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The significance of maar volcanoes for palaeoclimatic studies in China

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A B S T R A C T

The sediments of maar lakes often provide paleoenvironmental records which are highly suitable for palaeoclimatic studies. The main advantages of the records from maar lakes compared with other lacustrine records are as follows: First, the presence of varves (annually laminated layers) and tephra layers, as well as other materials (like terrestrial plant macrofossils, charcoals, organic carbon, organic shells) suitable for isotopic dating (like AMS ^{14}C, ^{210}Pb, ^{137}Cs, $^{238}U/^{230}Th$, $^{40}Ar/^{39}Ar$), provides the possibility of developing several independent chronologies, enabling the development of robust, high-resolution chronologies. Second, maars and maar lakes can provide continuous sedimentary records spanning tens of thousands of years (Tianyang Maar in China is hosted the longest known record spanning at least 400 kyr BP) that are ideal for the investigation of climate change on different timescales, including orbital, millennial-centennial and annual-decadal. Third, recent studies of biomarkers based on long-chain alkenones (LCAs) and glycerol dialkyl glycerol tetraethers (GDGTs) have demonstrated the potential of maar lakes for quantitative paleotemperature reconstruction. In this study, we review some of the more significant achievements of palaeoclimatic research based on maar lake sediment sequences from China, with the focus on chronology, multiple timescales and quantitative paleoclimatic reconstruction.

Contents

1. Introduction

Maar-diatreme volcanoes are small volume monogenetic but commonly complex volcanoes formed in a relatively short time through phreatomagmatic explosive eruptions resulted and excavated and collapsed crater – the maar – cut into the *syn*-eruptive surface (Lorenz,

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1986; White and Ross, 2011; Németh and Kereszturi, 2015). The exact process behind the formation of the maar crater is under focused research in the last decade resulting two distinct endmember of explosive origin; (i) incremental growth of the crater vs. (ii) gradual growth by multi-explosive processes in near surface areas (White and Ross, 2011; Valentine et al., 2017). After the formation of the maar crater, it become the ideal terrestrial closed sedimentary basin (Negendank and Zolitschka, 1993a) that has a small surface area and in comparison to that deep basin where following the tephra ring erosion, quite long-lasting lacustrine sedimentation can take place (Pirrung et al., 2003).

Maar-diatreme structures can host climate-sensitive lakes in which long and continuous sedimentary sequences can accumulate. This is one of the reasons for the rapid increase of studies on maar-diatreme volcanoes (Creer, 1996; Creer and Morris, 1996; Marchetto et al., 2015; Turner, 1998; Sirocko, 2016; Zolitschka et al., 2000, 2013). Maar lakes are now widely acknowledged to be of great significance in the research field of palaeoclimatic change research on the continents. In the past decade intensive paleclimatic researches were conducted also in the southern hemisphere including maars in Argentina (e.g. Zolitschka et al., 2013) and New Zealand (e.g. Augustinus, 2007).

Palaeoclimatic research is a major topic in earth science. In recent decades, studies of deep-sea sediments, and ice and loess deposits have demonstrated the occurrence of orbitally-forced climatic cycles on multi-millennial timescales, which have confirmed that orbital forcing is a major driver of large-scale changes in earth's climate and environment (Berger, 1988). Later research revealed that the climate system also exhibits higher-frequency changes and abrupt events on various timescales, ranging from millennial to annual (Bond et al., 1997). A major objective of global change research is to forecast future trends in climate, especially over the next few decades, and to achieve these goals, palaeoclimatic records should be of interdecadal to annual resolution. The longest global observed temperature records only span the last ~150 years (Brohan et al., 2006), and therefore they are of limited usefulness for assessing climate changes on interdecadal or longer scales. This limitation hinders our understanding of the mechanisms behind both gradual and abrupt climate change, and consequently there in an ongoing search for continuous, long-duration, high resolution geological archives for which multi-proxy environmental indicators are available (Creer, 1996; Creer and Morris, 1996; Garcin et al., 2006; Augustinus et al., 2012; Zaarur et al., 2018). In this context, the sedimentary record of maar lakes, as a continental archive, make a significant contribution.

Maar lakes are formed by phreatomagmatic volcanic eruptions; they consist of a crater cut into the pre-eruptive ground, surrounded by an ejecta ring, underlain by a diatreme (Lorenz, 1973, 2003, 2007; Negendank and Zolitschka, 1993b; Liu et al., 1996; Valentine, 2012). Maar-diatreme structures can host climatically-sensitive lakes which preserve long and continuous sedimentary sequences, which is one of the main reasons for the rapid increase in the number of studies of maar-diatreme volcanoes (White and Ross, 2011; Zolitschka et al., 2000), and maar lakes are now widely acknowledged to be of high significance for palaeoclimatic research on continents. The major advantages of maar lakes for paleoenvironmental studies can be summarized as follows:

(i) Maar lakes generally do not have inflows and outflows and the water level is mainly controlled by groundwater influx (Büchel, 1993); thus, the hydrology and sedimentation processes of maar lakes are relatively simple to interpret in terms of climatic change, compared with lakes with more complex hydrological settings.
(ii) The size, original depth and shape of maar craters result in a relatively low surface area/depth ratio, which limits the effects of waves on the sedimentary record, providing suitable conditions for the preservation of annual laminations or varves (Graettinger, 2018).
(iii) The bottom waters of some deep maar lakes are hypoxic, which substantially limits the number and activity of benthic organisms; the resulting suppression of bioturbation also promotes the preservation of the protogenic structure of the sediment (Zolitschka et al., 2015).
(iv) The sediments of maar lakes provide a highly diverse and complementary suite of proxy climatic indicators. They include biological indicators such as pollen derived from the terrestrial vegetation, and numerous aquatic organisms such as diatoms, chrysophytes, chironomids, ostracods; and physical and chemical parameters such as magnetic properties, and the stable isotopes of oxygen and carbon (Marchetto et al., 2015). Cross-comparison of different indicators analyzed from the same sedimentary sequence enables robust and reliable multi-proxy-based palaeoclimate reconstructions to be produced.

In summary, maar lakes provide optimal conditions for the accumulation and preservation of high-resolution sedimentary records on continents, and these natural archives are of high value for multi-proxy studies of palaeoenvironmental and palaeoclimatic changes.

2. Study areas

Prior to the 1980s, Europe was the main study region for maars and pioneering research was carried out in the West-Eifel Volcanic Field, in northwest Germany (Ollier, 1967; Lorenz, 1975; Büchel and Lorenz, 1982; Negendank, 1984). At that time, research focused on the structure, formation and geology of maars rather than on their climatic records. In the late 1980s, the International Geosphere-Biosphere Programme (IGBP) advocated the search for more high-resolution terrestrial sedimentary records worldwide, and to this end various research agencies in Europe launched and funded a series of drilling programs, such as GEO-MAARS, EURO-MAARS, the European Lake Drilling Program (ELDP) and the ELSA Project (Eifel Laminated Sediment Archive) (Büchel, 1993; Creer, 1996; Sirocko et al., 2013; Sirocko, 2016). Consequently, research on maar lakes moved from Germany to Italy, and records from maar lakes in central and southern Italy provide continuous lacustrine sedimentary records back to at least 70 kyr BP (Creer and Morris, 1996). At the end of the 20th century, there was a global expansion of maar lake research, which extended the regions of study to central France and central Spain, and sporadic studies were also reported from Asia, Africa and Australia (Augustinus, 2012; Barker et al., 2003; D'Costa and Kershaw, 1995; Juvigné et al., 1993; Liu et al., 1996; Ortiz et al., 2013). In addition, the Laguna Potrok Aike Scientific Drilling Project (PASADO) was conducted in South America, in the southernmost tip of Argentina (Zolitschka et al., 2009). Locations and details of research projects on maar lakes are provided in Fig. 1 and Table 1. Numerous continuous sedimentary records from maar lakes have been obtained, with important findings in the fields of chronology (e.g. Brauer et al., 1999; Lane et al., 2013), sedimentology (e.g. Giguet-Covex et al., 2010; Chu et al., 2013), geochemistry (e.g. Parplies et al., 2008), micropaleontology (e.g. Kattel and Sirocko, 2011), and paleomagnetism (e.g. Creer and Morris, 1996) as the most common research focuses. Thus, maar lakes are exhibiting great potential for addressing significant questions about long-term terrestrial climatic change.

