Invited Research Article

Indian summer monsoon variability over last 2000 years inferred from sediment magnetic characteristics in Lugu Lake, southwest China

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ABSTRACT

Knowledge of climatic change during the past 2000 years in southwestern China is important for understanding the evolution of the Indian summer monsoon (ISM). For this study, we conducted systematic analysis of magnetic minerals in sediments from Lugu Lake in northwestern Yunnan Province. Magnetic measurements suggest that magnetite dominated the studied magnetic mineral assemblages. Both natural origins and anthropogenic activities are considered to be the sources of the magnetic minerals based on the correlations of χ vs. $\chi_{fd}\%$ and χ_{ARM}/χ . The magnetic minerals of natural origins can be attributed to terrestrial detrital input rather than biogenic sources. Combined with diatom and geochemical records, magnetic parameters including χ , $\chi_{fd}\%$, and S_{ratio} can be used as sensitive indicators of ISM change, and suggest that two significant dry periods occurred in the Medieval Warm Period (MWP, 800–1300 CE) and Roman Warm Period (RWP, 0–400 CE) and two relatively wet intervals in the Dark Ages Cold Period (DACP, 400–800 CE) and Little Ice Age (LIA, 1300–1850 CE). Significant shifts of magnetic parameters in Lugu Lake samples revealed sensitivity to precipitation-controlled catchment erosion. The climatic patterns shown by the magnetic characteristics were generally similar to those in extensive areas dominated by the ISM. We speculate that rainfall caused by the ISM during the last 2000 years may be related to the variations of El Niño/Southern Oscillation (ENSO) and the mean position migration of the ITCZ.

1. Introduction

Understanding of paleoenvironmental change in the past 2000 years is important for investigating global climate dynamics. The past 2000 years of environmental change included the period of environmental change dominated by natural conditions before 1800 CE and that dominated by natural and anthropogenic influence after 200 CE, which is also a period for which historical documents and natural environmental records coexist (Ge et al., 2013a). Many environmental records show that precipitation and temperature variations in the Northern Hemisphere over the past 2000 years generally followed similar trends on centennial timescales. The environmental and climatic events during the past 2000 years mainly included the Roman Warm Period (RWP,

0–400 CE), the Dark Ages Cold Period (DACP, 400–800 CE), the Medieval Warm Period (MWP, 800–1300 CE), the Little Ice Age (LIA, 1300–1850 CE), and the Current Warm Period (CWP, 1850 CE–present) (Lamb, 1977). Proxy-derived temperature records have revealed significant temporal and spatial differences in the last 2000 years (Diaz et al., 2011; Graham et al., 2011; Yan et al., 2011; Chen et al., 2015; Dixit and Tandon, 2016; Gu et al., 2020). This variability might be related to the spatiotemporal patterns of changes in atmospheric circulation (An et al., 2015). To understand the driving forces of hydrologic and climate changes in this region, it is important to first reconstruct the paleoenvironmental changes of different areas over the last 2000 years using empirical data from specific locations.

The Asian summer monsoon (ASM), including the westerlies from

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Fig. 1. Map showing a summer mean 700 hPa streamline based on the NCEP/NCAR reanalysis during 1971–2000. Black pentagram indicates the location of Lugu Lake. EASM, ISM, and Westerlies represent the East Asian Summer Monsoon, Indian Summer Monsoon, and Westerlies, respectively. b Lake bathymetry and coring site (solid rectangle). c Climate diagram from the meteorological station in Yanyuan, Sichuan Province (27° 25' N, 101° 30' E; 2540 m above sea level), near Lugu Lake, showing monthly temperature and precipitation data. These data are 62-year climate averages for the period from 1951 to 2012 from the Yanyuan weather station, China Meteorological Data Sharing Service Platform, <http://cdc.cma.gov.cn>.

inner Asia, the Indian summer monsoon (ISM) from the Indian Ocean, and the East Asian summer monsoon (EASM) from the Pacific Ocean, plays an important role in transporting moisture and heat from the tropical oceans to the higher latitudes of Asia (An et al., 2000) (Fig. 1a). Changes of monsoonal precipitation can lead to extreme floods or droughts, affecting more than 60% of the world's population in most areas of East and South Asia (Wang, 2006). Some studies have shown that ASM intensity and related precipitation changes are closely related to the prosperity and decline of ancient human civilizations (Wu and

Liu, 2004; Dixit et al., 2014). Therefore, it is important to understand the mechanisms and possible driving forces of monsoon changes on different time scales. Several studies have focused on the variations of the ASM over the past 2000 years using marine sediment records (Agnihotri et al., 2002; Anderson et al., 2002), tree ring records (Cook et al., 2010; Sano et al., 2011; He et al., 2013), lake sediment records (Liu et al., 2011; Sheng et al., 2015; Cui et al., 2018; Feng et al., 2019), stalagmite records (Zhang et al., 2008; Tan et al., 2019), and historical literature (Zheng et al., 2006; Tan et al., 2008; Chen et al., 2019). These

Fig. 2. Comprehensive profile of Lugu Lake sediments including AMS ¹⁴C age (Wang et al., 2020), magnetic parameters and sedimentary units.

studies have shown ASM intensity over decadal to centennial scales in the last 2000 years.

