

Article

The Influence of Magnetic Mineral Dissolution on PT2 Core Lacustrine Sediments from Southwestern China and Its Correlation with Indian Summer Monsoon Variability

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Abstract

The varying sensibilities of diverse proxies to Indian Summer Monsoon (ISM) variables lead to inconsistencies across individual studies. To attain a comprehensive understanding of the ISM driving mechanisms, it is essential to compile multi-proxy paleorecords from diverse monsoon-influenced areas. However, terrestrial ISM records spanning the last 200 ka remain sparse. Here, we performed a magnetic analysis of the PT2 core lacustrine sediments from the Heqing Basin, covering the past 184 ka, to reconstruct ISM variations from millennial to orbital timescales. According to the rock magnetic results, samples displaying strong magnetization are dominated by substantial amounts of magnetite and maghemite, accompanied by a broad grain-size distribution. Conversely, samples with weak magnetization show only limited quantities of fine-grained magnetite. The decrease in magnetic mineral concentration is attributed to the reduction in both coarse and fine-grained particles. Magnetic mineral dissolution intensity (MMDI) which combines magnetic susceptibility and frequency-dependent magnetic susceptibility, is highly sensitive to ISM changes. Consequently, we derived an ISM index from the MMDI and geochemical indicators of the PT2 core lacustrine sediments. This index exhibits pronounced “glacial–interglacial variations”, aligning with other regional ISM indicators from southwestern China and a variety of ISM-related proxies from a broader range of ISM-influenced areas. This suggests that ISM intensity is more sensitive to glacial boundary conditions in high-latitude ice sheets.

Keywords: rock magnetism; magnetic mineral dissolution; lacustrine sediments; Indian summer monsoon; Quaternary



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1. Introduction

The Indian Summer Monsoon (ISM) transferred heat and moisture from the Southern Hemisphere across the equator to the Asia mainland [1–4]. It significantly impacts the hydrological cycle, affecting the lives of billions in regions under its influence. Therefore, gaining a deeper understanding of the ISM driving forces is deemed crucial for predicting future climate changes [5–7].

Over recent decades, paleoclimatic research within the ISM region has been enriched by well-dated speleothem records [6,8–10], marine sediments [2,3,11–14], and lacustrine

and wetland sediments [1,4,15–18]. These studies have greatly enhanced our comprehension of the ISM dynamics and driving mechanisms at orbital and millennial timescales. However, there are still notable divergences in the timing and amplitude of these millennial fluctuations across different paleoclimate records [4,13,17,19]. Within the age uncertainties of different studies, each proxy may respond differently to climatic variables like temperature and precipitation, causing discrepancies in regional comparisons of monsoon intensity and variability [13,20]. Stalagmite $\delta^{18}\text{O}$ is commonly used as an ISM proxy [6,9,10], yet it may also be subject to the influence of diverse moisture inputs, subsurface water exchange, and regional climatic conditions [3,10]. Therefore, multiproxy paleorecords from different monsoon regions are necessary to gain a more comprehensive appreciation of the factors driving ISM variability [13].

The lacustrine successions in Southwest China provide continuous, high-resolution archives of continental climate and environmental change, recording the evolution of the ISM [1,4,16–18,21]. Nevertheless, the chronology of these successions depends largely on AMS ^{14}C dating, which is constrained to ages younger than ~50 ka. As a result, most prior investigations have concentrated on climatic fluctuations from the Last Glacial Maximum through the Holocene, and only a few well-constrained records extend further back into the late Quaternary. In response, we perform an integrated magnetic study on a drill core from the Heqing Basin, covering the past 184 ka. The integrated ISM indicator in this study showed pronounced “glacial–interglacial variations”. This was consistent with widespread ISM-related proxies from southwest China, North India and the Bay of Bengal. This suggests that the “glacial–interglacial” cycle is an intrinsic characteristic of the Indian monsoon, and ISM intensity is more sensitive to glacial boundary conditions in high-latitude ice sheets.

2. Materials and Methods

2.1. Study Area

The Heqing Basin, located at the southeastern edge of the Tibetan Plateau in southwestern China, is a north–south elongated basin confined by faults (as shown in Figure 1). It is a representative fault-controlled depression basin within Heqing County and constitutes one of the major intermontane basins in the Hengduan Mountains of northwestern Yunnan. Situated near a south–north axis, the basin is encircled by mountain ranges with summits exceeding 2500 m in elevation. The terrain within the basin is elevated in the northwest and descends towards the southeast. The bedrock of the catchment area consists of Triassic limestone in the western region, and Paleogene calcareous conglomerate, sandstone, and silt shale in the eastern part [1]. The regional climate is primarily influenced by the Indian monsoon, which brings about warm, humid summers and cold, arid winters [1,22,23]. Prior research on core samples from the basin revealed the presence of aquatic herb pollen [22] and freshwater diatoms [1] in the core sediments. Consequently, it is established that the sediments in the Heqing Basin are of a typical lacustrine origin [1,23]. To obtain a late Quaternary lacustrine record with elevated accumulation rates, we drilled the PT2 core at Pengtun village, which lies close to the modern sedimentary center of the Heqing Basin (geographic coordinates: 26°35′24.0″ N, 100°11′08.2″ E; elevation 2188 m). The core has a calibrated sedimentary interval of 33.9 m and a core recovery of 92%. Lithologically, the sediments are mainly grayish-brown and grayish-yellow calcareous muds and silt-bearing clays, punctuated by thin layers of silt and fine sand. In addition, conspicuous shell accumulations are observed in the clay-dominated sections between roughly 15.2 and 17.1 m.

