Elemental Geochemical Records of Holocene Sediments from the Wenquan Area, Western Tianshan Mountains, and Their Paleoenvironmental Significance (Postprint)

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Abstract

Through comprehensive analysis and comparative study of five characteristic elemental ratios (Rb/Sr, Sr/Ca, Ti/Sr, Mg/Ca, Zr/Sr) in borehole sediments from the Wenquan Wetland in the Western Tianshan Mountains, the Holocene climate change forcing pattern of the wetland was identified. The results demonstrate that: (1) The Wenquan Wetland sediments provide a reliable record of Holocene climate change in Xinjiang, with the Holocene climate undergoing a five-stage variation process: warm-dry (10300–7700 cal a BP) – transitional period from warm-dry to warm-wet (7700–7000 cal a BP) – warm-wet (7000–4200 cal a BP) – temperate-dry (4200–2900 cal a BP) – cold-wet (2900–81 cal a BP). (2) These findings correspond well with climate changes indicated by other proxy indicators in neighboring regions, verifying the Holocene climate pattern of warm-dry conditions in the early period and cold-wet conditions in the mid-to-late period in Xinjiang, and indicating that the Holocene climate in Xinjiang follows a westerlies pattern. (3) The cooling process indicated by the chemical elemental ratios of the Wenquan Wetland sediments during 7700–7000 cal a BP is a response to the global cooling event at 8200 cal a BP; the warming process indicated during 4200–2900 cal a BP may be related to the secondary warming event of the Holocene reflected in the Dunde ice core during 3000–2900 cal a BP. Simultaneously, comparison with other proxy indicators in surrounding regions reveals that the gradual wetting trend in Xinjiang may be the result of combined effects of Holocene temperature decrease and precipitation increase.

Full Text

Holocene Sediment Element Geochemical Records and Their Paleoenvironmental Significance in the Wenquan Area of the Western Tianshan Mountains

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Abstract

This study presents a comprehensive analysis of five characteristic element ratios (Rb/Sr, Sr/Ca, Ti/Sr, Mg/Ca, Zr/Sr) from Holocene sediment cores in the Wenquan wetland of the western Tianshan Mountains, Xinjiang. Through integrated analysis and comparative research with regional proxy records, we identify the dominant climate forcing patterns in the Wenquan wetland during the Holocene. The results demonstrate that the Wenquan wetland sediments provide a reliable record of Holocene climate change in Xinjiang, revealing five distinct climatic stages: a warm-dry period (10300–7700 cal a BP), a transition from warm-dry to warm-wet conditions (7700–7000 cal a BP), a warm-wet period (7000–4200 cal a BP), a warm-dry period (4200–2900 cal a BP), and a cold-wet period (2900–81 cal a BP). This sequence aligns well with climate changes indicated by other proxy indicators in adjacent regions, confirming that Xinjiang experienced a warm-dry early Holocene and a cool-wet mid-to-late Holocene, consistent with the westerly-dominated climate pattern. The sediment geochemical ratios also show a clear response to the global 8.2 ka cooling event around 8200 cal a BP, while the warming trend during 4200–2900 cal a BP may correlate with the Holocene sub-high temperature event reflected in the Dunde ice core. Comparative analysis with regional proxies suggests that the gradual humidification trend in Xinjiang likely resulted from the combined effects of decreasing temperature and increasing precipitation during the Holocene.

Keywords: wetland; element ratio; Holocene; climatic environment; regional comparison; Xinjiang

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1. Study Area Overview

The study area is located in the Bortala River National Wetland Park (44°58 – 45°12 N, 80°53 –81°39 E) in Wenquan County, Xinjiang [Figure 80: see original paper]. The Tianshan Mountains represent the most precipitation-rich region in Xinjiang, though Wenquan County receives relatively limited rainfall due to topographic constraints. The area experiences a continental mid-temperate arid to semi-arid climate, primarily controlled by mid-latitude westerly circulation [1,2]. Characterized by indistinct seasons, long winters without severe cold, and short summers without extreme heat, the region's climate is shaped by its position in the northwest arid zone of China where westerly circulation is particularly significant [3,4]. The ecological system is fragile and the natural environment is structurally simple, making it highly sensitive to climate responses and thus a focal point for paleoclimate research [5,6].