Lugu Lake is located on the southeast edge of the Qinghai–Tibet Plateau in Southwest China. The lakes in this area are tectonic lakes with fragile ecosystems, and can respond to environmental changes on scales from decades to millions of years (Chen et al., 2014; Wang et al., 2019). Magnetic measurement is a rapid, intensive, and non-destructive method to characterize high-resolution mineralogical changes, and is widely used in marine sequence comparison, paleoclimate, and provenance research (Peters et al., 2010; Chang et al., 2016; Wang et al., 2018a, 2018b) on lacustrine (Hu et al., 2015; Xu et al., 2020) and aeolian sediments (Gao et al., 2018). Magnetic mineralogy has become one of the most important proxies in paleoenvironmental and paleoclimatic reconstruction (Su et al., 2013; Lise-Pronovost et al., 2014). However, because authigenesis/diagenesis and biogenesis after deposition can influence the concentrations and grain size of magnetic minerals in lacustrine sediments, and even form new magnetic minerals. (Hu et al., 2015; Wei et al., 2018). How to reveal sensitive slow-scale (decadal to centennial scale) climatic and paleoenvironmental events using magnetic parameters remains undetermined and is a problem of urgent concern. Therefore, in this study, we systematically investigated the magnetic characteristics of sediments from Lugu Lake deposited in the past 2000 years. First, variations of the magnetic mineral assemblages with respect to age were evaluated. Second, we examined the sources of magnetic minerals and the relationship between magnetic parameters and precipitation-controlled catchment erosion. Then, the responses of sediment magnetic properties to the ISM and possible driving forces of ISM variability were explored.

2. Regional setting

Lugu Lake (100°45′–100°50′E, 27°41′–27°45′N) is located in southwestern Sichuan Province and northwestern Yunnan Province on the southeastern edge of the Qinghai–Tibet Plateau (Fig. 1b). It's a semi-closed lake with a maximum water depth of 93.5 m and a mean depth of 40.3 m. It has a surface area of 48.45 km², and a catchment drainage area of 171.4 km² (Wang and Dou, 1998). Lugu Lake is fed hydrologically by rainfall, seasonal inflow, and surface runoff. The Gaizu River, which is the only outlet of Lugu Lake, is connected with the lake by the Caohai wetland (Wang et al., 2018a, 2018b). The basin bedrock is mainly composed of sandstone, limestone, and mudstone. Soils in the catchment of Lugu Lake include mainly Mollisols, Alfisols, Entisols, and Oxisols (Zhang et al., 1997). The study area is characterized by a typical monsoon climate with distinct wet and dry seasons. The region is mainly affected by warm and humid airflow from the Bay of Bengal in summer, the southern branch of the westerlies in winter, and the local climate over the Qinghai–Tibet Plateau. The average annual temperature is 12.8 °C, with average temperatures of 5.6 °C in January and 19.4 °C in

July. The mean annual rainfall is 900 mm, and summer precipitation from June to September accounts for 80% of the annual precipitation (Fig. 1c).

3. Sampling and methods

Seven sediment cores (LGS) (27°41′48″N, 100°48′5″E) were collected from a water depth of 42.5 m in the southeast basin of Lugu Lake using an Austrian UWITEC Gravity Corer in June 2012 (Fig. 1b). The core sites were at intervals of 1 m, and the cores stratigraphically overlapped. Cores LGS-1, LGS-2, and LGS-4 were subsampled at 0.5 cm intervals. Core LGS-4 (length: 98 cm) was used for magnetic measurement. Core LGS-1 (length: 104 cm) was used for pigment and cladoceran measurement. Core LGS-2 (length: 93.5 cm) was used for grain-size, diatom, and geochemical analysis. In addition, to provide appropriate samples for ²¹⁰Pb and ¹³⁷Cs dating, core LGS-7 (a short sediment core), with a clear mud–water interface, was obtained and squeezed at 0.5 cm sections. All the subsamples were collected into numbered plastic bags, placed in a refrigerator at 4 °C, and immediately returned to the laboratory for further analysis.

The age–depth model was established using radiometric ²¹⁰Pb, ¹³⁷Cs, and accelerator mass spectrometry (AMS) ¹⁴C dating. The activities of ²¹⁰Pb and ¹³⁷Cs were measured at the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. AMS dating of bulk organic sediments may be affected by the reservoir effect of ‘old’ carbon, which can cause significant uncertainty in age models (Hou et al., 2012). In this study, we used terrestrial plant remains to establish a reliable age model (Grimm et al., 2009). Six samples of terrestrial plant remains were collected along the entire core (Wang et al., 2020). The AMS ¹⁴C analyses were performed at the Beta Radiocarbon Analytic Laboratory (Miami, FL, USA). All AMS ¹⁴C dates were calibrated to calendar years (0 yr BP = 1950 CE) using the IntCal13 calibration dataset and the program Calib 7.1 (Reimer et al., 2013).