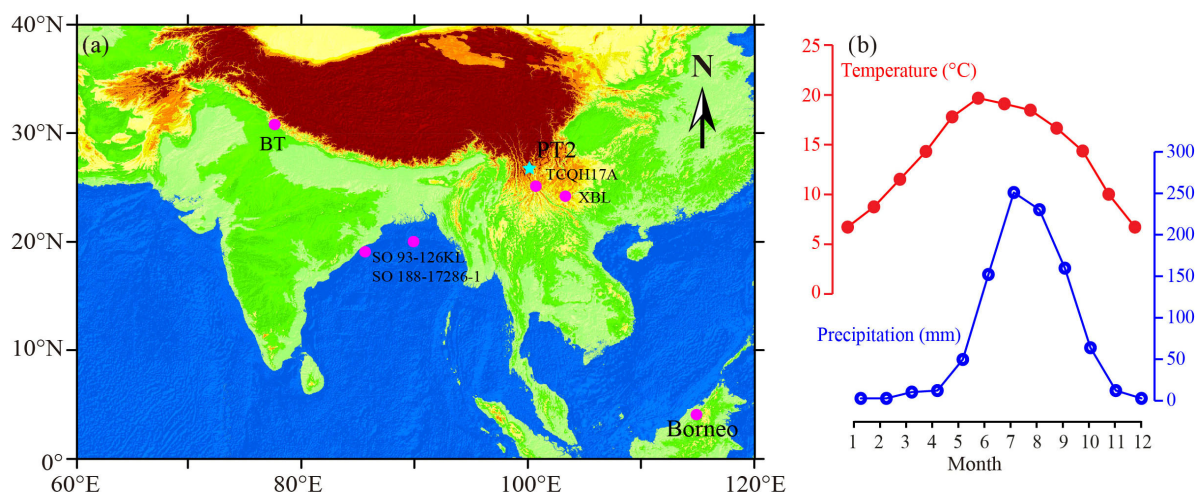


Figure 1. (a) Location of the PT2 drill core. The sites discussed in this study are shown in the figure. BT, Bittoo cave, Northern India [9]; XBL, Xiaobailong cave, southwest China [8]. (b) The climate of the study region from Heqing meteorological station (1981–2006) [1].

2.2. Chronology of the PT2 Drill Core

The age–depth model of the PT2 lacustrine core was based on age ties from geomagnetic excursions, peak-to-trough values of relative paleointensity curve and AMS ^{14}C dating results [16]. Taking four pieces of AMS ^{14}C dating data together with a single stratigraphic correlation point (correlated χ of PT2 core with the adjacent sedimentary core HQ2002) as constraints, four geomagnetic excursions were identified as Mono Lake, Laschamp, post-Blake and Blake excursions. Consequently, there were four relative paleointensity minima coinciding with troughs in the NRM/ARM record from the nearby HQ2002 core between 150 and 175 ka [16]. Between 60 and 100 ka, three lows in relative paleointensity were found to correlate with the minima of the global PISO-1500 stack [16]. Using these age ties as constraints, we estimated the age–depth model of the PT2 lacustrine succession, which extends over the past 184 ka (Figure 2).

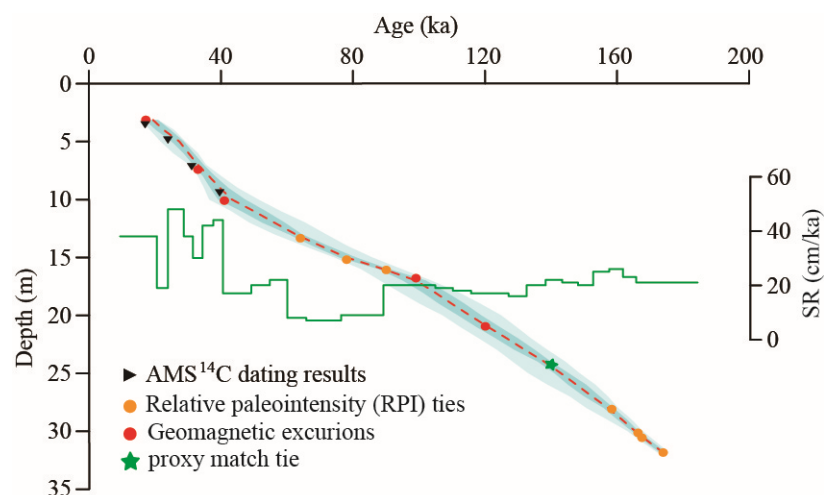


Figure 2. Chronology framework of the PT2 lacustrine core. Age constraints for the depth–age model were derived from four independent sources: radiocarbon measurements (AMS ^{14}C) are represented by black triangles; geomagnetic field excursions by red dots; RPI pinning points by brown dots; and stratigraphic correlation markers by green stars. The dark and light shading are 68.2 and 95.4 percentiles, respectively.