In China, research on maar lakes began in 1996 (Liu et al., 1996). The main study areas are the Leiqiong Volcanic Field in South China and the Longgang Volcanic Field in Northeast China (Fig. 2). The Leiqiong Volcanic Field is part of the epi-continental rift volcanic belt that crosses Leizhou Strait in Southern China (Fig. 2a). The volcanic field is characterized by a variety of basaltic volcanoes, typical lava flow structures and long lava tunnels (the longest one is longer than 12 km) (Tao, 2007). Volcanic activity began in the Oligocene and lasted through the Holocene. Early volcanism was dominated by quartz tholeiites and olivine

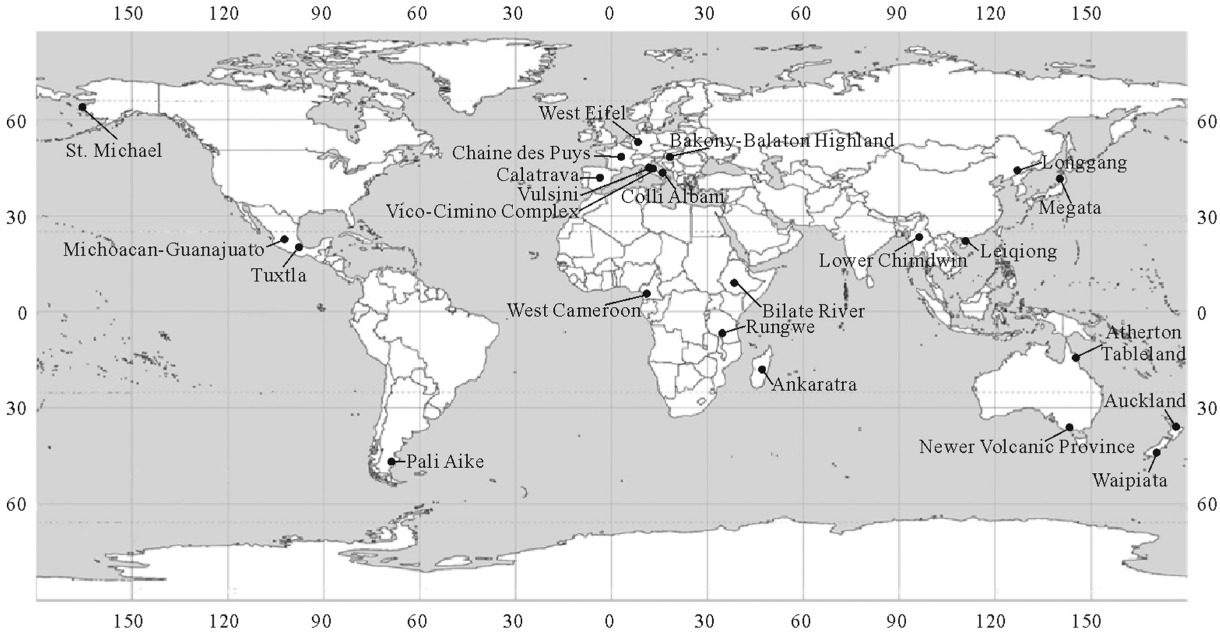

Fig. 1. Location of the maars and maar lakes with reported palaeoclimatic records.
(Modified from Liu et al., 2013).

tholeiites, and late volcanism was dominated by alkali olivine basalts and basanites (Huang et al., 2007). There are numerous maars located in this volcanic field: for example, Huguangyan (21°09′N, 110°17′E), Tianyang (20°31′N, 110°18′E), Jiudouyang (20°38′N, 110°02′E), Qingtongyang (20°34′N, 110°10′E), and Shuangchiling Maar (19°57′N, 110°11′E) (Hunag et al., 1993; Mingram et al., 2000; Fuhrmann et al., 2003; Yang et al., 2009). Most are dry maars, except for Huguangyan and Shuangchiling Maar Lake. Tianyang Maar is one of the largest craters in China, with a diameter of ~3000 m and a maximum depth of 223 m, and was formed by at least 400 kyr BP (Zheng and Guiot, 1999).

Longgang Volcanic Field located in southeastern Jilin province (Northeast China) has a length of 85 km from south to north, a width of 50 km from east to west, an area of about 4250 km^2, and an area covered by volcanic rocks of approximately 1700 km^2 (Fan et al., 1999, 2002). The basement is mainly composed of Pre-Cambrian basement rocks, such as Archean migmatitic gneiss, granite and leptynite in the Anshan group. The distribution of volcanoes generally follows alignments associated with major structural lineaments of the basement (NWW or near EW), always at the intersection of NE and EW, part of the East Asian continental rift system (Liu et al., 2009). Quaternary volcanic activity in Longgang Volcanic Field produced basaltic magmatic and phreatomagmatic eruptions, which formed at least 160 monogenetic volcanoes. Eight maar lakes (Sihailongwan, Donglongwan, Xiaolongwan, Sanjiaolongwan, Erlongwan, Donglongwan, Nanlongwan and Longquanlongwan) are located in this volcanic field (Fig. 2b). It is a key region for research on regional climate change controlled by the East Asian Monsoon. The tephra rings of these maars typically consists of pyroclastic beds of base surges, lava flows and scoria fall deposits (Fan et al., 1999, 2002).

After >20 years' research, studies of Chinese maars have progressed substantially, especially in the areas of geochronology, palaeoclimatology, and currently their volcanology. We now review progress in first two major research areas.

3. Chronology

A reliable chronology is a fundamental requirement for palaeoclimate studies and is the basis for local, regional and global correlation of climatic events and for determining phase relationships between signals. The presence of laminations in maar sediments provides the most robust chronological framework, providing the annual character of the laminations is confirmed (Zolitschka et al., 2015). If not, a reliable chronological framework can still be established based on isotope dating or tephrochronology.

3.1. Varve chronology

The term 'varve' is used to describe all types of annually laminated layers deposited in terrestrial and marine settings (De Geer, 1912; Zolitschka et al., 2015). The most significant aspect of a varve chronology for palaeoclimatic and paleoenvironmental research is that it provides precise dating for different temporal scales and for specific events, which can then be used as isochrones on a regional or global scale (Nakagawa et al., 2012; Zolitschka et al., 2015). Varves were first recognized and defined in glacial lake sediments from high latitude regions (De Geer, 1912), where there are pronounced seasonal variations in climatic and depositional processes which result in stronger contrasts than is the case for mid- and low latitude lakes. Despite the disadvantage of less pronounced seasonal changes in climate, maar lakes located in mid- and low latitude areas still provide favorable conditions (low surface area/depth ratio, deep water with a stratified water column and hypoxic bottom water) which facilitate the formation and preservation of varves. Thus, maar lake sediments with varves are considered among the most valuable environmental archives of past climatic changes in continental areas.