Magnetic susceptibility was measured using an AGICO MFK-1 Kappabridge susceptometer at 976 and 15,616 Hz and was then normalized by mass (χ_{lf} and χ_{hf}). Frequency-dependent susceptibility (χ_{fd}) was calculated using the formula χ_{fd} (%) = [(χ_{lf} – χ_{hf})/χ_{lf}] × 100. Anhyseretic remanent magnetization (ARM) was imparted with a peak alternating field of 100 mT and a direct current bias field of 0.05 mT using a long-core cryogenic magnetometer (2-G Enterprises Model 755–1.65UC). The ARM susceptibility (χ_{ARM}) was obtained by dividing the ARM intensity by the DC field strength. Isothermal remanent magnetization (IRM) was imparted using an MMPM9 pulse magnetizer and measured with a Molspin Minispin magnetometer. The IRM at 1 T was considered the saturation IRM (SIRM), then applied a 300 mT reverse field (IRM_{-300mT}), and calculated the hard isothermal remanent magnetization (HARM) by (SIRM+IRM_{-300mT})/2 and S-ratio by (IRM_{-300mT}/SIRM). HARD% that reflected the relative concentrations of hard

Table 1
Comparison of the ranges and mean values of magnetic parameters in different units.

Sample	Values	χ (10^{-8} m ³ /kg)	χ_{fd} (%)	χ_{ARM} (10^{-8} m ³ /kg)	SIRM (10^{-6} Am ² /kg)	S-ratio	χ_{ARM}/χ	$\chi_{ARM}/SIRM$ (10^{-4} m/A)	HIRM (10^{-4} Am ² /kg)	HARD (%)
Unit 5 (18–0 m)	Range	20.20–173.90	10.01–15.06	231.85–869.17	1862.75–8419.64	0.94–0.99	4.65–11.48	0.08–0.14	22.06–219.40	0.70–3.84
	Mean	87.16	13.91	508.52	4589.72	0.96	6.80	0.12	88.05	1.88
Unit 4 (31.5–18 cm)	Range	18.65–25.13	7.67–10.46	199.45–286.17	1717.75–2504.46	0.94–0.98	9.83–13.18	0.10–0.13	22.19–72.82	1.22–3.52
	Mean	20.85	9.29	240.17	1977.65	0.95	11.55	0.12	46.95	2.36
Unit 3 (47.5–31.5 cm)	Range	24.00–33.49	7.75–10.79	258.07–353.14	2506.83–3234.71	0.94–0.98	9.61–11.32	0.10–0.11	35.00–90.31	1.09–3.10
	Mean	27.25	9.62	290.16	2703.90	0.96	10.65	0.11	60.58	2.25
Unit 2 (61.5–47.5 cm)	Range	22.64–29.93	7.14–8.97	250.50–307.03	2307.50–2880.54	0.94–0.96	10.11–11.29	0.10–0.12	45.89–99.71	1.92–3.52
	Mean	24.95	8.11	273.40	2525.84	0.95	10.96	0.11	64.92	2.56
Unit 1 (73–61.5 cm)	Range	25.73–38.64	8.94–11.29	262.22–356.83	2338.94–3017.05	0.94–0.97	8.26–10.86	0.10–0.12	40.17–76.84	1.50–2.83
	Mean	33.39	10.53	312.77	2705.48	0.96	9.42	0.12	55.40	2.05

magnetic minerals were calculated using the formula $HARD = (HIRM/SIRM) \times 100$. In addition, some representative samples selected based on the above magnetic parameters were used to measure high-temperature κ -T curves, IRM demagnetization curves, and magnetic hysteresis loops. High-temperature κ -T curves (room temperature to 700 °C, then back to room temperature) were obtained using an AGICO KLY-3 Kappabridge with a CS-3 high-temperature furnace. IRM demagnetization curves and magnetic hysteresis loops were measured using a Princeton Measurements MicroMag Corporation 2900 alternating gradient magnetometer with a maximum field of 500 mT. All the magnetic measurements in this study were carried out at the Department of Geosciences, Tübingen University, Germany.

4. Results

4.1. Age–depth model and stratigraphic variations of sediment properties of Lugu Lake

Radiometric ²¹⁰Pb and ¹³⁷Cs dates of core LGS-7 and six AMS ¹⁴C dates of core LGS-2 have been reported by Wang et al. (2020). The age–depth model was ultimately developed using a combination of the ¹³⁷Cs date of 1963 CE and six AMS ¹⁴C dates by fitting the smooth-spline model with the Clam 2.2 software. This model covered the past 2800 years with a mean sedimentation rate of 2.5 cm/100 years and a rapid increase of the sedimentation rate during the past 200 years.

4.1.1. Unit 1 (73–61.5 cm, 0–400 CE)

This unit showed a significant decrease in pelagic cladocerans (*Bosmina coregoni*), coeval with a decline in abundance of planktonic taxa (*C. dubius*) and an increase in *Bosmina longispina*. (Wang et al., 2020). The mean grain size before 400 CE was moderately high, and Al and Ti contents showed low levels with means of 47 mg/g and 8 mg/g, respectively, before 400 CE (Wang et al., 2020) (Fig. 3). Magnetic susceptibility (χ) and saturation isothermal remanent magnetization (SIRM) can be used to reflect the changes of magnetic minerals concentrations, especially ferrimagnetic minerals like magnetite. The mean values of χ and SIRM were 33.39×10^{-8} m³/kg and 2705.48×10^{-6} Am²/kg, respectively. $\chi_{fd}\%$ can be used to show the contribution of superparamagnetic minerals. The mean value of $\chi_{fd}\%$ was approximately 10.53%, indicating the presence of superparamagnetic (SP) grains at room temperature. Hard isothermal remanent magnetization (HIRM) and S-ratio bear information about absolute and relative concentrations of high coercivity minerals. The mean S-ratio and HIRM values were approximately 0.96 and 55.40×10^{-6} Am²/kg, respectively, indicating that dominant remanence contributions are mainly from soft magnetic minerals (e.g., magnetite and maghemite) (Fig. 2, Table 1).