2.3. Magnetic and Geochemical Measurements

A total of 682 bulk samples were collected at 5 cm intervals for environmental magnetic and geochemical analysis. The magnetic susceptibility (χ) of each bulk sample, which weighed around 10 g, was determined using a Bartington Instruments MS2 magnetic susceptibility meter at frequencies of 465 and 4650 Hz. Each sample was tested twice, and the results were averaged to obtain the final value. The frequency-dependent magnetic susceptibility (χ_{fd}) was derived from the difference in χ values measured at the two different frequencies. Based on the peaks and troughs observed in the χ and χ_{fd} records, a subset of 28 samples was chosen for more detailed rock magnetic analysis. We measured the temperature-dependent magnetic susceptibility (χ -T) of these representative samples on an MFK1-FA Kappabridge (AGICO, s.r.o., Brno, Czech Republic) apparatus equipped with a CS-3 furnace. The measurements covered a range of 40–700 °C, with a ramp rate of 11 °C per minute. All heating and cooling runs were carried out in an argon environment to avoid oxidation of the sediment components. A Model 3900 vibrating sample magnetometer (VSM) (Princeton Measurements Corporation, Princeton, NJ, USA) was used to measure First-order reversal curve (FORC) diagrams. The maximum applied field was set at 1 T. We carried out all the measurements at the Environmental Magnetism Laboratory (Institute of Earth Environment, Chinese Academy of Sciences) in Xi'an, China.

Elemental concentrations (Rb, Sr, Ca, Ti, etc.) in the bulk sediments were measured by WD-XRF on an Axios instrument (PANalytical, Almelo, The Netherlands). A 5 g portion of dried sample was first pressed into a 32 mm pellet at 30 tons force for XRF analysis. For CaCO_3 determination, we adopted a titration method: 0.3 g of air-dried sample in a centrifuge tube was treated with 30 mL of 0.2 M HCl; after complete reaction, the supernatant was titrated with 0.1 M NaOH, with phenolphthalein (two drops) as an indicator until a pink color persisted. All analytical work was performed at the Institute of Earth Environment, Chinese Academy of Sciences (Xi'an).

In this paper, the min–max normalization method was used to normalize the magnetic parameters and element indicators.

3. Results

3.1. Downcore Variations in Paleoclimate Proxies in the PT2 Core

As illustrated in Figure 2, all the paleoclimate proxies, such as χ , χ_{fd} , Rb/Sr ratio, TOC, Ti and CaCO_3 content, exhibited significant differences in down-core variation. High χ is consistently associated with elevated Rb/Sr ratios and Ti content, whereas low χ_{fd} , low TOC and CaCO_3 content are observed. This is consistent with the previous studies on the adjacent sedimentary core HQ2002 [1,24,25] and HQ1996 [23] in the same basin. Collectively, these studies suggest that the Rb/Sr ratio and CaCO_3 content could serve as indicators of chemical weathering [23,24], while TOC content reflects the integration of terrestrial and aquatic organic matter [1]. Consequently, during glacial periods (approximate corresponds to MIS6), an intense input of terrigenous debris and physical weathering result in high χ , Rb/Sr ratio, and Ti content. Conversely, high χ_{fd} , TOC, and CaCO_3 content during interglacial periods (approximately corresponding to MIS5) are attributed to robust chemical weathering and the dissolution of magnetic minerals. However, as shown in Figure 3, the minimal variations in χ , Rb/Sr ratio, and Ti content during interglacial/interstadial periods, as well as in χ_{fd} , TOC, and CaCO_3 content during glacial/stadial periods, constrained our ability to fully comprehend the variability of the ISM using these proxies. To address this, we performed rock magnetic measurements on representative samples from both strong and weak magnetic intervals, with the aim of investigating the rock magnetic signatures of the lacustrine sedimentary samples and further discussing the reasons behind the subdued fluctuations in χ (χ_{fd}) during interglacial/interstadial (glacial/stadial) periods.