Different types of varve are recognized in maar lake sediments according to their composition, and there are three main types: clastic, biogenic and endogenic (Table 2). Among them, biogenic or clastic-biogenic varves have the widest distribution. Well-known examples of this type of varve occur in Lake Barrine in Australia (Walker, 2011; Walker and Owen, 1999), Lac Pavin and Lac du Bouchet in France (Giguet-Covex et al., 2010; Stebich et al., 2005), Lake Albano in Italy (Lami et al., 1994), and Holzmaar (Zolitschka, 1998) and Meerfelder Maar (Brauer et al., 1999; Lane et al., 2015; Martin-Puertas et al., 2017) in Germany. Calcareous (endogenic) varves occur in Lake Twintaung in Myanmar (Sun et al., 2016b), and Lake Hoya La Alberca and Lake Hoya Rincón de Paranguceo in Mexico (Kienel et al., 2009). Until now, the longest continuous absolute varve chronology established from a maar lake is that for Holzmaar in the West-Eifel Volcanic Field in Germany, which spans ~23,220 years (Zolitschka, 1998).

Table 1
Details of the maars and maar lakes referenced in the text.

Site	Latitude	Longitude	Volcanic field	Country	Interval of study (year BP)	Reference
Lake Holzmaar	50°07′N	6°53′E	West Eifel Volcanic Field	Germany	0–23,220	Zolitschka, 1998; Zolitschka et al., 2000
Lake Meerfelder Maar	50°06′N	6°45′E			0–12,700	Brauer et al., 1999
Lake Schalkenmehrener Maar	50°10′N	6°51′E			0–16,500	Kattel and Sirocko, 2011
Lake Ulmener Maar	50°13′N	6°59′E			0–10,895	Zolitschka et al., 1995; Sirocko et al., 2013
Eckfeld Maar	50°07′N	6°49′E			Eocene	Mingram, 1998
Alleret Maar	45°11′N	3°28′E	Chaine des Puys	France	550,000-725,000	Nomade et al., 2010
Lac Pavin	45°30′N	2°53′E			0–700	Stebich et al., 2005
Lake Albano	41°45′N	12°40′E	Coli Albani Complex	Italy	0–11,480	Ariztegui et al., 2001
Lagaccione Maar	42°34′N	11°51′E	Vulsini volcanic district		0–100,000	Magri, 1999
Lago di Mezzano	42°37′N	11°46′E			0–34,000	Ramrath et al., 1999, 2000
Lago Grande di Monticchio	40°56′N	15°36′E	Monte Vulture		0–75,000	Ramrath et al., 1999, 2000; Creer and Morris, 1996; Wulf et al., 2004
Lago di Vico	42°19′N	12°10′E	Vico-Cimino Complex		0–90,000	Frank, 1969; Narcisi, 2001
Pula Maar	46°59′N	17°36′E	Bakony-Balaton Highland Volcanic Field	Hungary	2,600,000–3000,000	Willis et al., 1999
Fuentillejo Maar	38°56′N	4°03′W	Calatrava Volcanic Field	Spain	0–220,000	Ortiz et al., 2013
Lake Tritrivakely	19°47′S	46°55′E	Ankaratra Volcanic Field	Madagascar	0–46,000	Williamson et al., 1998; Disnar et al., 2005
Lake Masoko	9°20′S	33°45′E	Rungwe Volcanic Field	Tanzania	0–50,000	Gibert et al., 2002; Barker et al., 2003; Garcin et al., 2006
Lake Tilo	7°04′N	38°06′E	Bilate River Field	Ethiopian	0–9000	Telford and Lamb, 1999; Lamb et al., 2000
Lake Barombi Mbo	4°40′N	9°24′E	West Cameroon Volcanic Field	Cameroon	0–25,000	Giresse et al., 1994
Laguna Potrok Aike	51°58′S	70°23′W	Pali-Aike Volcanic Field	Argentina	0–51,000	Kliem et al., 2013; Zolitschka et al., 2013
Lago Verde	18°37′N	95°21′W	Tuxtla Volcanic Field	Mexico	0–150	Ruiz-Fernández et al., 2007
Hoya San Nicolás	20°23′N	101°15′W	Michoacán-Guanajuato		0–11,600	Chaparro et al., 2008; Park et al., 2010
Hoya Rincón de Parangueo	20°26′N	101°15′W	Volcanic Field		0–9600	Kienel et al., 2009; Park et al., 2010;
Hoya La Alberca	20°23′N	101°12′W			−23–98	Kienel et al., 2009
Zagoskin Lake	63°27′N	162°6′W	St. Michael Volcanic Field	America	0–41,000	Muhs et al., 2003
Lake Terang	38°15′S	142°55′E	Newer Volcanics	Australia	25,000-75,000	D'Costa and Kershaw, 1995
Lake Keilambete	38°12′S	142°53′E	Province		−40-110	Jones et al., 2001; Wilkins et al., 2012
Lake Gnotuk	38°13′S	143°06′E			−40-110	Jones et al., 2001; Wilkins et al., 2012
Lake Bullenmerri	38°15′S	143°06′E			−40-110	Jones et al., 2001
Lake Barrine	17°15′S	145°38′E	Atherton Volcanic Province		0–9000	Dimitriadis and Cranston, 2001; Walker, 2007
Foulden Maar	45°32′S	170°13′E	Waipiata Volcanic Field	New Zealand	Oligocene-Miocene transition	Lindqvist and Lee, 2009
Onepoto Maar	36°48′S	174°45′E	Auckland Volcanic Field		7000–30,000	Augustinus et al., 2012; Sikes et al., 2013
Lake Pupuke	36°47′S	174°46′E			24,500-54,000	Nilsson et al., 2011
Lake Ichi-no-Megata	39°57′N	139°44′E	Megata Volcanic Group	Japan	0–31,000	Okuno et al., 2011
Lake Ni-no-Megata	39°57′N	139°43′E			0–2900	Yamada et al., 2010
Lake San-no-Megata	39°56′N	139°42′E			0–2250	Yamada et al., 2010
Lake Twintaung	22°22′N	95°02′E	Lower Chindwin Volcanic Field	Myanmar	0–530	Sun et al., 2016a, 2016b
Tianyang Maar	20°31′N	110°18′E	Leiqiong Volcanic Field	China	0–400,000	Zheng and Lei, 1999; Zheng and Guiot, 1999
Lake Hugangyan	21°09′N	110°17′E			0–78,000	Liu et al., 2000; Chu et al., 2002; Chu et al., 2017; Mingram et al., 2004b; Liu et al., 2005a; Wang et al., 2007, 2012; Yancheva et al., 2007; Wang et al., 2008, 2012; Hu et al., 2015, 2016
Lake Shuangchiling	19°57′N	110°11′E			0–9000	Yang et al., 2009
Lake Sihailongwan	42°17′N	126°36′E	Longgang Volcanic Field		0–16,700	Chu et al., 2000, 2005a, 2005b, 2011; Liu et al., 2005b; Schettler et al., 2006a, 2006b, 2006c; Parplies et al., 2008; Stebich et al., 2009, 2015
Lake Xiaolongwan	42°18′N	126°21′E			0–1600	Chu et al., 2008, 2009, 2013
Lake Erlongwan	42°18′N	126°21′E			0–13,000	You et al., 2008; You and Liu, 2012

Because of its high quality, the Holzmaar chronology is regarded as a standard stratigraphic sequence for the Late-glacial in Europe, which can be used to supplement or replace the chronologies derived from Greenland ice cores (Litt et al., 2001; Litt and Stebich, 1999). This illustrates the great potential of maar lakes in Europe in establishing highly robust varve chronologies.

In China, absolute varve chronologies have been established from maar lakes in Longgang Volcanic Field, Northeast China, such as Lake Sihailongwan, Erlongwan and Xiaolongwan, and their duration exceeds 14,000 years (Chu et al., 2009; Schettler et al., 2006b; You et al., 2008). In these three lakes, the varves are of the clastic-biogenic type. Based on the dominant types of algae contained in the sediments, the biogenic varves of Lake Sihailongwan can be classified into Chrysophyte and diatom-biogenic varves (Chu et al., 2005a); those of Lake Erlongwan into Dinocyst and diatom-biogenic varves (You et al., 2008); and those of Lake Xiaolongwan into Dinocyst and Chrysophyte-biogenic varves (Chu et al., 2009). Until now, they represent the only absolute varve chronologies in China that are older than 10 kyr BP.