4.1.2. Unit 2 (47.5–61.5 cm, 400–800 CE)

This unit was characterized by a significant increase in the species of planktonic diatoms (especially *C. dubius*). In this unit, the biomass of primary producers was at the lowest level, indicated by stable pigment indicators of lower plant abundance and total algae. Lutein and zeaxanthin contents decreased significantly in this unit, indicating a decrease in production (Wang et al., 2020). The mean grain size was low but variable in this unit. Significant increases in Al and Ti were observed in this unit, corresponding to minimum values of total organic carbon (TOC), the carbon accumulation rate (CAR) and a low sand fraction (Wang et al., 2020) (Fig. 3). The χ and SIRM values were lower in this unit than in Unit 1, showing a decrease of magnetic mineral concentration. Compared with Unit 1, the S-ratio (mean of 0.94) and $\chi_{fd}\%$ (mean of 8.11%) were lower, indicating a decrease of soft and SP magnetic mineral contents, which was also confirmed by the increase of HIRM. χ_{ARM}/χ and $\chi_{ARM}/SIRM$ have been used to trace relative changes in the grain size of magnetic minerals. The χ_{ARM}/χ values were higher than those of Unit 1, indicating that magnetic grain sizes were finer than

Fig. 3. Vertical variations of magnetic parameters (a–h) (this study), the relative abundance of *C. dubius* (i), Hill's N_2 diversity (j), the percentages of herbs and trees (k–l), TN (m), TN (n), Al (o), and Ti (p) contents (Wang et al., 2020) in Lugu Lake sediments.

those in Unit 1 (Fig. 2, Table 1).

4.1.3. Unit 3 (31.5–47.5 cm, 800–1300 CE)

This unit was marked by an increase in the abundance of small Fragilariaceae species and a decrease in the abundance of the planktonic species *C. dubius*. The Hill's N_2 diversity and diatom accumulation rate (AR) started to decline in this unit. The concentrations of Al and Ti gradually decreased during the period of 1000–1300 CE, and the mean grain size and sand fraction then decreased significantly during the MWP (1000–1300 CE) (Wang et al., 2020) (Fig. 3). Compared with Unit 2, the increased χ values (mean of $27.25 \times 10^{-8} \text{ m}^3/\text{kg}$) and SIRM values (mean of $2703.90 \times 10^{-6} \text{ Am}^2/\text{kg}$) indicated the increase of magnetic mineral contents. HARD% is proportional to the concentration of anti-ferromagnetic materials. The S_{ratio} , HIRM, and HARD values suggest that soft magnetic minerals dominated the magnetic components. The χ_{ARM}/χ and $\chi_{\text{ARM}}/\text{SIRM}$ values were lower than those in Unit 2, indicating that the magnetic grain sizes became coarser (Fig. 2, Table 1).

4.1.4. Unit 4 (18–31.5 cm, 1300–1850 CE)

This unit is characterized by a clear increase of the relative abundance of small benthic Fragilariaceae species and a sudden disappearance of planktonic *C. rhomboideo-elliptica*. The sand fraction and mean grain size rose markedly during the period of 1300–1850 CE, which also corresponded to an abrupt increase in the abundance of cyanobacteria, as well as the disappearance of *C. rhomboideo-elliptica* and sediment-dwelling *Leydigia* sp. During the period of 1300–1850 CE, the abundance of the planktonic taxon *C. rhomboideo-elliptica* decreased significantly, and the content of pigments from diatoms increased markedly (Wang et al., 2020) (Fig. 3). The χ and SIRM values in this unit were the lowest of the entire core. In unit 4, the values of χ_{ARM}/χ and $\chi_{\text{ARM}}/\text{SIRM}$ were highest, indicating that the grain sizes of magnetic minerals were the finest in the entire core. The $\chi_{\text{rd}}\%$ values decreased, indicating a decrease in SP magnetic mineral contents. The S_{ratio} values were lower, and the HIRM and HARD values were higher. These findings show that the contents of soft magnetic components were lower (Fig. 2, Table 1).

4.1.5. Unit 5 (0–18 cm, 1850–2012 CE)

Based on the diatom records, this unit was subdivided into two subunits deposited in 1850–1950 CE and 1950–2012 CE. There was a sharp increase in small-sized Fragilariaceae species, particularly *Pseudostaurosira brevistriata*, during 1850–1950 CE. The contents of both the sand and fine silt/clay fractions increased considerably during 1850–1950 CE, whereas both remained low after 1950 CE. The Al and Ti values rose to their highest levels after 1950 CE, corresponding to the rapid declines of TOC and total nitrogen (TN) contents (Wang et al., 2020) (Fig. 3). Division of the two subunits was also supported by magnetic parameters. The χ and SIRM values showed that the contents of magnetic minerals in the 1950–2012 CE subunit were higher than those in the 1850–1950 CE subunit. The χ_{ARM}/χ values of the

1950–2012 CE subunit were lower than those of the 1850–1950 CE subunit, indicating that the magnetic grain sizes deposited during 1950–2012 CE were coarser than those deposited during 1850–1950 CE (Fig. 2, Table 1).

