrogen content (TN) were measured using a CE Model 440 Elemental Analyzer after removing carbonates with 10 % HCl. Replicate analyses of well mixed samples showed that precision was ca.  $\pm <0.1\%$  (1 SD). C/N values were derived from these data. All these methods were analyzed at 4-cm intervals.

Pollen samples were taken at 10–20 cm intervals. Each sample was treated with 10 % HCl, 10 % KOH, HF and a hot acetolysis mixture, in accordance with the standard methods (Faegri et al. 1989). Lycopodium spores with known numbers were added to each sample in order to facilitate the calculation of pollen concentrations before the chemical treatment. Diatom samples were analyzed at 4-cm intervals. 0.5 g wet sediment for each sample was treated using standard procedures with 10 % HCl and 30 %  $\text{H}_2\text{O}_2$  (Battarbee et al. 2001). Four replicate subsamples are potentially available from each sample. Diatom valves were enumerated on each of two prepared slides from each sample, resulting in two replicate abundance estimates. At least 300 valves were counted per sample and taxon abundances expressed as percentage of total count. Counts were made using an Olympus microscope (BX 51) with oil immersion objective (magnification  $\times 1,000$ ).

All these multi-proxy analyses were performed in the State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences.

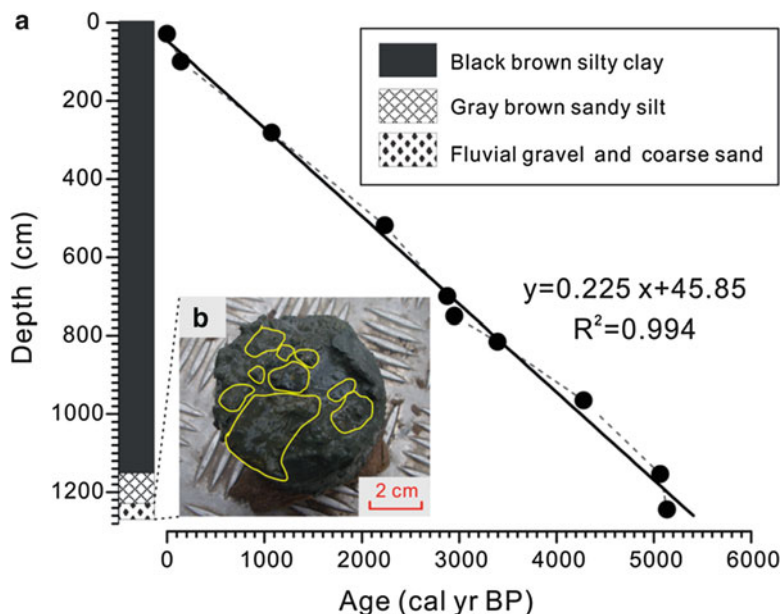


## 7.4 Results and Discussion

### 7.4.1 Lithology and Chronology

The lithology of the core JP-C is mainly composed of silty clay and/or clayey silt, except for the coarse sand and fluvial gravel emerging at the deepest part of the core (Fig. 7.2). The core can be subdivided into three major sedimentological units (Fig. 7.2): the lower unit (below 1,232 cm) consists of yellowish-brown coarse sand and fluvial gravel, the middle unit (1,232–1,154 cm) consists of gray brown sandy silt, and the upper unit (above 1,154 cm) consists of black brown silty clay and dark brown clayey silt.

The results of the ten AMS  $^{14}\text{C}$  ages of the core JP-C are presented in Table 7.1 and Fig. 7.2. Terrestrial plant macrofossils (such as leaves and charcoal) from lake sediments for AMS  $^{14}\text{C}$  ages can yield reliable radiocarbon dates. Therefore, the age–depth model was established by linear interpolation between each pair of the mid-points of the 2-sigma calibrated age range. The basal age of the core is  $\sim 5,150$  cal. yr BP, and the age–depth model shows a linear relationship ( $R^2 = 0.994$ ). The sediment accumulation rate (SAR) of the 954–1,154 cm interval is 0.24 cm/year, below 1,154 cm depth the SAR is 1.32 cm/year.