3.2. Radioisotope dating

Radioisotopic dating methods are necessary for the establishment of a high-resolution chronology, even in maar lakes with varved sediments. Radiocarbon dating is the most widely used dating method for establishing chronologies for maar lake sediments. The bottom waters of maar lakes are typically depleted in dissolved oxygen, which favors the preservation of terrestrial plant remains in the sediments. The use of these terrestrial plant remains potentially avoids the ‘hard water’

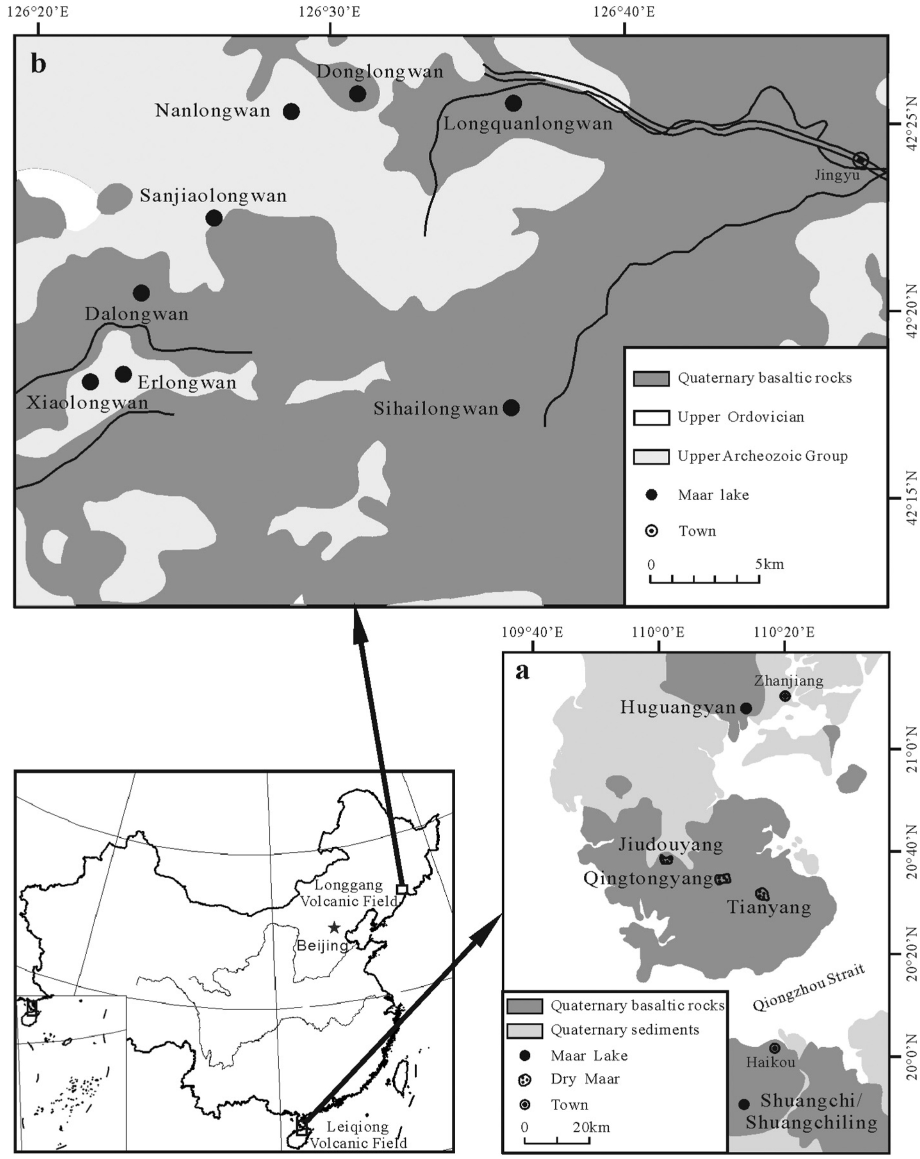

Fig. 2. Locations of maar volcanoes in China mentioned in text. a. Leiqiong Volcanic Field; b. Loanggang Volcanic Field.

and 'carbon reservoir' effects and maximizes the accuracy of radiocarbon dating (Sirocko et al., 2013). The use of accelerator mass spectrometry (AMS) radiocarbon dating considerably reduces the required minimum mass of the samples to be dated and allows the much wider application of the technique. Radiocarbon dating may be used as the primary method for establish chronologies, as at Fuentillejo maar lake in

Table 2
Details of the varve and other chronologies available for the maars and maar lakes referenced in the text.

Name of maar	Country	Type of chronology	Chronology	Varve type	Varve years	Reference
Holzmaar	Germany	Absolute	Varve, ^{14}C, optically stimulated luminescence, thermoluminescence, paleomagnetism, tephra	Various	23,220	Zolitschka, 1998; Zolitschka et al., 2000
Meerfelder Maar	Germany	Floating	Varve, ^{14}C, paleomagetism, tephra	Clastic-biogenic	12,700	Brauer et al., 1999; 2000
Lac Pavin	France	Absolute	Varve	Biogenic (diatom)	700	Stebich et al., 2005
Lake Albano	Italy	Absolute	Varve/^{14}C, tephra, pollen stratigraphy	Biogenic (calcite)	46	Lami et al., 1994; Ariztegui et al., 2001
Lake Hoya La Alberca	Mexico	Floating	Varve, ^{210}Pb, tephra	Calcareous	121	Kienel et al., 2009
Lake Hoya Rincón de Parangueo	Mexico	Floating	Varve, ^{14}C,^{210}Pb, tephra	Calcareous	104	Kienel et al., 2009
Lake Barrine	Australia	Absolute	^{14}C, ^{210}Pb	Detritus poor and - rich calcareous	3000	Walker, 2011
Lake Twintaung	Myanmar	Absolute	Varve, ^{210}Pb,^{137}Cs, ^{14}C		530	Sun et al., 2016b
Lake Xiaolongwan	China	Absolute	Varve, ^{14}C, ^{210}Pb, ^{137}Cs, tephra	Clastic-biogenic (dinoflagellate) cysts	1500	Chu et al., 2009
Lake Erlongwan	China	Absolute	Varve, ^{14}C, ^{137}Cs	Biogenic (clastic)	12,766	You et al., 2008
Lake Sihailongwan	China	Absolute	Varve, ^{14}C, tephra	Clastic-biogenic	13,759	Schettler et al., 2006b

Central Spain (Ortiz et al., 2013), Zagoskin maar lake in western Alaska (Muhs et al., 2003) and Maar Lake Massoko in Tanzania (Gibert et al., 2002), but it is also used to verify varve chronologies from maar lakes, as in Holzmaar in Germany (Hajdas et al., 1995) and Lac du Bouchet in France (Williams et al., 1998). Due to the limitations of the radioactive half-life of ^{14}C, the maximum limit of radiocarbon dating is ~50 kyr BP, and to establish a chronology for older sediment sequences other dating methods are needed.

Other radioisotopic dating methods, such as ^{210}Pb and ^{137}Cs, are generally used for palaeoclimatic reconstruction on short timescales, as in the case of Hoya La Alberca and Hoya Rincón de Parangueo maar lakes in Mexico (Kienel et al., 2009), or for dating the uppermost part of the sedimentary sequence (Sirocko et al., 2013).

In China, radiocarbon dating has been the primary method used for building a chronology at Huguangyan Maar Lake in the Leiqiong Volcanic Field (Mingram et al., 2004b), and was also used to verify the varve chronologies established for Sihailongwan and Erlongwan Maar Lakes in Longgang Volcanic Field (Schettler et al., 2006b; You et al., 2008). In addition, ^{210}Pb and ^{137}Cs dating were used to date the upper part of the sedimentary sequences of several maar lakes in Longgang Volcanic Field (Chu et al., 2005a, 2008; You et al., 2008), and for comparison with the results derived from sediment trap sampling with the aim of determining whether the laminations were annual.