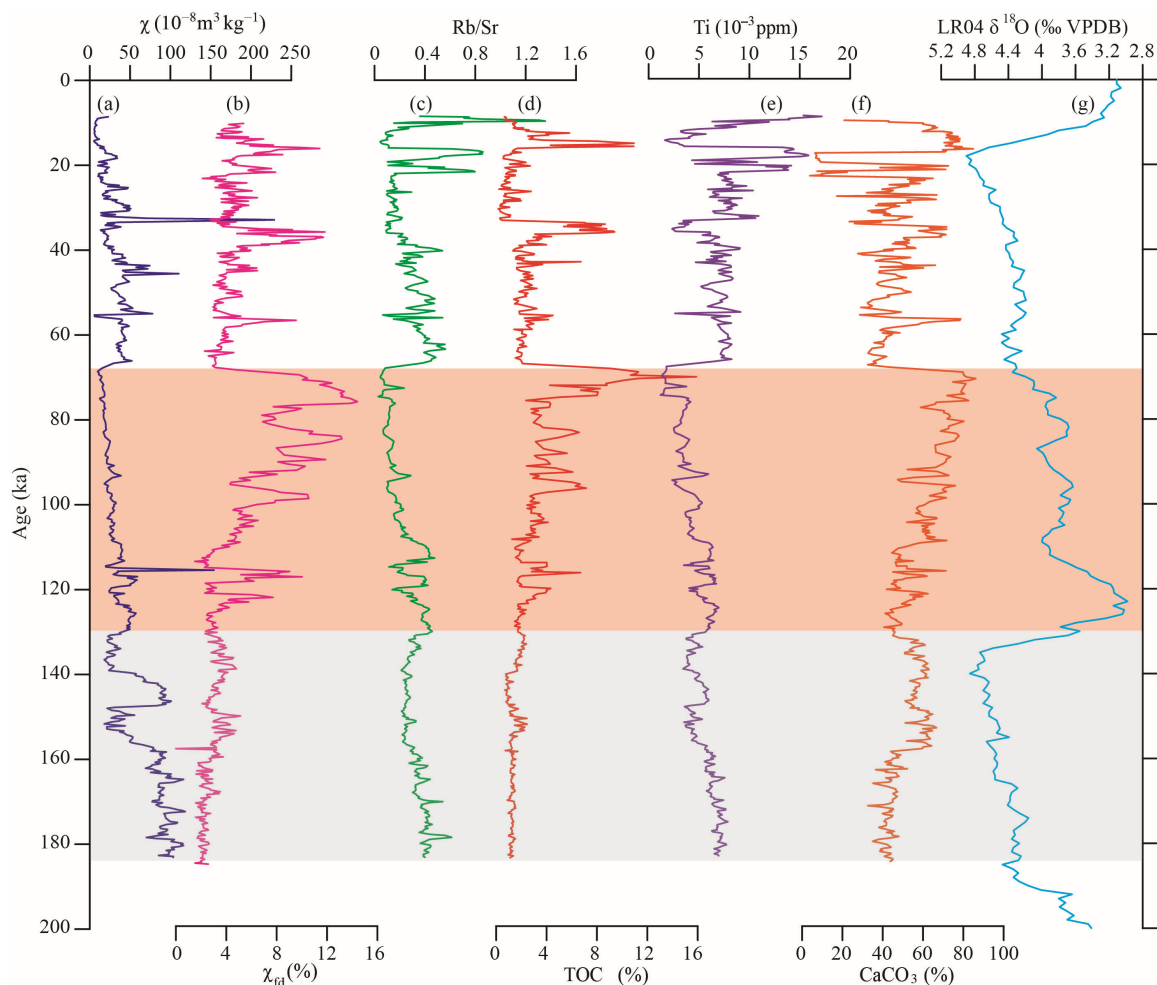


Figure 3. Stratigraphic variations in magnetic and geochemical data for the lacustrine sequence of core PT2. (a) χ ; (b) χ_{fd} ; (c) Rb/Sr ratio; (d) TOC; (e) Ti; (f) CaCO_3 content; and (g) LR04 $\delta^{18}\text{O}$. Reddish bar represents the interglacial-like period when χ , Rb/Sr ratio, and Ti content exhibited minimal variations. Gray bar represents the glacial-like period when χ_{fd} , TOC, and CaCO_3 content exhibited minimal variations.

3.2. Rock Magnetic Results of Typical Samples from the PT2 Core

The FORC diagram is a valuable tool for assessing the domain state of ferrimagnetic minerals. The representative FORC diagrams in Figure 4 exhibit two main characteristics: closed contours centered at ~20 mT, and a vertical “wall” for B_c values < 5 mT. The former coercivity (around 20 mT) indicates that soft magnetic phases—namely, magnetite and maghemite—are present as single-domain (SD) grains [26]. The latter feature, on the other hand, implies that superparamagnetic (SP) grains may also contribute to the magnetic signal [27]. The significant vertical spread contours in the FORC diagrams (Figure 4) indicate that detrital magnetic grains in vortex states existed in strong magnetic samples [28]. Therefore, samples from the strong magnetic intervals showed a broader magnetic grain size distribution, which encompassed SD, SP, PSD and vortex state magnetic grains. In comparison, samples from weak magnetic intervals had fewer SP and SD particles.