The Bortala and Otuksay Rivers are the two main waterways in the county, fed by precipitation and glacier meltwater. Grassland vegetation predominantly occurs at elevations between 1200–2400 m, with coverage below 50% [7]. According to meteorological station data, Wenquan County exhibits low temperatures, high humidity, and low evaporation rates [8], with a multi-year average precipitation of 394.3 mm (maximum: 223.5 mm; minimum: 77.8 mm), mean annual temperature of 3.7 °C, and average annual evaporation of 1540.3 mm.

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2. Materials and Methods

In September 2017, we collected a 126.75 cm semi-cylindrical peat core from the center of Wenquan wetland (44°58 N, 80°01 E) using a Russian corer with an inner diameter of 5 cm. The core was sectioned at 0.25–1 cm intervals, with samples stored in labeled polyethylene bags, yielding 127 samples (1–2 g per sample). The upper 50.25 cm section was not fully recovered due to high water content and loose compaction of the peat layer. The lower 76.5 cm section was used for this study. The core consists of an upper brown-black peat layer (34.75 cm) and a lower black-gray silt layer (41.75 cm) [Figure 2: see original paper].

We selected 14 samples for AMS ^{14}C dating and established an age-depth model using the Bacon software package [9] [Figure 2: see original paper]. In the laboratory, samples were ground to 200 mesh and digested with HNO_3-$HClO_4$-HF at 105 °C. Element concentrations (Rb, Sr, Ti, Zr, Mg, Ca) were measured using a Leeman Labs Profile ICP-AES (inductively coupled plasma atomic emission spectrometer) at the State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences. Parallel analysis error was less than $±$5%.

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3. Analysis

3.1 Environmental Significance of Geochemical Element Ratios During supergene geochemical processes, Rb is a weakly mobile element that remains in weathering products, while Sr is highly mobile and can be transported by surface runoff to accumulate in low-lying areas. Therefore, the Rb/Sr ratio indicates the intensity of chemical weathering in the watershed—higher ratios reflect weaker weathering intensity, reduced rainfall, and relatively dry climate [10].

In arid regions, Sr/Ca and Mg/Ca ratios in sediments commonly indicate cold-warm and dry-wet conditions. The solubility of Ca^{2+} carbonates or sulfates is relatively low, precipitating in early stages, while Mg^{2+} and Sr^{2+} salts have higher solubility and generally precipitate after continued concentration following Ca^{2+} precipitation. Thus, high Sr/Ca and Mg/Ca ratios indicate strong evaporation, relatively arid climate, and low effective moisture, whereas low ratios suggest reduced evaporation, relatively humid climate, and higher effective moisture [11,12].

Ti and Zr are stable elements that typically reside in minerals. Ti/Sr and Zr/Sr ratios primarily reflect rainfall leaching intensity—increased rainfall and relatively humid climate lead to lower ratios, while reduced rainfall results in higher ratios [13,14].

3.2 Reconstruction of Holocene Environmental Evolution in Wenquan Wetland Based on the climatic and environmental significance of the five element ratios and their variation characteristics [Figure 3: see original paper], combined with ^{14}C chronology, the Holocene paleoclimate evolution recorded in the WQ-1 core can be divided into five stages:

Stage 1: Warm-dry climate period (126.75–112.75 cm, 10300–7700 cal a BP). During this period, all five element ratios reached their highest and most stable values throughout the profile, indicating relatively high temperatures and low rainfall in the Wenquan wetland. Under these hydrothermal conditions, weathering intensity in the watershed was weak, evaporation was strong, and effective moisture was low. This warm-dry climate pattern is traceable in adjacent regions, such as the aeolian deposits in Ulungur Lake and Bosten Lake during 10000–7000 cal a BP [15,16], and the significant lake regression in Sayram Lake around 7800 cal a BP [17], which was a swamp or marsh environment in the early Holocene [18].