4.2. Magnetic hysteresis loop curves, κ -T curves, demagnetization and IRM acquisitions curves

Magnetic hysteresis loops can contain a large amount of information whether the coercivity of the magnetic mineralogy is high or low (Thompson and Oldfield, 1986). The magnetic hysteresis loops of all the samples (samples: 9, 24, 52, 100, 148, and 192) showed that the loops could be saturated under 300 mT, suggesting that soft magnetic minerals were the dominant magnetic minerals. In addition, all the loops showed an increase from 300 to 1000 mT, indicating the presence of hard magnetic or paramagnetic minerals (Fig. 4a–f). In addition, the demagnetization curves of all the samples showed that the remanent magnetization could be easily demagnetized under 30–40 mT, which shows that soft magnetic minerals were dominant in all the samples (Fig. 4p). Similarly, the IRM acquisition curves of all samples indicate that IRM at 300 mT is generally >90% of the SIRM, which also reveals that soft magnetic minerals are predominant in these sample and the hard magnetic mineral contribution is low (Fig. 4q).

High-temperature κ -T curves can be used to identify magnetic phases according to different magnetic minerals with different Curie temperatures (T_c). All the heating curves of the representative samples are shown in Fig. 4h–n. The heating curves show that magnetic susceptibility clearly increased at approximately 220 °C, indicating the unblocking temperature of finer grain sizes near the boundaries of SP and SD ferrimagnetic particles (Liu and Deng, 2009; Ge et al., 2015), and then decreased significantly near 300–400 °C because thermally unstable maghemite transformed into hematite during heating (Hao and Guo, 2005; Chen et al., 2005; Ma et al., 2020). Above 400 °C, a peak of all the heating curves occurred with a temperature of approximately 500 °C, which may be related to the transformation of paramagnetic minerals into ferrimagnetic minerals (Pan et al., 2000; Ge et al., 2015). There were clear T_c values of approximately 580 °C, indicating that the dominant magnetic minerals were magnetite. All the heating curves have transition position at near 675 °C, representing the Neel temperature of hematite (Dunlop and Ozdemir, 1997). In addition, the magnetic susceptibilities of all the cooling curves were higher than those of the heating curves, which also indicated the formation of ferrimagnetic minerals during heating (Fig. 4h–n).

We further applied a log-Gaussian decomposition of IRM acquisition curves proposed by Kruijer et al. (2001). Two components with distinct magnetic coercivities can be separated in Fig. 5. Component 1 with $B_{1/2}$ values (the coercivity field at half of the SIRM) of 41.7–49 mT, a mean value of 45.57 mT, DP (dispersion parameter) of 0.51–0.67, and M_{H} (remanence contribution) of 95–98%. Component 2 with $B_{1/2}$ values of

Fig. 4. The depths of representative samples shown in the S_{ratio} curve (g). Magnetic hysteresis (a–f), high-temperature κ -T curves (i–n), demagnetization curves (p) and IRM acquisition curves (q) of a representative sample from Lugu Lake.

631–794.3 mT, a mean value of 738.2 mT, DP of 0.60–1.00, and M_{ri} of 2–5%. The SIRM values of representative samples are between 2101.62 and $7973.39 \times 10^{-6} \text{Am}^2/\text{kg}$ (Table 3). Combined with the results of the heating curves, we concluded that component 1 can be interpreted as magnetite and maghemite, and the high-coercivity component 2 may represent hard magnetic minerals.

5. Discussion

5.1. Sources and characteristics of magnetic minerals

The primary principle that needs to be clarified when magnetic parameters are used to reconstruct paleoenvironmental change is the origin of the magnetic minerals in the sediments. At a large scale, there are two magnetic minerals types in the lake sediments: anthropogenic and natural. Previous studies showed that correlations between χ and both $\chi_{fd}\%$ and χ_{ARM}/χ can be used to identify anthropogenic magnetic

Fig. 5. Quantification of magnetic coercivity components using log-Gaussian decomposition of IRM acquisition curves (Kruiver et al., 2001). Two components are separated: component 1 represents soft magnetic minerals (magnetite), while component 2 represents hard magnetic minerals (hematite).

Fig. 6. Scatterplots of (a) χ vs. $\chi_{IR}\%$, (b) χ vs. $\chi_{ARM}/SIRM$, and (c) $\chi_{ARM}/\chi_{IR}\%$ vs. χ_{ARM}/χ for the samples from Lugu Lake. The blue, red, and green circles represent samples from depths of 0 to 7 cm (1950–2012 CE), 7 to 18 cm (1850–1950 CE), and 18 to 73 cm (0–1850 CE), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Pearson correlation coefficients of magnetic parameters and other environmental proxies.