The thermal analysis of typical samples showed a notable decline in the heating curve of χ at around 585 °C, which matched the Curie temperature of magnetite. The mild to moderate decline in the heating curve of χ between 320 °C and 350 °C (Figure 4) was also observed in samples from topsoil samples from the Heqing Basin [23] and lacustrine sediments from HQ2002 core [25]. It was interpreted as the results of the thermal transformation of maghemite into hematite during the heating process [16,23]. Therefore, we

infer that the samples exhibiting strong magnetization contain magnetite, with maghemite also being a possible constituent, whereas the weak magnetic samples have a reduced concentration of magnetite.

Rock magnetic analyses have identified magnetite and maghemite with low coercivity as the predominant magnetic minerals in the PT2 core lacustrine sediments. Figure 4 reveals a clear negative correlation between magnetic concentration (χ) and grain-size-sensitive parameter (χ_{fd}). In terms of sample characteristics, the strongly magnetic samples are rich in magnetite and maghemite, indicating a considerably broad spectrum of grain sizes, whereas those with weak magnetism are composed of only minor SP and SD magnetite. As χ decreased, the vertical and horizontal contours in areas where B_c exceeds 20 mT gradually weakened and nearly vanished in the weak magnetic samples. Concurrently, the closed contours centered at approximately $B_c = 20$ mT, indicative of an SD signal, also diminished. The shift in the contour center towards the Bu axis and their progressive merging with the SP signal suggest that magnetic particles became finer over time. Hence, we conclude that the reduction in magnetic mineral concentration in the PT2 core lacustrine sediments is due to the decrease in both coarse-grained (PSD and vortex states) and fine-grained (SP and SD) particles. Ultimately, coarse-grained (PSD and vortex states) particles converted to fine-grained (SP and SD) ones, resulting in elevated χ_{fd} values in the weak magnetic samples.

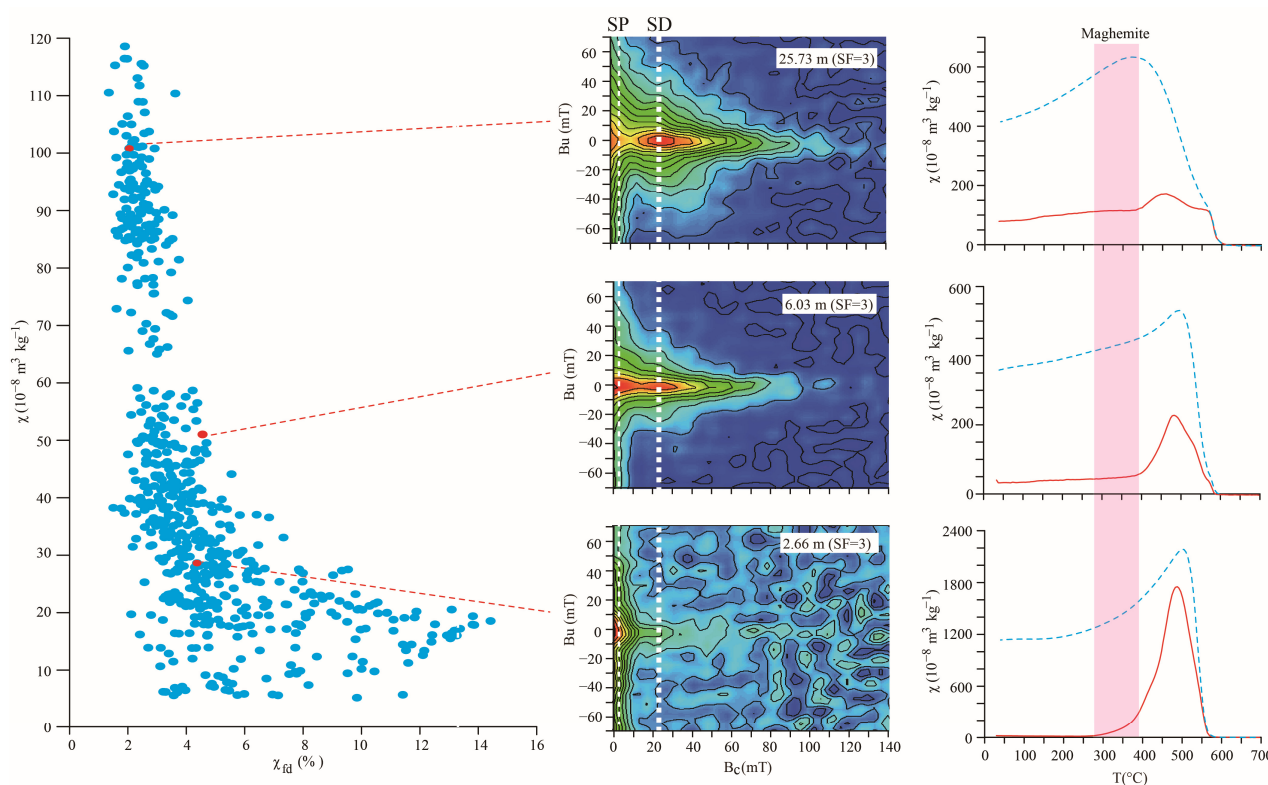


Figure 4. Magnetic characterization of selected samples based on FORC analysis and χ -T (temperature-dependent susceptibility) curves. Representative samples were collected by different combinations of χ and χ_{fd} (**left panel**). In the middle panel in FORC diagrams, SD is a single domain and SP represents superparamagnetic particles. In the **right panel**, the shallow red bar in the χ -T curves indicated the thermal conversion of maghemite to hematite.