**Fig. 7.2** (a) Sediment lithology and age–depth model of the sediment core JP-C from Jingpo Lake. (b) A fieldwork photo showing the sediment bottom of the JP-C core, *yellow line* indicates the fluvial gravel

**Table 7.1** Conventional and calibrated AMS  $^{14}\text{C}$  radiocarbon dates for JP-C core from Jingpo Lake, Heilongjiang Province, NE China

Lab number	Sample name	Core depth (cm)	Dated material	Age ( $^{14}\text{C}$ yr BP $\pm 1\sigma$ )	$^{13}\text{C}/^{12}\text{C}$ ‰	Calibrated age (cal. yr BP) $2\sigma$ ranges	Median age (cal. yr BP)
Beta-330281	JPP-1	28.5	Leaf fragment	Modern carbon	NA	Modern carbon	Modern
Beta-330291	JPP-11	100	Leaf fragment	110 $\pm$ 30	-29.8	10-270	140
Beta-330282	JPP-2	282	Leaf fragment	1,150 $\pm$ 30	-26.8	980-1,170	1,075
Beta-330283	JPP-3	519	Leaf fragment	2,210 $\pm$ 30	-27.0	2,140-2,330	2,235
Beta-330285	JPP-5	700	Leaf fragment	2,790 $\pm$ 30	-25.4	2,800-2,960	2,880
Beta-330286	JPP-6	750	Leaf fragment	2,830 $\pm$ 30	-27.2	2,860-3,040	2,950
Beta-330287	JPP-7	815	Leaf fragment	3,160 $\pm$ 30	-27.6	3,350-3,440	3,395
Beta-330289	JPP-9	965	Leaf fragment	3,850 $\pm$ 30	-27.1	4,150-4,410	4,280
Beta-330290	JPP-10	1,154	Leaf fragment	4,420 $\pm$ 30	-28.0	4,870-5,260	5,065
Beta-330295	JPP-12	1,244	Charcoal	4,470 $\pm$ 30	-25.8	4,970-5,300	5,135

### 7.4.2 *Proxy Interpretations*

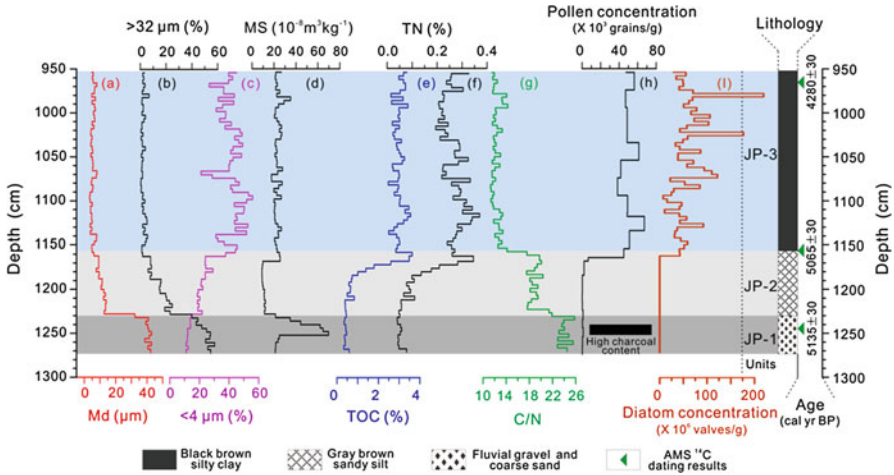
The grain size composition variability in lacustrine sediment core can indicate the changes of the sedimentary environment (Lambiasi 1980) related to hydrologic energy variations, such as transport capacity (Hakanson and Jansson 1983; Liu et al. 2008) and lake levels (An et al. 2012). But if the source of the sediments does significant change, the grain-size can give information about changes in the hydrodynamics of inflowing streams, changes in the internal hydrodynamics, and external factors affecting the catchment erosion (Sun et al. 2002). The magnetic susceptibility of sediments has been used as an indicator of the relative proportion of terrestrial magnetic minerals in the sediments (Thompson and Oldfield 1986).