3.3. Tephrochronology

Tephra includes all unconsolidated pyroclasts sourced from explosive volcanic eruptions in various grain sizes: ash (grains < 2 mm in diameter), lapilli (2–64 mm), and blocks (>64 mm) (White and Houghton, 2006). The primary tephra deposits from an eruption essentially have the same near-instantaneous age everywhere they occur, which form isochrons very soon after the eruption (Lowe, 2011). Therefore, the primary definition of tephrochronology is the formation of isochronous marker beds, which are used to connect or correlate sedimentary sequences (marine and lacustrine sediments, ice deposits and other continental sequences) within the area of distribution of the tephra (Lowe, 2011). Tephra layers can be well preserved in maar sediments. If the ages of the tephra layers are known from modern observation, historical documents, ^{40}Ar—^{39}Ar dating or other dating methods, they can provide absolute dating points for the chronology (Liu et al., 2018; Lowe, 2011). Alternatively, the ages of some tephra layers can also be deduced based on the pre-existing chronology of the corresponding sedimentary archive. In addition, because of the isochronous character of tephra layers, they are very useful for synchronizing regional climatic and environmental changes, once they are recognized and characterized, in various regional sedimentary archives (Lane et al., 2013).

The results of tephrochronology on water-filled and dry maars in the west Eifel volcanic field in Germany show that the tephra layers were produced by several large eruptions during the Middle and Late Pleistocene (Ulmener Maar – 10,904 varve years BP; Laacher See – 12,880 varve years BP; Neapolitan Yellow Tuff/Campi Flegrei volcano – 14 kyr BP; Dümpel Maar – 116 kyr BP; Glees Maar – 151 kyr BP) and they can be used as isochrons for inter-core and inter-site correlations (Brauer et al., 1999; Lane et al., 2015; Sirocko et al., 2013). Among them, the Ulmener Maar Tephra (UMT) and Laacher See Tephra (LST) have been detected in sediment cores from Meerfelder Maar, Schalkenmehrener Maar, Holzmaar, Dehner Maar and Lago Grande di Monticchio, and are important correlation markers between Holocene and Late-glacial core segments from maar lakes in Europe (Lane et al., 2012, 2015; Wulf et al., 2004). Other tephra layers provide additional chronological reference points and the isochrones are either close to or exceed the age limit of ^{14}C dating in Europe and South America. Examples are the Campanian Ignimbrite (CI) Tephra (~39 kyr BP) detected in Lago Grande di Monticchio in Italy (Wulf et al., 2004); the tephra layers detected in Lac du Bouchet Maar and Alleret Maar in France, which were emitted by the Mont-Dore/Sancy strato-volcano (Pastre et al., 2007); and the lowermost tephra layers detected in Laguna Potrok Aike in Argentina, derived from eruptions of Mt. Burney (Wastegård et al., 2013).

In East Asia, there are several widespread tephra layers that can be traced from Japan to northeast China, such as the Aira-Tn tephra (AT, ~30 kyr BP), the ash from the Changbaishan Millennium eruption (also called the Baitoushan-Tomakomai tephra, B-Tm, AD 946), and the ash from the Changbaishan Qixiangzhan eruption (QEA, ~8100 cal yr BP) (Machida and Arai, 1983; Mingram et al., 2008; Sun et al., 2015, 2016a, 2018). The AT and B-Tm tephras can be correlated from maar lake Ichi-no-Megata in Japan to Sihailongwan in China; in addition, the B-Tm tephra is present in Greenland ice cores (Mingram et al., 2008; Okuno et al., 2011; Sun et al., 2014, 2015, 2016a). Thus, these tephras are regional marker horizons for palaeoclimatic studies. Sihailongwan Maar Lake also preserves several local basaltic tephra layers, and the varved sediments can be used to determine the relative timing of these eruptions (Liu et al., 2009; Mingram et al., 2004a).

In summary, the characteristics of the deposits that compose maar sediments enable the application of multiple dating methods, which greatly enhances the precision of the chronologies of the sedimentary sequences from maar lakes and dry maars.

4. Climate change on multiple timescales

The maar sedimentary archives enable the decipherment of natural climatic variability from annual to orbital scale (Fig. 3), especially in Quaternary. They also have great potential for providing precise and accurate inter-archive correlations (Vos et al., 2000), for recording cyclical and high-frequency climate signals (Lenz et al., 2010, 2017; Willis and Braun, 1997; Willis et al., 1999), and for identifying the physical mechanisms responsible for the observed changes in climate (Marchetto et al., 2015). Besides Quaternary sites, some older maars provide sedimentary records for palaeoclimate researches from Pliocene to Eocene (Fox et al., 2010, 2011; Mezger et al., 2013; Németh et al., 2008; Richter et al., 2017; Sabol et al., 2004), based on macrofossils such as plant fossils (Bannister et al., 2012; Conran et al., 2014; Grein et al., 2011; Reichgelt et al., 2013) and animal fossils (De Soler et al., 2012; Kaulfuss et al., 2011; Vass et al., 2000; Wappler et al., 2011), and some microfossils like pollen, algaes and coprolites (Conran et al., 2014; Goth and Suhr, 2003; Lenz et al., 2011, 2014).

4.1. Modern climate in the context of long-term orbitally-forced climate change

According to the Milankovitch theory (Milankovitch, 1941; Berger, 1988), glacial-interglacial cycles are primarily forced by summer insolation variations at high latitudes of the Northern Hemisphere. Records from deep-sea sediment cores, ice cores, loess-paleosol profiles and stalagmites, reveal that the cyclical climate changes ranging from ~20 to ~100 kyr in length are caused by variations in Earth orbital eccentricity, obliquity and precession (Fig. 3a). Spectral analysis of a biomarker record from Fuentillejo maar in Spain, spanning the last 220 kyr, revealed significant periodicities at 103, 41, 23 and 19 kyr, which provides strong evidence for the validity of the Milankovitch theory (Ortiz et al., 2013). However, the mechanisms behind the development of glacial stages and their timing remain controversial, and are one of the most challenging issues in palaeoclimate research. Besides summer insolation variations at high latitudes of the Northern Hemisphere, changes in the sea surface temperature (SST) of the tropical oceans and in the carbon reservoir are also regarded as forcing factors of glacial-interglacial cycles (Lea et al., 2000; Wang et al., 2003).

Based solely on Milankovitch theory, the duration of interglacials should be about 10 kyr, which means that the present interglacial, which has already lasted for 11.5 kyr, should have ended about 1.5 kyr ago, and a new glacial stage should have been initiated (e.g. Broecker,