4. Discussion

4.1. The Impact of Magnetic Iron Oxide Dissolution on Magnetic Mineral Concentration and Grain Size

As depicted in Figure 3, the magnetic concentration parameters in the PT2 sedimentary core display significant down-core variations. During glacial-like periods (approximately corresponding to MIS6), the magnetic concentration parameter (χ) is elevated and variable, while the magnetic grain size parameter (χ_{fd}) is low and stable. Conversely, interglacial-like periods (approximately corresponding to MIS5) are marked by high χ_{fd} values with significant fluctuations and low χ values with minimal variation. This contrasting pattern of changes in magnetic concentration and grain size parameters between “glacial/stadial and interglacial/interstadial” climate states is common in lacustrine sediments from paleo-Lake Heqing [23,25], Lake Tengchongqinghai [29], Lake PumoyumCo [30], Lake Ohri [31], Dahu Swamp [32], Lake Junín [33], and Tobago Basin [34], as well as in marine sediments from the equatorial Indian Ocean [35], northern Mariana Basin [27], Nankai Trough [36], eastern Mediterranean Sea [37], and Isfjorden [38], and is typically attributed to the reductive dissolution of magnetic oxides [16,39–42]. Experimental studies have demonstrated that fine-grained iron oxides (particularly maghemite) undergo dissolution more readily than their coarser counterparts [43,44], which ultimately gives rise to an overall increase in the grain size of detrital magnetic minerals. However, the interval with a high magnetic concentration (χ) and low fine-grained parameter (χ_{fd}) in the PT2 core lacustrine sediments (Figure 3) is not captured. This implies that intensive and prolonged dissolution may convert coarse-grained particles (MD and PSD) to finer ones, along with the dissolution of fine-grained (SP and SD) magnetic minerals, resulting in an overall decrease in magnetic mineral grain sizes (higher χ_{fd}) [39].

In the PT2 core lacustrine sediments, intervals of weak magnetic mineral dissolution are characterized by higher magnetic mineral concentration and a more extensive grain-size spectrum covering SP, SD, and PSD fractions. In contrast, intervals of strong magnetic mineral dissolution have a higher proportion of fine-grained particles and a narrower magnetic grain-size distribution (primarily SP and SD particles). During the weak magnetic mineral dissolution state, although the fine-grained particles were dissolved preferentially, significant distributions in FORC diagrams (Figure 4) indicate that a considerable amount of fine-grained particles remain. Both fine-grained and coarse-grained particles are dissolved simultaneously, reducing the total content of detrital magnetic particles. The broader magnetic grain-size distribution evident in FORC diagrams suggests a limited increase in the proportion of fine-grained particles (a 2–3% increase in χ_{fd}). Therefore, during the weak magnetic mineral dissolution state, the magnetic concentration parameter is sensitive to dissolution changes, while the magnetic grain size parameter is less responsive. Conversely, during the strong magnetic mineral dissolution state, intensive and prolonged dissolution removes most dissolvable magnetic grains, significantly reducing the magnetic concentration parameter to a very low value with minimal fluctuation. The original fine magnetic grains are removed, and the original coarse magnetic grains are gradually dissolved into fine grains, making the magnetic grain size parameter more sensitive to changes in magnetic mineral dissolution. Thus, the magnetic grain size parameter is more sensitive during strong magnetic mineral dissolution, while the magnetic concentration parameter is more sensitive during weak magnetic mineral dissolution, as shown in Figure 3. Subsequently, we used normalized χ_{fd} minus normalized χ as a proxy of magnetic mineral dissolution intensity (MMDI). As shown in Figure 5, the MMDI generally has a linear correlation with χ in weak magnetic mineral dissolution states (MMDI < 0.2) and with χ_{fd} in strong magnetic mineral dissolution states (MMDI > −0.2). This suggests that the MMDI is a reliable and effective indicator in paleoclimatic research on lacustrine sediments.