The type and amount of lacustrine sedimentary organic matter (OM) reflects past fluctuations in lake productivity and terrestrial inputs linked to climate-induced environmental changes, catchment-related processes and lake internal changes (Meyers 1997; Meyers and Lallier-vergés 1999; Talbot and Lærdal 2000; Meyers and Teranes 2001; Leng and Marshall 2004; Leng et al. 2006; Cook et al. 2012). In general, the amount of organic matter in lake sediments is a function of changes in organic production in the lake, catchment vegetation changes and transfer of terrestrial particulate and dissolved organic matter to the lake, loss processes, and dilution effects (by varying inorganic inputs) (Meyers and Lallier-vergés 1999; Meyers and Teranes 2001; Cook et al. 2012). The two known major sources of organic matter (OM) in lake sediments are autochthonous, i.e. aquatic plants living in the lake water column, and allochthonous, i.e. terrestrial plants growing in the catchment (Meyers and Lallier-vergés 1999; Meyers and Teranes 2001). The C/N ratios has been used to distinguish these two source of sedimentary OM (i.e., whether primarily derived from terrestrial or aquatic sources), owing to the distinguishing characteristics of aquatic and vascular plants (Meyers and Lallier-vergés 1999; Talbot and Lærdal 2000; Meyers and Teranes 2001; Leng et al. 2006). Since aquatic OM is relatively enriched in nitrogen rich proteins, and vascular plant OM is relatively enriched in nitrogen depleted lignin and cellulose, the ratio of carbon to nitrogen is much lower in aquatic OM than in OM of terrestrial origin. Therefore, aquatic OM source has C/N ratios less than 10, while C/N ratios in terrestrial plants are commonly higher than 20 (Meyers and Lallier-vergés 1999; Talbot and Lærdal 2000; Meyers and Teranes 2001; Leng et al. 2006). C/N ratios between 10 and 20 typically indicate a mix of aquatic and terrestrial organic matter (Meyers 1997; Meyers and Lallier-vergés 1999; Talbot and Lærdal 2000; Meyers and Teranes 2001; Leng and Marshall 2004; Leng et al. 2006; Cook et al. 2012).

### 7.4.3 *The Formation Age of the Jingpo Lake*

The core JP-C was divided into three major sedimentary units according to multi-proxy analyses results of grain size (Fig. 7.3a-c), magnetic susceptibility (MS) (Fig. 7.3d), TOC (Fig. 7.3e), TN (Fig. 7.3f), C/N (Fig. 7.3g), pollen concentration (Fig. 7.3h) and diatom concentration (Fig. 7.3i).





**Fig. 7.3** Results of the core JP-C in Jingpo Lake: (a) median grain size, (b) the contents of grain size >32 μm, (c) the contents of grain size <4 μm, (d) magnetic susceptibility, (e) TOC content, (f) TN content, (g) C/N ratios, (h) pollen concentration, (i) diatom concentration. *Black bar* indicate high charcoal content layer, and *green solid triangles* represent terrestrial plant macrofossils AMS <sup>14</sup>C ages

### 7.4.3.1 Fluvial Sedimentary Facies (Unit JP-1, 1,272–1,232 cm)

Unit JP-1 (1,272–1,232 cm; ~5,150–5,120 cal. yr BP). This unit is characterized by the highest contents of grain size >32 μm (ranging from 40.0 to 57.6 %, mean of 50.0 %) and the median grain size (Md) values (ranging from 32.3 to 42.9 μm, mean of 40.2 μm) for the entire core, and the lowest contents of grain size <4 μm (ranging from 11.0 to 14.8 %, mean of 12.6 %). An important feature of this unit is the highest MS values with large fluctuations, and range from 21.2 to 69.7 × 10<sup>-8</sup> m<sup>3</sup> kg<sup>-1</sup>, with an average value of 37.3 × 10<sup>-8</sup> m<sup>3</sup> kg<sup>-1</sup>. TOC and TN results exhibit broadly similar changes for the entire core. In this unit, TOC and TN values vary between 0.86 and 1.64 % (mean of 1.04 %) and between 0.04 and 0.08 % (mean of 0.05 %), respectively. The C/N ratios range from 21.9 to 25.6 with a mean ratio of 23.9. Almost no pollen grains and diatom valves were found in this unit.