Stage 2: Transition from warm-dry to warm-wet conditions (112.75–109.00 cm, 7700–7000 cal a BP). During this period, the five element ratios declined rapidly, likely indicating rapid temperature decrease, significantly increased rainfall, and more suitable climate compared to the previous stage. These hydrothermal conditions facilitated chemical weathering, enhanced weathering intensity in the watershed, and increased hydrodynamic forces, causing significant decreases in Rb/Sr, Ti/Sr, and Zr/Sr ratios. Simultaneously, reduced temperatures decreased Ca^{2+} precipitation, leading to lower Sr/Ca and Mg/Ca ratios. This transition reflects a rapid increase in regional effective moisture and temperature decrease, possibly corresponding to the global 8.2 ka cooling event [19], which is also evident in other Xinjiang Holocene records, such as the cold-wet environment event reflected by ostracod stable isotopes in Ulungur Lake around 7630 cal a BP [20] and the strong cold-wet event indicated by Ebinur Lake during 8250–7900 cal a BP [21].

Stage 3: Warm-wet climate period (109.00–89.25 cm, 7000–4200 cal a BP). The five element ratios showed a "two peaks with a valley" pattern, with slightly decreased values, indicating continued temperature decline, increased rainfall, and further enhanced weathering intensity. Increased surface runoff promoted the accumulation of mobile elements, reducing Rb/Sr, Ti/Sr, and Zr/Sr ratios. The region experienced warm-wet conditions, possibly representing the Holocene climate optimum for Wenquan wetland. Similar patterns are observed in Sayram Lake (6500–3500 cal a BP) [22] and Barkol Lake (7000–4200 cal a BP) [23], where low Sr/Ca and Ti/Sr values indicate relatively humid climate. After the early Holocene, large-scale effective moisture increase across Xinjiang led to the development of numerous lakes [20,35,41].

Stage 4: Warm-dry climate period (89.25–83.25 cm, 4200–2900 cal a BP). During this period, the five element ratios increased, indicating rising temperatures, reduced rainfall, weakened weathering intensity, and decreased hydrodynamic forces. Reduced Sr input caused Rb/Sr, Ti/Sr, and Zr/Sr ratios to increase, while higher temperatures promoted Ca^{2+} precipitation, increasing Sr/Ca and Mg/Ca ratios. The inverse variation of element ratios peaked around 3300 cal a BP, suggesting a possible high-temperature drought event that may correlate with the Holocene sub-high temperature event reflected in the Dunde ice core [24]. Similarly, Sayram Lake [25] and Barkol Lake [26] records indicate relatively dry climate during 4300–2300 cal a BP, while the sudden decrease in cellulose $\delta^{13}C$ in Caotanhu peat also suggests a high-temperature event during 3000–2800 cal a BP.

Stage 5: Cold-wet climate period (83.25–50.25 cm, 2900–81 cal a BP). In the late Holocene, the five element ratios continuously decreased to their minimum values, indicating persistent temperature decline and continuous rainfall increase, with gradually enhanced weathering intensity. Increased rainfall and runoff enhanced Sr input, reducing Rb/Sr, Ti/Sr, and Zr/Sr ratios, while persistent temperature decrease lowered Sr/Ca and Mg/Ca ratios. This pattern is supported by records from Ebinur Lake [27], Sayram Lake [28], Barkol Lake [29], and Torekul Lake [30], which all indicate humid climate in the late Holocene. The XARM/SIRM ratio from Lujiaowan [31] and Caotanhu Lake [32] also shows gradually increasing values since 3000 cal a BP, indicating increased effective moisture.

3.3 Regional Climate Record Comparison Our reconstruction based on sediment geochemical ratios reveals a Holocene climate succession in the study area characterized by warm-dry early Holocene and gradually humidifying mid-to-late Holocene. This pattern shows high consistency with other proxy indicators in Xinjiang [20,26,35-45,64]. The gradual humidification trend in Xinjiang is also supported by climate model simulations. For example, the Kiel Climate

Model simulation shows that mean annual effective moisture in the mid-latitude arid zone (40°–55°N, 70°–97.5°E) fluctuated upward during 10000–1200 cal a BP [70]. Simulations of average lake level, regional evaporation, and precipitation in northern Central Asia indicate that regional Holocene precipitation and average lake level increased significantly, while evaporation decreased slightly [71].

However, the humidity changes in Wenquan wetland are out-of-phase with those in the East Asian monsoon region. Reconstructions from the East Asian monsoon margin show gradual humidification in the early Holocene and significant humidity decrease in the mid-to-late Holocene [66]. Cheng et al. [67] suggest that low $\delta^{18}O$ values in stalagmites during periods of high summer solar radiation may result from direct or indirect Asian monsoon influence.