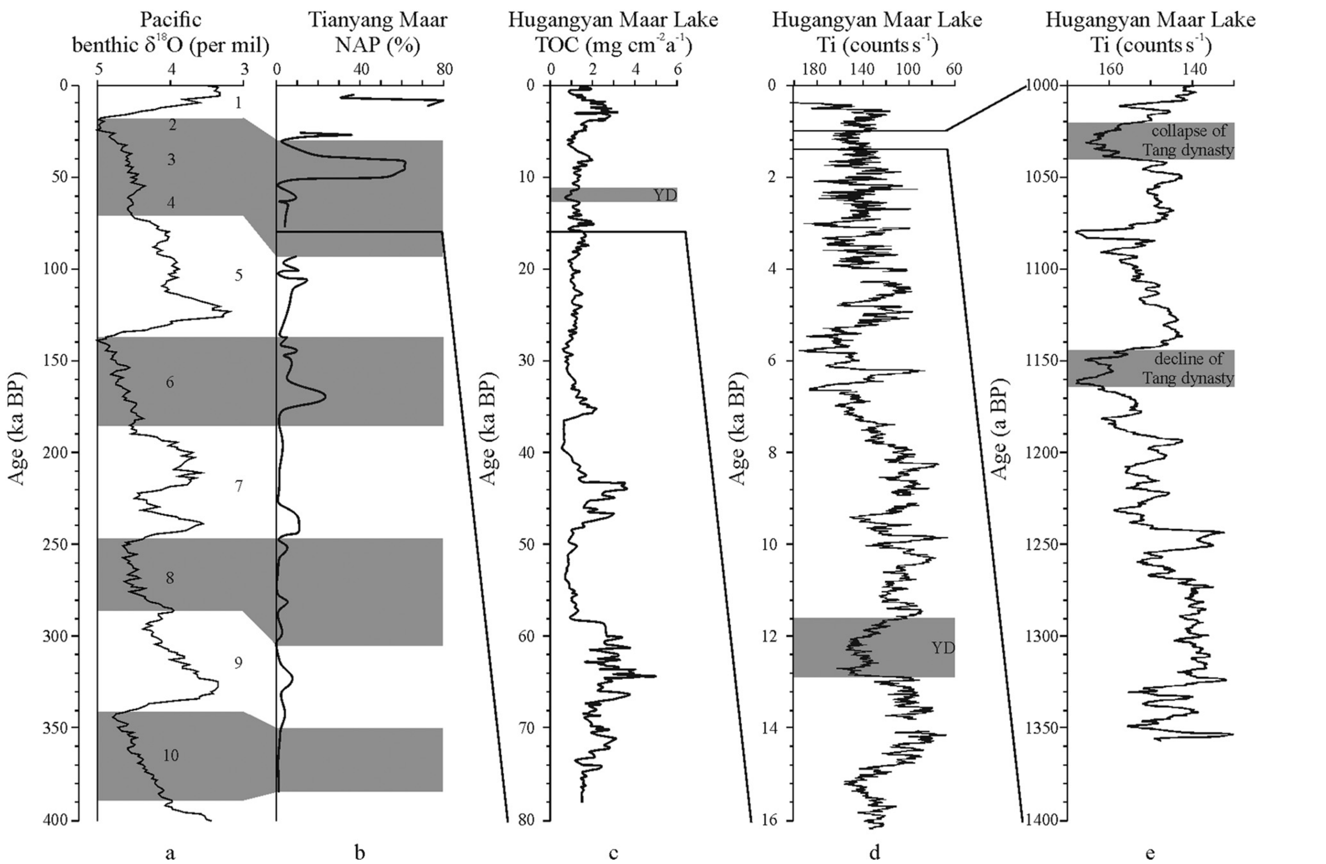

Fig. 3. Paleoclimatic records from maar lakes compared with the marine $\delta^{18}O$ record. a) Pacific benthic $\delta^{18}O$ record (Lisiecki and Raymo, 2009). b) Non-arboreal pollen (NAP) record from Tianyang Maar, plotted on an orbital time scale (Zheng and Lei, 1999). c) Total organic matter (TOC) flux from Hugangyan Maar Lake (Mingram et al., 2004a, 2004b). d) Record of titanium content from Hugangyan Maar Lake. e) Centennial-millennial-scale record of titanium content from Hugangyan Maar Lake (Yancheva et al., 2007). Dark shading indicates glacial periods and cold events such as the Younger Dryas (YD).

1966). However, others have suggested that the duration of the present interglacial will be 40–50 kyr, or even 100 kyr, because of the elevated levels of atmospheric CO_2 and its effects on Arctic ice sheets (Berger and Loutre, 2002; Ganopolski et al., 2016; Hao et al., 2012). Investigations of maar lake sedimentary sequences in Italy (Lago di Vico) and France (Lac du Bouchet, Praclaux, Ribains) showed that they recorded climatic variations from the present to at least the penultimate glacial period (the Saalian glacial) (Follieri et al., 1998; Turner, 1998), and these records may help to address questions regarding the length of glacial/interglacial cycles. These long records can provide further information on the last interglacial period, which is regarded as an analogue of the present interglacial and may help us to properly understand the position of modern climate in glacial/interglacial cycles. A multi-proxy lacustrine record of climate change during the last interglacial period, based on diatom and pollen analysis, from Ribains maar in France, indicates that the climate in central and southern Europe was warm and stable during the first 10–12 kyr of the last interglacial period, and somewhat colder but still stable during the subsequent ~10 kyr (Rioual et al., 2007). This implies that the climate of the current interglacial may become somewhat colder but will still remain stable and last for a further 10 kyr (Rioual et al., 2007).

In China, the continuous sedimentary record from Tianyang Maar (Leiqiong Volcanic Field/South China) spans at least the last 400 kyr (Zheng and Guiot, 1999, Fig. 3b). A quantitative pollen-based temperature record from the site provides an improved correlation between terrestrial and marine records, such as the records of sea-level change and SST in the adjacent South China Sea (Zheng and Lei, 1999). This correlation suggests that the low-latitude tropical climate in China responded sensitively to global ice volume and/or sea level changes; however, higher resolution studies of the long sedimentary records from maars in China are needed. Undoubtedly, such studies will improve our understanding of glacial-interglacial cycles and the modern climate in the context of orbital forcing.

4.2. Millennial-scale abrupt climate events and their forcing mechanisms

Climatic instability is characteristic of the Late Pleistocene and the Holocene. During the Late Pleistocene, climatic variability on a millennial scale is evidenced by Dansgaard-Oeschger (D-O) cycles (Dansgaard et al., 1993), which are detected in marine sediments and ice cores (Bond et al., 1997). The Holocene equivalent of D-O cycles is a series of climatic shifts with a cyclicity close to 1470 ± 500 years (Bond et al., 1997). The evidence for D-O cycles is the presence of ice-rafted, carbonate-rich debris layers in marine sediments which are interpreted as indicating the extension of ice sheets onto shelf areas (Baumann et al., 1995; Bond and Lotti, 1995). Packets of D-O cycles. Packets of D-O cycles are terminated by a pronounced cold event which in sediment cores from the North Atlantic are represented by ice-rafted detrital layers, termed Heinrich events, which result from massive discharges of icebergs from the Laurentide Ice Sheet (Bond et al., 1992). The corresponding temperature changes in North Atlantic surface waters are amplified by the thermohaline circulation and may impact the atmospheric circulation that has a substantial influence on large areas of the Northern Hemisphere, and even globally. However, the causal mechanism of these events remains disputed. A solar forcing mechanism is supported by the close correlation between inferred changes in the production rates of cosmogenic nuclides ^{14}C and ^{10}Be and by centennial-to-millennial scale changes in drift ice proxies measured in deep-sea sediment cores (Bond et al., 2001). However, the millennial-scale cyclicity of solar activity is most significant at periods of 1000 and 2115 years, but not at periods of 1400 and 1500 years, which are the most pronounced cycles observed in marine sediment records (Damon and Jirikowic, 1992).

Late Pleistocene glacial events detected in the lacustrine data from three European maar lakes, Lago di Mezzano, Lago Grande di Monticchio in Italy and Fuentillejo in Spain, are potentially correlative with the Heinrich events recorded in North Atlantic sediments (Ortiz et al., 2013; Ramrath et al., 1999). This relationship is interpreted as evidence for the Late Pleistocene climate in Europe being influenced by North Atlantic climatic forcing, which may be related to Dansgaard-Oeschger cycles (Ortiz et al., 2013; Ramrath et al., 1999). In contrast, in the sedimentary record from maar Lake Masoko in Tanzania, in tropical southern Africa (Garcin et al., 2006), there is no evidence of the ~6000-year cycles and ~1500-year cycles which characterize North Atlantic climate and iceberg surges during glacial and post-glacial times (Dansgaard et al., 1993; Grootes et al., 1993; Schulz et al., 1999).