The base of the core JP-C (Unit JP-1) is distinctly different from the remainder of the sediment core. This unit is composed mostly of fluvial gravel and coarse sand. The coarse, angular and poorly sorted gravel and coarse sand at the very bottom of the core is of fluvial origin (Fig. 7.2b), that require a high energy transported by the Mudanjiang River to the coring site at Jingpo Lake formed before. The fluvial sedimentary environment is not conducive to the organic matter growth and accumulation and microbiological fossils sedimentation and preservation, therefore, the extremely low TOC, TN, pollen concentration, and diatom concentration observed in this unit (Fig. 7.3). The C/N ratios are greater than 21 in this unit

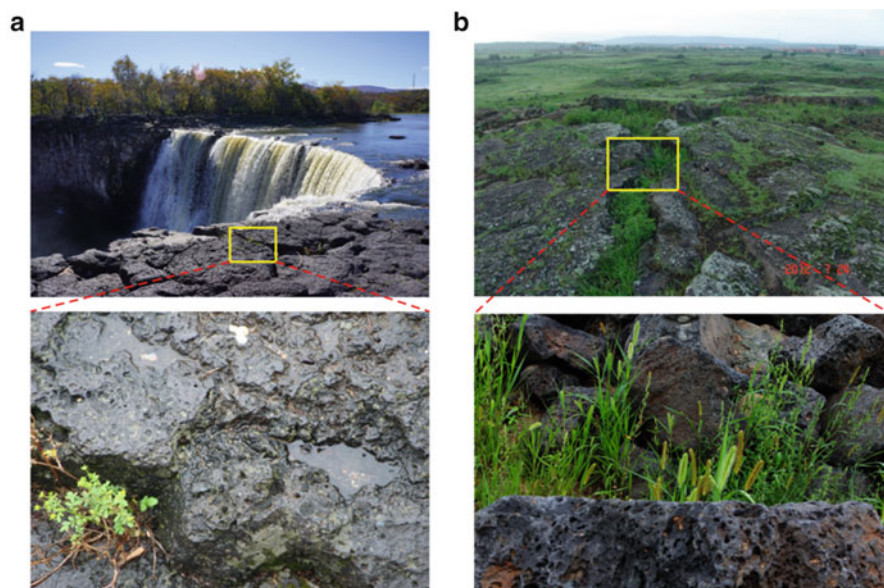
(Fig. 7.3g), indicate that the organic matter is derived from terrestrial plant sources. Altogether, we suggest that this unit represents fluvial sedimentary facies period.

Notably, a significant high MS values and charcoal contents were observed between 1,250 and 1,240 cm intervals (Fig. 7.3). When volcanic activity occurs, the physical and chemical characteristics of sediments will change significantly. During and after the Jingpo volcanoes eruption, large number of vegetation was burning by the blazing lava, which produces large amounts of charcoal. In the meantime, the fall tephra was contains large amounts of Fe and other metal elements (Zhang et al. 2002; Fan et al. 2003, 2005). Therefore, between 1,250 and 1,240 cm intervals, the highest MS values and high amounts of charcoal could be the result of the Jingpo volcanoes eruption at  $\sim 5,135$  cal. yr BP (Fig. 7.3). Our result is consistent with the volcanic eruption of Jingpo volcanoes had been occurred between 5,500 and 5,200 cal. yr BP, based on measured section of air fall clastic rock and  $^{14}\text{C}$  dating of carbonized wood and charcoal samples (Fan et al. 2003, 2005; Chuvashova et al. 2007; Jia et al. 2013).