4. Discussion

Some studies suggest that the summer monsoon may have penetrated into Xinjiang during the mid-Holocene [68]. However, Zhang et al. [69] compiled several climate proxy records from Xinjiang and concluded that the region remains dominated by the westerly pattern. The five chemical element ratios from Wenquan wetland indicate a warm-dry early Holocene and gradually cold-wet mid-to-late Holocene, consistent with Zhang et al. [26] and showing out-of-phase relationship with typical monsoon and East Asian monsoon marginal regions.

The sedimentary environment transitioned from silt to peat during 4200–2900 cal a BP, and peat formation and accumulation depend on stable and sufficient water supply [65]. Around 7700 cal a BP, temperature recovery and alpine glacier meltwater replenishment may have promoted vegetation growth, providing abundant organic matter for peat formation. After the high-temperature drought event around 3300 cal a BP, the climate turned warm-wet with sufficient water supply, and the previously grown plants accumulated rapidly under waterlogged conditions, forming peat. Thus, peat formation corroborates the gradual humidification trend in Wenquan wetland.

Mechanistic studies of Holocene climate change in Xinjiang suggest that humidification may be related to winter solar radiation intensity and temperature increase [26,75]. Since the early Holocene, enhanced winter solar radiation in the Northern Hemisphere has increased the temperature gradient between mid- and high-latitude regions, strengthening westerly intensity [37,77-78]. Meanwhile, increased evaporation from the Caspian Sea, Black Sea, and Mediterranean Sea introduced more moisture into the westerly system, bringing additional moisture to Xinjiang [35,78]. Numerical simulations show that enhanced winter westerly intensity increased upstream evaporation and moisture transport [78]. Reduced glacier meltwater and enhanced evaporation introduced more water vapor into the westerly system, gradually humidifying Xinjiang [25,78]. Additionally, decreasing summer solar radiation during the Holocene reduced evaporation in Xinjiang, increasing effective moisture [37].

The Holocene climate change in Wenquan wetland shows slight temporal differences in humidification timing and optimal climate periods compared with neighboring regions, but the overall trends are similar. This consistency suggests that solar radiation is the primary driver of regional temperature change, and temperature significantly influences regional humidity change [50]. Therefore, the climate change mechanisms in Wenquan wetland are similar to neighboring regions, likely resulting from combined temperature decrease and precipitation increase.

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5. Conclusions

1) Variations in sediment geochemical element ratios from Wenquan wetland indicate that since 10300 cal a BP, the climate in Xinjiang has experienced five stages: a warm-dry period (10300–7700 cal a BP), a transition from warm-dry to warm-wet conditions (7700–7000 cal a BP), a warm-wet period (7000–4200 cal a BP), a warm-dry period (4200–2900 cal a BP), and a cold-wet period (2900–81 cal a BP).
2) The climate evolution in Wenquan wetland aligns with records from Sayram Lake, Ebinur Lake, Ulungur Lake, Barkol Lake, and other regional archives, confirming that Xinjiang's moisture-temperature combination follows a warm(cold)-dry(wet) pattern similar to the westerly-dominated climate regime.
3) The cooling event indicated during 7700–7000 cal a BP corresponds to the global 8.2 ka cooling event, while the warming trend during 4200–2900 cal a BP may correlate with the Holocene sub-high temperature event recorded in the Dunde ice core. Comparative analysis with regional proxies suggests that the gradual humidification trend in Xinjiang was likely determined by the combined effects of Holocene temperature decrease and precipitation increase.

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[80] [Figure 80: see original paper] Location map of the study area.

[81] [Figure 1: see original paper] Holocene humidity changes recorded by sediment proxy indicators in Xinjiang.

[82] [Figure 2: see original paper] WQ-1 core age-depth model of Wenquan wetland.

[83] [Figure 3: see original paper] Change trend graph of chemical element ratios in WQ-1 core section of Wenquan wetland.

[84] [Figure 4: see original paper] Holocene humidity changes in Xinjiang recorded by other proxy indicators.

[85] [Figure 5: see original paper] Possible forcing mechanisms of Holocene moisture evolution in the westerly area.

Note: Figure translations are in progress. See original paper for figures.