Age		χ	χ_{ARM}	SIRM	S _{ratio}	χ_{ARM}/χ	$\chi_{\text{ARM}}/\text{SIRM}$	HIRM	SIRM/ χ	Trees	Herbs	TOC	TN	Ti	Al	Grain size
0-1850 CE	χ	1	0.941	0.824	0.253	−0.866	0.350	0.224	−0.851	0.293	−0.365	0.028	−0.443	0.712	0.673	−0.132
	χ_{ARM}		1	0.873	0.217	−0.660	0.383	0.263	−0.702	0.282	−0.327	−0.053	−0.338	0.693	0.542	−0.021
	SIRM			1	0.125	−0.629	−0.112	0.425	−0.416	0.215	−0.272	−0.269	−0.411	0.744	0.673	0.003
	S ratio				1	−0.170	0.201	−0.753	−0.235	0.060	−0.150	0.043	−0.391	−0.169	0.146	−0.174
	χ_{ARM}/χ					1	−0.134	−0.128	0.853	−0.118	0.187	−0.017	0.346	−0.321	−0.533	0.225
	$\chi_{\text{ARM}}/\text{SIRM}$						1	−0.262	−0.636	−0.022	0.064	0.494	0.340	−0.556	−0.635	−0.067
	HIRM							1	0.051	0.025	0.009	−0.214	0.076	0.536	0.243	0.181
	SIRM/ χ								1	−0.129	0.155	−0.422	−0.032	0.353	0.214	0.374
	Trees									1	−0.541	0.132	−0.223	0.493	−0.024	−0.418
	Herbs										1	−0.129	0.261	−0.507	−0.029	0.356
	TOC											1	0.621	−0.024	−0.773	−0.144
	TN												1	−0.184	−0.701	0.188
	Ti													1	0.359	−0.186
	Al														1	0.064
	grain size															1
	χ	1	0.990	0.980	−0.229	−0.901	−0.772	0.855	−0.795	−0.298	0.133	0.643	−0.156	−0.375	0.336	0.557
1850-2012 CE	χ_{ARM}		1	0.974	−0.219	−0.879	−0.724	0.854	−0.789	−0.240	0.135	0.569	−0.274	−0.268	0.355	0.529
	SIRM			1	−0.229	−0.866	−0.854	0.865	−0.704	−0.324	−0.057	0.656	0.061	−0.419	0.079	0.484
	S ratio				1	0.052	0.227	−0.609	−0.013	−0.007	0.203	−0.004	0.760	−0.491	−0.779	−0.491
	χ_{ARM}/χ					1	0.705	−0.696	0.936	0.290	−0.083	−0.656	−0.310	0.569	−0.013	−0.480
	$\chi_{\text{ARM}}/\text{SIRM}$						1	−0.727	0.416	0.080	0.316	−0.577	−0.494	0.530	0.398	−0.273
	HIRM							1	−0.561	−0.158	−0.200	0.308	−0.575	0.108	0.635	0.594
	SIRM/ χ								1	0.061	−0.274	−0.061	0.335	−0.113	−0.391	−0.385
	Trees									1	−0.876	−0.388	−0.517	0.598	0.472	0.384
	Herbs										1	0.352	0.447	−0.487	−0.434	−0.620
	TOC											1	0.740	−0.853	−0.852	0.238
	TN												1	−0.877	−0.940	−0.521
	Ti													1	0.867	0.051
	Al														1	0.745
	grain size															1

Table 3

Coercivity component parameters of the representative samples from Lugu Lake (SIRM: saturation isothermal remanent magnetization, $B_{1/2}$: the coercivity field at half of the SIRM, DP: dispersion parameter, M_{ri} : romance contribution).

Sample	SIRM (10^{-6} Am ² /kg)	Components	Log($B_{1/2}$) (mT)	$B_{1/2}$ (mT)	DP	M_{ri} (%)
LG09	7973.36	1	1.65	44.9	0.51	96
		2	2.80	631	0.88	4
LG24	3124.64	1	1.69	49	0.64	98
		2	2.86	695	1.00	2
LG52	2101.62	1	1.68	45.3	0.65	95
		2	2.93	732	0.67	5
LG100	2831.97	1	1.67	46.8	0.67	96
		2	2.89	785.2	0.62	4
LG148	2829.69	1	1.62	41.7	0.55	97
		2	2.87	791.7	0.66	3
LG192	2369.74	1	1.64	45.7	0.66	95
		2	2.91	794.3	0.60	5

minerals (Ma et al., 2014; Wang et al., 2018a, 2018b). Based on the relationships of χ vs. $\chi_{fd}\%$ and χ vs. χ_{ARM}/χ , the samples can be divided into three parts. The samples deposited between 1950 and 2012 CE were influenced by heavy metal pollution, which was caused by modern industrial activities (Lin et al., 2018; Wang et al., 2018a, 2018b). Although the values of TOC (total organic carbon) and TN (total nitrogen) are lower between 1950 and 2012 CE, showing the increase in human activities decrease significantly. The previous studies have shown that the causes of heavy metal pollution were mainly from atmospheric metal deposition from anthropogenic sources (Lin et al., 2018; Wang et al., 2018a, 2018b). We estimated that increase of magnetic mineral contents between 1950 and 2012 CE was caused by the atmospheric metal deposition rather than the local mining wastewater (Fig. 4). As also shown by TOC and TN values, intensified agriculture and catchment erosion caused by population expansion affected the samples deposited between 1850 and 1950 CE (Fig. 7h). The χ values of the samples deposited from 0 to 1850 CE were low, which indicated that natural sources were the main sources of magnetic minerals (Fig. 7a).