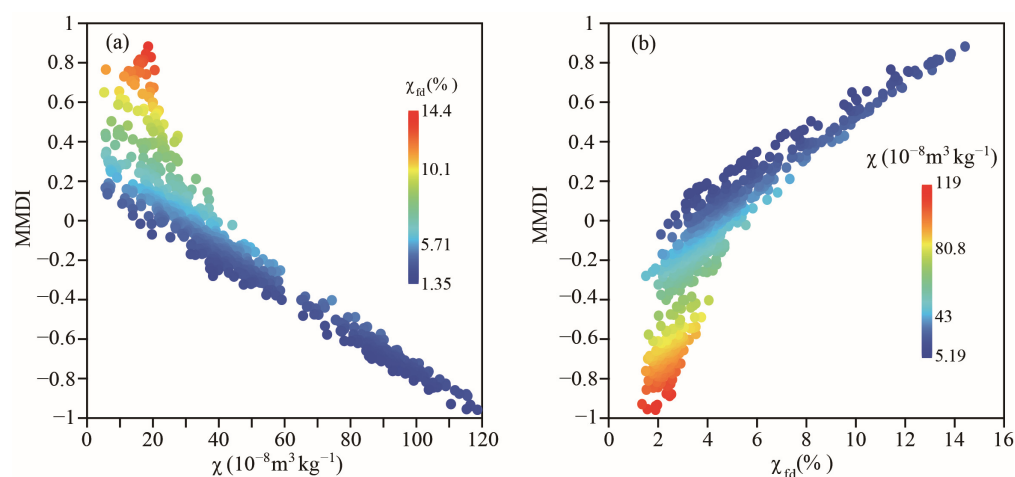


Figure 5. (a) Correlation between the magnetic mineral dissolution index (MMDI) and magnetic mineral concentration (χ) in the PT2 core lacustrine sediments. (b) Correlation between the MMDI and magnetic mineral grain size (χ_{fd}) parameters in the PT2 core lacustrine sediments.

4.2. “Glacial–Interglacial” Variations in the ISM Domain and Its Possible Mechanisms

Previous research has shown that the dissolution of magnetic minerals is tightly linked to changes in the sedimentary environment [25,39,41]. MMDI from the PT2 core lacustrine sediments clearly shows strong ISM during interglacial periods (MIS 1 and 5) and weak ISM during glacial periods (MIS2–4). This “glacial–interglacial” pattern aligns with other regional ISM indicators from Southwest China, such as mean annual air temperature (MAAT) [18] and mean annual precipitation (MAP) [17] reconstructions from Lake Tengchongqinghai and speleothem $\delta^{18}\text{O}$ of the XBL cave [8]. However, it differs from the pure precession cycle observed in speleothem $\delta^{18}\text{O}$ records from East China [45]. As shown in Figure 6, extensive evidence from rock magnetic data obtained from the western equatorial Indian ocean [14], sea surface temperature (SST) [11], sea surface salinity (SSS) [46], δD records [47] and some other precipitation-related proxies [5,12] from the Bay of Bengal, the δD record from Southern Sumatra [48] and speleothem $\delta^{18}\text{O}$ record from northern Borneo [49], suggests that the “glacial–interglacial” pattern is an inherent characteristic of the ISM. Such observations are broadly in line with the hypothesis that ISM variations are particularly susceptible to glacial boundary conditions in high-latitude ice sheets and greenhouse gases [6,12,14,49]. The similar “glacial–interglacial” variations in the $^{231}\text{Pa}/^{230}\text{Th}$ record (a proxy for AMOC activity) from North Atlantic ocean [50] and mean grain size of sortable silt and fine sand record (used as the Antarctic Circumpolar Current flow speed proxy) from the central Drake Passage [51] suggested a closed association between ISM and variations in AMOC and Antarctic Circumpolar Current flow. A potential driving mechanism is that the heat and moisture in the ISM domain, transported from the Southern equator–tropical Indian Ocean and Pacific Ocean, are controlled by the mean annual position of the Inter-Tropical Convergence Zone (ITCZ) [20,21,52]. The migration of the ITCZ is believed to be triggered by hemispherically asymmetric changes in the extra-tropics in the AMOC energy transport [52]. Furthermore, a multiproxy stalagmite record from central Vietnam revealed sea-level modulation of southeast Asian autumn monsoon rainfall variability [6]. The model simulation presented that in the low-latitude monsoon area, variations in the ice sheet were more important than insolation in impacting the location of ITCZ [53].