In China, the existence of a common millennial-scale periodicity during the Holocene has been detected in the records of maar lakes in both low and mid-latitude region (Chu et al., 2014; Wang et al., 2016). A ~1500-year cycle detected in the records from maar lakes Huguangyan (1140 years) and Xiaolongwan (1020–1050 and 1750–2041 years) implies that the millennial monsoon cycle in East China is associated with sea surface temperature (SST) variations of the North Atlantic circulation, which suggests that solar insolation also exerts a profound influence on the East Asian Monsoon (Chu et al., 2014; Liu et al., 2000; Wang et al., 2016).

4.3. Prediction of future climate change on annual to decadal scales

Since the climate of the past 2000 years provides the background for predicting and simulating future climate changes, both PAGES and IPCC have established a global database comprised of records from various geological archives spanning this interval. To predict and simulate future climate change, these archives need to be comparable with, and potentially combined with, instrumental data and historical archives which have a high temporal resolution. Therefore, research on climate change over the past 2000 years focuses on annual-decadal scales. However, few geological archives and proxies of climate change can achieve annual-decadal resolution. In this respect, maar lakes with annually-laminated sediments can provide seasonal-annual-scale records which enable the study of climate change at a high temporal resolution, especially in low-mid latitude continental regions.

The maar lake records from Hoya La Alberca and Hoya Rincón de Parangueo in Mexico, span the interval 1830–1980 CE, and confirm that El Niño was the cause of regional droughts in Central Mexico that were recorded in historical documents (Kienel et al., 2009). El Niño-Southern Oscillation (ENSO) frequencies (Allan et al., 2003) of ~2–8 years are also evident in an annually-laminated sediment sequence spanning the past 530 years from Maar Lake Twintaung in Myanmar, which confirms the close relationship between regional rainfall and ENSO (Sun et al., 2016b). The ENSO frequencies not only occur in modern or Quaternary climatic records, but they are also present in Miocene sedimentary sequences (Lindqvist and Lee, 2009). Periodic variations (~3–7 years) reflected in the couplet thickness of laminated diatomite from Foulden Maar in New Zealand, which is comparable with Quaternary records of ENSO variability and indicates that the climate at low altitudes in New Zealand in the beginning of the Early Miocene was seasonal and strongly ocean-influenced, just like today (Lindqvist and Lee, 2009). In addition to ENSO, Schwabe sunspot cycles are also clearly resolved on an annual-decadal timescale in maar lake sedimentary sequences. The 11-year cycle detected in annually laminated sediments from Holzmaar in Germany and Lake Twintaung in Myanmar provide strong evidence for the presence of sunspot cycles in Quaternary sediments (Vos et al., 1997; Sun et al., 2016b). Furthermore, the 5.5-year cycle found in the laminated Eocene sediments of Eckfeld Maar from the Eifel region in Germany and the 11-year cycle found in Miocene laminated sediments of Foulden Maar in New Zealand support the conclusion that a sun-climate relationship at the annual-decadal scale existed long before the Quaternary (Mingram, 1998; Lindqvist and Lee, 2009).

In China, periodicities of 2.6, 3.5, 53–55, 87–89 and 105–110 years were detected in a high-resolution minor element dataset covering the past 1300 years from the annually-laminated sediments of Lake Xiaolongwan, in Northeast China (Chu et al., 2013). The occurrence of classical ENSO periodicities and solar oscillations in the record implies that the variability of precipitation in Northeast China was associated with ENSO and solar activity during the past 1300 years (Chu et al., 2013).

5. Quantitative paleotemperature reconstructions

Numerous proxies have been used to produce climatic reconstructions from maar sediments, including analysis of the stable isotopes of oxygen and carbon, magnetic properties, palynology, and aquatic biological indicators such as diatoms, chrysophytes, chironomids and ostracods (Marchetto et al., 2015). Some of these indicators are still in the process of development for application in quantitative palaeoclimatic reconstruction. Traditionally, quantitative reconstructions are based on the modern analogue approach in which paleodata are compared with a modern database. The most successful cases are reconstructions of temperature and precipitation using pollen records (Nakagawa et al., 2002). However, considering the time lag (150–250 years) between the responses of vegetation to climate change (Chapin and Starfield, 1997), new climatically-sensitive proxies that can be measured at high temporal resolution are needed.

The most promising among such new proxies are long-chain alkenones (LCAs) and glycerol dialkyl glycerol tetraethers (GDGTs). They have been widely used for quantitative paleotemperature reconstruction, since they respond rapidly to temperature change during the growing season. LCAs are temperature-dependent lipids produced by several species of haptophyceae that are widely distributed in marine and lacustrine sediments (Sun et al., 2007). Previous studies indicated that the $U^{k}_{37}/U^{k'}_{37}$ index, originally developed using di-, tri- and tetra-unsaturated ketones ($C_{37:2}$, $C_{37:3}$, and $C_{37:4}$), was linearly related to sea-surface temperature or culture temperature within the range of roughly 10–22 °C (Brassell et al., 1986; Sun et al., 2007). LCAs are widely applied in sea surface temperature reconstruction, and they are now attracting increasing attention for lake temperature reconstruction, especially in volcanic lakes.

Glycerol dialkyl glycerol tetraethers (GDGTs) are a group of ubiquitous membrane lipids produced by archaea or bacteria, which consist of two types of molecule with different structures and sources, named isoprenoid GDGTs (iGDGTs) and branched GDGTs (brGDGTs). These compounds mainly occur in soils and lake sediments. The development of the Methylation index of Branched Tetraethers (MBT), the Cyclisation ratio of Branched Tetraethers (CBT) (Weijers et al., 2007b) and brGDGTs-based temperature calibration (Foster et al., 2016; Loomis et al., 2012; Pearson et al., 2011; Tierney et al., 2010; Weijers et al., 2007b; Zink et al., 2016), have enabled the reconstruction of mean annual air temperature (MAAT) variations and have generated significant interest within the terrestrial palaeoclimate research community working on lake sediments (Castañeda et al., 2011; Chu et al., 2017; Fawcett et al., 2011; Hu et al., 2015; Zink et al., 2010), peat deposits (Wang et al., 2017; Zheng et al., 2017), loess (Peterse et al., 2014; Peterse et al., 2011) and other sediments (Weijers et al., 2007a). The MBT and CBT proxies are defined and their relationship between the distribution of brGDGTs and mean annual air temperature in numerous studies of soil brGDGTs worldwide are discussed in Weijers et al. (2007b). The GDGTs-temperature calibration was built by analyzing the relationship between GDGTs from many lakes sites worldwide and mean annual air temperature, and temperature reconstructions from the GDGTs-

Table 3
Location, hydrological status and genetic classification of maar lakes in which GDGTs and LCA are detected.

No.	Lake	Latitude	Longitude	Elevation (m)	Water depth (m)	pH	Volcanic area	Country	Sample type	Biomarkers	Reference
1	Grande di Monticchio	40°56′N	15°36′E	656	36	6.7	Monte Vulture	Italy	Surface	GDGTs	Blaga et al., 2010
2	Nyamiteza	0°26′N	30°14′E	1254	34	8.2	Kyatwa	Uganda	Surface	GDGTs	Tierney et al., 2010
3	Kanyamukali	0°24′N	30°14′E	1161	10	8.1					
4	Lugembe	0°27′N	30°17′E	1280	18	7.3					
5	Nyabikere	0°30′N	30°20′E	1463	45	6.8					
6	Ntambi	0°25′N	30°14′E	1158	42	9.3					
7	Donglongwan	42°26′N	126°31′E	620	127	8.4	Longgang	China	Surface	GDGTs	Chu et al., 2005b;
8	Sihailongwan	42°17′N	126°36′E	778	50	7.9			Surface, core	GDGTs, LCA	Sun et al., 2011;
9	Sanjiaolongwan	42°22′N	126°26′E	722	76	7.8			Surface	LCA	Hu et al., 2015, 2016
10	Xiaolongwan	42°18′N	126°21′E	643	15	6.8			Surface	GDGTs	
11	Huguangyan	21°09′N	110°17′E	16	22	7.7	Leiqiong		Surface, trap, core	GDGTs, LCA	
12	Pupuke	36°47′S	174°46′E	12	57	7.7	Auckland	New Zealand	Core	GDGTs	Heyng et al., 2015

temperature calibration of lake sediments has been successfully applied in different lakes.