The magnetic minerals derived from natural sources, between 0 and 1850 CE, may be of biogenic and detrital origins with references intact (Liu et al., 2012; Wang et al., 2018a, 2018b). Magnetic mineral types must be confirmed before the natural sources of magnetic minerals are determined. First, S_{ratio} can indicate the relative proportions of hard

and soft magnetic minerals in the samples. The S_{ratio} values during the period of 0–1300 CE ranged from 0.94 to 0.98 with a mean of 0.96, which indicates that soft magnetic minerals dominated the magnetic signal of these sediments. Secondly, the magnetic hysteresis loop curves, κ -T curves, log-Gaussian decomposition of IRM acquisition curves and demagnetization curves demonstrate that magnetite dominated the magnetic mineral assemblage. Additionally, different magnetic minerals have different SIRM/ χ values, such as 11×10^3 A/m for magnetite, 209×10^3 A/m for pyrrhotite, and 261×10^3 A/m for hematite (Maher, 2007; Wang et al., 2018a, 2018b). The SIRM/ χ values of the sediments from Lugu Lake deposited during 0–1850 CE ranged from 6.52 to 11.10 $\times 10^3$ A/m, with a mean of 8.92×10^3 A/m. The SIRM/ χ values are similar to the values of magnetite, whose presence was also supported by the log-Gaussian decomposition of IRM acquisition curves. According to the bi-logarithmic plot of χ_{ARM}/χ vs. $\chi_{ARM}/\chi_{fd}\%$ in the lake sediments by Oldfield (1994), high $\chi_{ARM}/\chi_{fd}\%$ and χ_{ARM}/χ values, especially when $\chi_{ARM}/\chi_{fd}\%$ values are greater than 1.0×10^3 , indicate that the magnetite is biogenic in origin. As shown in Fig. 6c, the values of χ_{ARM}/χ ranged from 7.98 to 13.18, with a mean of 10.28, and $\chi_{ARM}/\chi_{fd}\%$ ranged from 19.61 to 43.02, with a mean of 29.61 (Fig. 5c). Both ranges are low, which indicates that the magnetic minerals of Lugu Lake sediments can primarily be attributed to detrital rather than biogenic sources.

However, many studies showed that magnetic minerals will be transformed or dissolved under excessive humid or water-logged conditions, represented by the dissolution of iron oxide (such as magnetite and maghemite) and the formation of iron hydroxide (such as goethite) and sulfides (such as greigite) (Roberts, 2015; Xu et al., 2020). The high κ -T curves indicate that magnetite and maghemite are the main magnetic carriers, and there are no signs for iron hydroxide or sulfides. In addition, previous studies have shown that the dissolution effects on magnetic minerals are modulated by the availability and reactivity by organic matter. When the contents of organic matter of sediments were high, both concentrations and grain size of magnetic minerals decreased (Snowball, 1993; Nowaczyk et al., 2001; Ao et al., 2010; Roberts, 2015; Wang et al., 2015). The positive relationship between χ and TOC and the negative relationship between χ_{ARM}/χ and TOC suggested that the dissolution effects for magnetic minerals are negligible (Table 2). All these indicated that dissolution effects for magnetic minerals were negligible. A significantly positive correlation exists between χ and SIRM (Table 2), which demonstrates a predominant contribution of ferrimagnetic minerals. Such a linear relationship between χ and SIRM

Fig. 7. Selected proxy parameters for (a) χ , (b) $\chi_{fd}\%$, and (c) S_{ratio} from Lugu Lake. (d) The ITCZ shifting index in the central Indo-Pacific region (Tan et al., 2019). (e) Composite temperature anomalies in China based on numerous proxy studies (Ge et al., 2013b). (f) Synthesized precipitation record of southwestern China (Tan et al., 2018). (g) SOI_{pr} (Southern Oscillation Index from precipitation proxies) (Yan et al., 2011). (h) Population variations of Yunnan, Sichuan (including Chongqing), Guangxi, Xizang, and Guizhou provinces during the past 2000 years (Zhao and Xie, 1988).

also reveals that changes in magnetization mainly reflect changes in the concentration rather than the grain size of magnetic particles.

5.2. Climatic variability derived from magnetic records and possible driving forces

Lugu Lake is a seasonal and closed alpine lake. The rivers flowing into Lugu Lake are quite short. Thus, magnetic minerals of the sediments mainly originate from the soil and weathered rock debris in the basin (Wang and Dou, 1998; Zhang et al., 2013). Compared with shallow lakes, the influences of water-level fluctuation on the sediments of Lugu Lake are negligible. Surface runoff intensity, erosion patterns, and provenance are the main factors affecting the magnetic minerals of sediments. The content and type of magnetic minerals in sediments are controlled by the weathering intensity. Generally, the weathering intensity is stronger in the warm and humid environment, which is more conducive to the formation and enrichment of magnetic minerals (Liu et al., 2021). Thus, we speculated that because of strong weathering and pedogenesis in tropical and subtropical areas of China, the ferromagnetic mineral contents of the surface sediments are high, and the grain size is coarse (Huang, 1996). When the chemical weathering of deep soil is relatively weak, the contents of antiferromagnetic minerals are higher. The χ values of deep soil are low, and the grain size are finer (Wang et al., 2011). Generally, when the amount of precipitation is small, the main erosion type is surface erosion (He et al., 2005). Conversely, when precipitation is strong, the main erosion types are mainly rill erosion, gully erosion, and bank erosion (He et al., 2005). Thus, most sediments carried by flowing water come from deeper soil. Precipitation variation determines the composition of terrestrial debris entering Lugu Lake by influencing the surface runoff intensity. Changes of catchment erosion types caused by changes in precipitation may have resulted in changes of the magnetic minerals, which also supported by the changes of grain size ($>63\ \mu\text{m}$). A previous study that reported χ values of 22 surface sediments and rock samples in the basin of Lugu Lake indicated that the average χ values of surface and rock samples were $575 \times 10^{-8}\ \text{m}^3/\text{kg}$ and $41 \times 10^{-8}\ \text{m}^3/\text{kg}$, respectively (Lin et al., 2017). As a result, χ , $\chi_{\text{fd}}\%$, and S_{ratio} can be used as sensitive indicators of paleoenvironmental change.