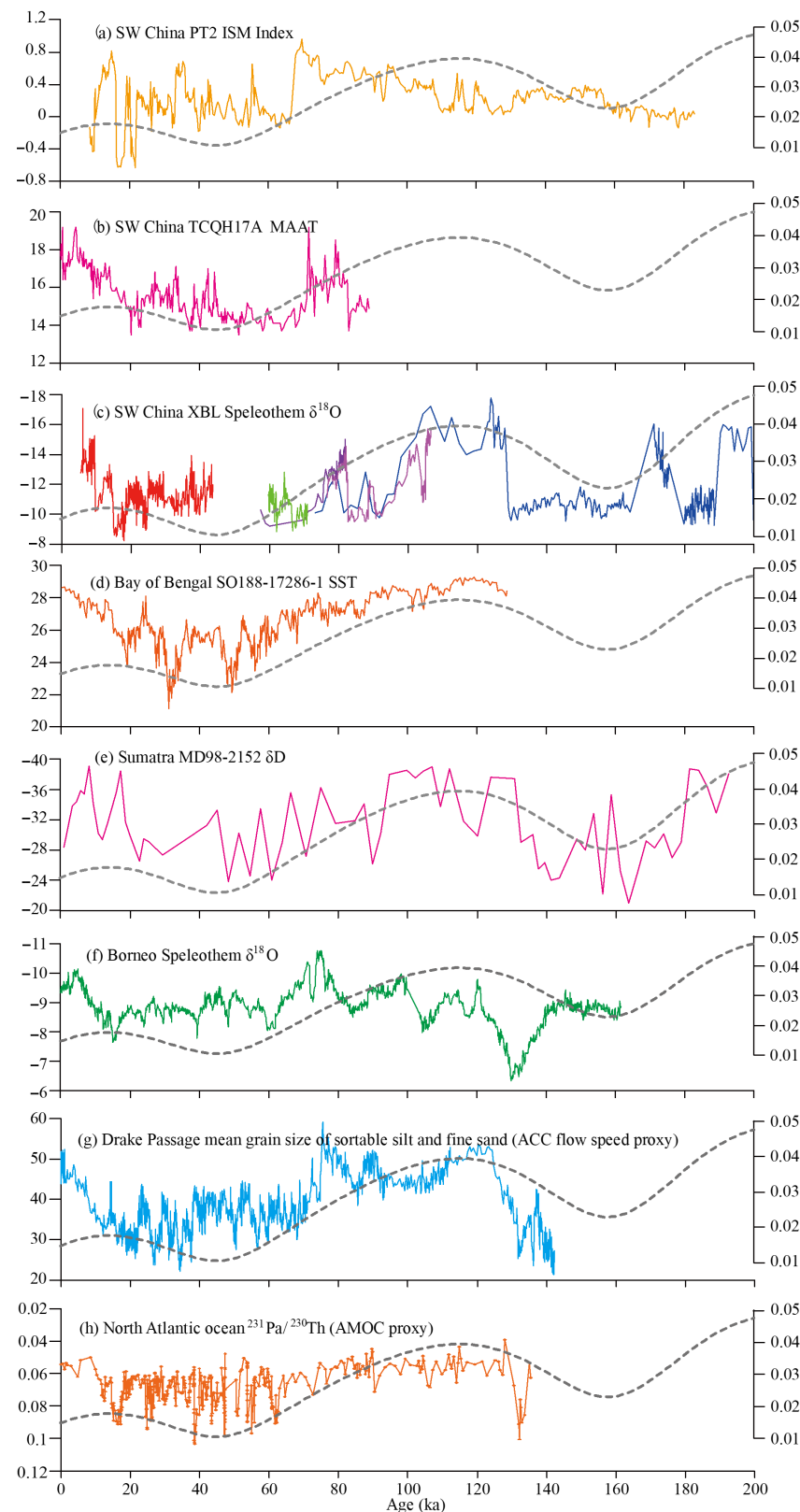


Figure 6. “Glacial–interglacial” variations in the ISM domain and its possible mechanisms. (a) Magnetic mineral dissolution intensity (MMDI) in PT2 core from SW China (this study); (b) MAAT reconstruction in TCQH17A core from SW China [18]; (c) Speleothem $\delta^{18}\text{O}$ in Xiaobailong (XBL) cave from SW China [8]; (d) SST reconstruction by $\text{U}^{k'}_{37}$ in SO188-17286-1 hole from the Bay of Bengal [11]; (e) δD record in MD98-2152 from Southern Sumatra [48]; (f) Speleothem $\delta^{18}\text{O}$ record from northern Borneo [49]; (g) Drake Passage mean grain size of sortable silt and fine sand (ACC flow speed proxy) [51] and (h) North Atlantic ocean $^{231}\text{Pa}/^{230}\text{Th}$ (AMOC proxy) [50]. The dashed gray line in each image is the eccentricity parameter.

5. Conclusions

Magnetic parameters showed that magnetic concentration was sensitive to ISM variations during glacial/stadial-like periods, while magnetic grain size was sensitive to the ISM variations during interglacial/interstadial-like periods. Higher magnetic mineral concentration was caused by broader magnetic grain-size distribution, while low magnetic mineral concentration was attributed to a limited number of SP and SD particles. The reduction in magnetic mineral concentration in the PT2 core lacustrine sediments is due to a decrease in both coarse-grained (PSD and vortex states) and fine-grained (SP and SD) particles. Magnetic mineral dissolution in the PT2 core lacustrine sediments was closely related to the ISM variations. The widespread “glacial–interglacial” variations in the PT2 core ISM index and other ISM proxies were consistent with the $^{231}\text{Pa}/^{230}\text{Th}$ record from North Atlantic ocean and mean grain size of the sortable silt and fine sand record (used as the Antarctic Circumpolar Current flow speed proxy) from the central Drake Passage. This suggests that the ISM is closely associated with variations in the Atlantic Meridional Overturning Circulation (AMOC) and Antarctic Circumpolar Current flow.

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Data Availability Statement: The datasets presented in this study can be found in the article.

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Conflicts of Interest: The authors declare no conflicts of interest.

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