There is an increasing use of LCAs and GDGTs in lacustrine sediments for terrestrial environmental reconstruction, including the sediments of maar lakes. LCAs have been found in >100 lakes worldwide, including in three maar lakes in China: Sihailongwan and Sanjiaolongwan in Northeast China and Huguanyan in South China (Chu et al., 2005b). GDGTs have been found in over 300 lakes globally, 11 of which are maar lakes, including one in Italy (Grande di Monticchio, Blaga et al., 2010), five in Uganda (Nyamiteza, Kanyamukali, Lugembe, Nyabikere and Ntambi, Tierney et al., 2010), four in China (Donglongwan, Sihailongwan, Xiaolongwan and Huguangyan, Chu et al., 2005b; Hu et al., 2015, 2016; Sun et al., 2011) and one in New Zealand (Pupuke, Heyng et al., 2015). Table 3 lists the pH values of LCAs and GDGTs-containing maar lakes, and the values vary from 6.6–9.3, from neutral to alkaline. This neutral regions in pH is most likely caused by the pH buffers of HSO_4^-/SO_4^{2-} and H_2CO_3/HCO_3^- (Marini et al., 2003), and several volcanic lakes with carbonate inputs may have pH values > 8 (Christenson et al., 2015; Pecoraino et al., 2015). This finding may indicate that carbonate-rich maar lakes have higher pH values and tend to contain abundant LCAs and GDGTs, which accords with the previous conclusion that sulfate-dominated or carbonate-dominated lakes also affect the occurrence and abundance of LCAs (Sun et al., 2004; Toney et al., 2010). The verification of this hypothesis requires further work, especially on unexplored maar lakes.

The high-resolution GDGTs-based temperature records from the sediments of Maar Lake Huguangyan in tropical China reveal that the mean temperature during the Oldest Dryas and Younger Dryas cold events, were 17.8 °C and 19.8 °C, respectively; these values are 5.6 °C and 3.6 °C colder than the respective modern mean annual air temperatures (Chu et al., 2017, Fig. 4). During the Holocene, the mean temperature of the Southern Hemisphere was lower in the early Holocene (15.6 °C), and it continued to rise until 1600 years·cal. BP (18.4 °C), which is revealed by a GDGTs-based temperature record from Lake Pupuke, New Zealand (Heyng et al., 2015, Fig. 4). The high-resolution LCAs-based reconstruction of the growing season temperature over the past 1600 years at Lake Sihailongwan, in Northeast China, indicates that the most pronounced cold spells occurred during 480–860 CE, 1260–1300 CE, 1510–1570 CE and 1800–1900 CE, with a temperature decrease of about 1 °C compared to today (Chu et al., 2011, Fig. 4). As more records of LCAs and GDGTs from maar lakes are obtained, high-

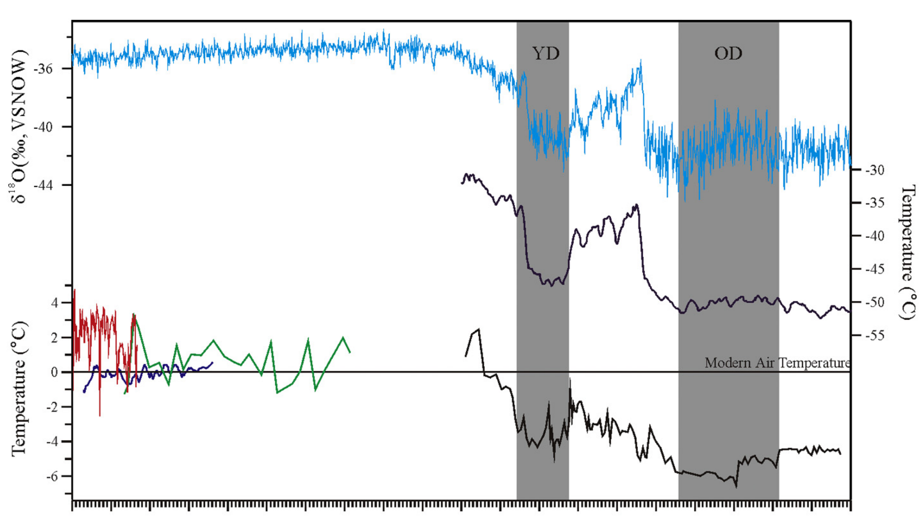

Fig. 4. Paleotemperature reconstructions from maars and maar lakes and comparison with the temperature and $\delta^{18}O$ record of the Greenland ice core. Black curve: winter temperature reconstruction from Huguangyan Maar Lake in China (Chu et al., 2017); green curve: annual mean temperature reconstruction from Pupuke Maar Lake in New Zealand (Heyng et al., 2015); dark blue curve: annual mean air temperature reconstruction from Huguangyan Maar Lake in China (Hu et al., 2015); red curve: growing season temperature reconstruction from Sihailongwan Maar Lake in China (Chu et al., 2011); purple curve: Greenland temperature during the Last Deglaciation (Buizert et al., 2014); light blue curve: $\delta^{18}O$ record of the Greenland NGRIP ice core (Rasmussen et al., 2006, 2008). The dark shading represents cold events such as the Younger Dryas (YD) and the Oldest Dryas (OD).

resolution quantitative temperature reconstructions at the regional and continental scales will become possible (Fig. 4).

6. Summary

Palaeoclimatic records of lacustrine sediments from >40 maars have been reported globally, providing continuous records spanning > 400 kyr. In China, numerous palaeoclimatic records from maar sediments have been reported from Leiqiong Volcanic Field and Longgang Volcanic Field.

Absolute varve chronologies spanning over 14,000 years have been established from maar lakes in Longgang Volcanic Field, and tephrochronology studies indicate that the AT tephra and the B-Tm tephra layers can be used as isochrones in East Asia. These results imply that the varve-based ages of maar sediments in Longgang Volcanic Field can be transferred to other sequences where the AT tephra and the B-Tm tephra are present, enabling the direct correlation of the maar sediment sequences in Northeast China and Japan, as well as with ice core sequences in Greenland.

Tianyang Maar from Leiqiong Volcanic Field provides a continuous sedimentary record spanning at least 400 kyr, and the record confirms that vegetation and climatic history of low-latitude tropical China was controlled by the ~10 kyr glacial-interglacial cycle. At a millennial scale, D-O cycles are present in the records of maar lakes from both low and mid latitude China. In particular, typical ENSO periodicities and evidence of solar oscillations can be identified in annual-scale minor element records from maar sediments in Longgang Volcanic Field, which implies that precipitation variability in Northeast China was related to ENSO and solar activity over the past 1300 years.

In addition to conventional climatic proxies, several new quantitative proxies, including LCAs and GDGTs, are being explored. These new proxies have already delivered high-resolution temperature records since the last deglaciation in China.

Maar sediments from Leiqiong and Longgang Volcanic Fields in China, whose precise chronologies are based on varves, isotope dating and tephrochronology, provide valuable palaeoclimatic records for this key region of East Asian Monsoon influence, and they contribute significantly to the global paleoenvironmental and palaeoclimatic database for maars and maar lakes.

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