The values of χ , $\chi_{\text{fd}}\%$, and S_{ratio} during 0–1850 CE can be divided into two periods with high values and two periods with low values (Fig. 7a–c). The two high-value periods lasted from 0 to 400 CE and from 800 to 1300 CE, which correspond to the RWP and MWP, respectively. The two low-value periods lasted from 400 to 800 CE and from 1300 to 1850 CE, which correspond to the DACP and LIA, respectively. Evidently, the main climatic fluctuations of the past 2000 years in the Northern Hemisphere have been documented by the magnetic parameters of the sediments of Lugu Lake. Previous proxy studies suggested that conditions were wetter in southwestern China during the LIA than during the MWP (Fig. 7e, f), which is also supported by the magnetic parameters. In contrast to the magnetic characteristics of the LIA, the magnetic parameters also indicated wet conditions during the DACP in southwestern China. The main erosion types in the DACP were rill erosion, gully erosion, and bank erosion, and more hard magnetic minerals were caught and deposited in Lugu Lake in the DACP. Decreased abundance of tree pollen and increased herb pollen percentages during the MWP and RWP showed that the climatic conditions were dry, which was also supported by the Ti and Al contents (Wang et al., 2020). In these periods, the main erosion type was surface erosion. More surface sediments were transported into Lugu Lake, which resulted in the increase of SP and soft magnetic mineral contents.

The high-resolution magnetic record from Lugu Lake during 0–1850 CE provided us with an opportunity to examine the driving forces of paleoenvironmental change. A large number of studies have shown that many factors likely affect climatic variability in the southwest region of China, including El Niño/Southern Oscillation (ENSO) (Wang et al., 2000; Kumar et al., 2006), tropical Indo-Pacific sea surface temperature

(SST) (Li et al., 2001; Chu et al., 2014), and the Intertropical Convergence Zone (ITCZ) (An et al., 2015; Tan et al., 2019). However, what drives paleoenvironmental change in the southwest region of China still remains unclear. The shifts of the ITCZ together with ENSO are generally thought to be the two fundamental forcings that drive subtropical/tropical environmental and climatic changes. It is generally believed that there is an inverse relationship between ENSO, the ITCZ, and precipitation on an annual to decadal timescale (Yan et al., 2011; Sheng et al., 2015; Tan et al., 2019; Xu et al., 2019). The southward displacement of the ITCZ during the MWP and RWP, as well as relative northward displacement during the LIA and DACP, could have led to changes of rainfall (with relatively drier conditions in the MWP and RWP but wetter conditions in the LIA and DACP). In addition, it is widely accepted that there exists an inverse relationship between ENSO and rainfall in annual to decadal times (with more ENSO conditions during the MWP and RWP, and less ENSO conditions during the LIA and DACP). The $\Delta^{18}\text{O}$ -based ITCZ shifting index (ITCZ IS) proposed by Tan et al. (2019) shows an overall southward movement trend over the past two millennia (Fig. 7d). The Southern Oscillation index from precipitation proxies (SOI_{pr}) by Yan et al. (2011) was proposed based on the strong and persistent correlation between the Southern Oscillation index and precipitation in the past 2000 years (Fig. 7g). Based on comparison between magnetic parameters and both the ITCZ IS and SOI_{pr} , the high contents of magnetic minerals (low precipitation) correspond to the southward of ITCZ and strong ENSO intensity, vice versa. We speculate that ENSO and the ITCZ may have played important roles in influencing magnetic minerals during the last 2000 years. Therefore, it is likely that the combined effect of ENSO and ITCZ shifts could be responsible for the “wet/dry” hydroclimatic conditions over the tropical/subtropical Asian monsoon region.

6. Conclusions

High-resolution proxy records for the last 2000 years including magnetic parameters, diatoms, and geochemistry from Lugu Lake, northwestern Yunnan Province, were used to investigate ISM precipitation variability. Detailed magnetic measurements demonstrated that the dominant magnetic particles were magnetite. Natural sources and anthropogenic activities are considered to be the sources of the magnetic minerals based on the correlations of χ vs. $\chi_{\text{fd}}\%$ and χ_{ARM}/χ . The magnetic minerals of natural origins can be primarily attributed to detrital input rather than biogenic sources. Magnetic parameters including χ , $\chi_{\text{fd}}\%$, and S_{ratio} can be used as sensitive indicators of ISM change, and suggest that two significant dry periods occurred in the MWP (800–1300 CE) and RWP (0–400 CE) and two relatively wet intervals in the DACP (400–800 CE) and LIA (1300–1850 CE). Significant shifts of magnetic parameters in Lugu Lake sediments revealed considerable sensitivity to precipitation-controlled catchment erosion, which then influenced the magnetic minerals. The rainfall caused by the ISM during the last 2000 years may have been influenced by variations of ENSO and the migration of the mean position of the ITCZ.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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