#### 7.4.3.2 Transition Sedimentary Facies (Unit JP-2, 1,232–1,154 cm)

Unit JP-2 (1,232–1,154 cm;  $\sim 5,120$ – $5,060$  cal. yr BP). This unit is characterized by an abrupt and simultaneous increase in TOC and TN values. TOC ranging from 0.87 to 5.85 % with an average value of 2.27 % and TN ranging from 0.05 to 0.35 % with an average value of 0.15 %, C/N ratios are stable at  $\sim 18$  (ranging from 12.6 to 21.4, mean of 18.3). The MS values fluctuate between  $9.1$  and  $25.0 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$  with a mean of  $12.6 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ . Md values (ranging from 4.7 to 14.0  $\mu\text{m}$ , mean of 10.3  $\mu\text{m}$ ) and the contents of grain size  $>32 \mu\text{m}$  (ranging from 1.3 to 24.7 %, mean of 12.8 %) exhibited rapid decreasing trends in this unit, concurrently, the contents of grain size  $<4 \mu\text{m}$  increased significantly (ranging from 18.9 to 45.4 %, mean of 25.2 %). At the end of this unit, the concentration of pollen and diatom increase significantly.

During and after the Jingpo volcanoes eruption, the large amount of lava flows rapidly enter lowland areas and valleys beyond the volcanoes where they may temporarily or permanently alter the valley bottom topography and disrupt the hydrologic regime of streams and rivers, and eventually dammed the Mudanjiang River and created Jingpo Lake (Fig. 7.4). Then the Jingpo Lake formed, almost all proxies show strong fluctuations, indicating a high variability in the sedimentary environment in this stage. The grain size component of  $>32 \mu\text{m}$  is decreasing and that of  $<4 \mu\text{m}$  is increasing since the beginning of this unit, suggesting a decreasing transport capacity and a rising river or lake levels. In addition, the gradually increase in TOC and TN values and the rapid increase in concentration of pollen and diatom at the end of this unit indicate that intense to weaker water dynamic depositional environment conducive to the accumulation and preservation of organic matter and microbiological fossils (Fig. 7.3). The decreasing C/N ratios (Fig. 7.3g), showing an increasing fraction of autochthonous organic matter, suggest that the plant organic matter in this unit is derived from a mixture of sources, especially algae and aquatic



**Fig. 7.4** (a) A photo of the Diaoshuilou waterfall, outlet of Jingpo Lake, the *yellow square* denotes the volcanic rock. (b) A fieldwork photo showing the basaltic plain formed by lava flows at  $\sim 1$  km north of Jingpo Lake, the *yellow square* indicates the basalt

vegetation and only a small contribution from terrestrial vegetation. In summary, the onset of Jingpo Lake formation (as indicated by the rapid deposition of clays, decrease in sands, and increase in TOC, TN, pollen, and diatom concentrations) occurred soon after the Jingpo volcanoes eruption ( $\sim 5,135$  cal. yr BP).

#### 7.4.3.3 Lacustrine Sedimentary Facies (Unit JP-3, 1,154–954 cm)

Unit JP-3 (1,154–954 cm;  $\sim 5,060$ – $4,230$  cal. yr BP). The characteristic feature of this unit is the lowest Md values (ranging from  $3.4$  to  $8.1$   $\mu\text{m}$ , mean of  $5.4$   $\mu\text{m}$ ) and the contents of grain size  $>32$   $\mu\text{m}$  (ranging from  $0.4$  to  $6.8$  %, mean of  $2.3$  %), but the highest contents of grain size  $<4$   $\mu\text{m}$  (ranging from  $21.0$  to  $55.9$  %, mean of  $47.1$  %). TOC and TN increased to their highest values (ranging from  $2.08$  to  $4.24$  % and  $0.20$  to  $0.37$  %, mean of  $2.80$  and  $0.27$  %, respectively), while the C/N ratios decreased to their lowest values (ranging from  $11.4$  to  $14.1$ , mean of  $12.3$ ). The MS values are relatively high, and ranging from  $17.7$  to  $35.2 \times 10^{-8}$   $\text{m}^3 \text{kg}^{-1}$ , with an average value of  $23.0 \times 10^{-8}$   $\text{m}^3 \text{kg}^{-1}$ . The most striking feature of this unit is that the both pollen concentration and diatom concentration increase significantly and reaches their maximum values, averaging up to  $50.4 \times 10^3$  grains  $\text{g}^{-1}$  and  $60.1 \times 10^6$  valves  $\text{g}^{-1}$ , respectively.

A stable lake system had formed during this unit, as indicated by the typical homogeneous lacustrine sediment characteristic. The highest contents of grain size  $<4\ \mu\text{m}$  and the lowest contents of grain size  $>32\ \mu\text{m}$  and Md values (Fig. 7.3) suggest the stable lake sedimentary environment in this period (low transport capacity). The relatively stable C/N ratios, less than 13 for most of the investigated period in JP-C (Fig. 7.3g), suggest that the organic matter is mainly from autochthonous sources. Moreover, the highest average values of TOC and TN indicate that lake sedimentary environment conducive to the organic matter growth, accumulation and preservation. In addition, the highest concentrations of pollen and diatom (Fig. 7.3) also suggest the stable lacustrine sedimentary environment (weaker water dynamic condition), because of lake environment conducive to the pollen preservation and algae (include diatom) accumulation and preservation. In general, the stabilization of the lacustrine sedimentary facies indicate that the Jingpo Lake eventually formed after  $\sim 5,065$  cal. yr BP.

## 7.5 Conclusion

The Jingpo Lake is the China's largest lava-dammed lake and formed by lava damming of the Mudanjiang River, however, the formation age of Jingpo Lake and associated volcanic eruption events are poorly understood and still under controversy. In this study, we obtained a 12.72-m-long sediment core (JP-C) from Jingpo Lake (lava-dammed lake) in south Heilongjiang Province, northeast China, and used AMS radiocarbon dating of terrestrial plant macrofossils to provide a robust chronology. This study will focus on the sediments below 954 cm depth. Lithology and multi-proxy analyses results indicate that the core JP-C can be subdivided into three major sedimentological units: (i) Unite 1, fluvial sedimentary facies (below 1,232 cm, prior to  $\sim 5,120$  cal. yr BP); (ii) Unite 2, transition sedimentary facies (between 1,232 and 1,154 cm, from  $\sim 5,120$  to 5,060 cal. yr BP); (iii) Unite 3, lacustrine sedimentary facies (above 1,154 cm, after  $\sim 5,060$  cal. yr BP). Therefore, the core will provide an opportunity to determine the formation age of Jingpo Lake and the directly related to the timing of volcanic eruption events. Lithology and analyses results suggest that Unite 1 represents fluvial sedimentary facies, while the lacustrine sedimentary facies developed afterwards. Between 1,250 and 1,240 cm intervals, the highest MS values and high amounts of charcoal could be the result of the Jingpo volcanoes eruption at  $\sim 5,135$  cal. yr BP. This volcanic eruption is consistent with the Holocene volcanic eruption of Jingpo volcanoes had been occurred between 5,500 and 5,200 cal. yr BP. During and after the volcanic eruptions, the lava flows descending along lowland areas and valleys may block many river valleys and eventually dammed the Mudanjiang River and created Jingpo Lake. Therefore, the core JP-C provides clear evidence that the Jingpo Lake was gradually formed after the Holocene volcanic eruption of Jingpo volcanoes (after  $\sim 5,135$  cal. yr BP). The stabilization of the lacustrine sedimentary facies had

formed after the beginning of the Unite 3 was reflected by the typical homogeneous lacustrine sediment characteristic and multi-proxy analyses data. Namely, our data indicate that the Jingpo Lake eventually formed after  $\sim 5,065$  cal. yr BP.

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