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A stalagmite record of abrupt climate change and possible Westerlies-derived atmospheric precipitation during the Penultimate Glacial Maximum in northern China

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A B S T R A C T

The geochemistry and petrography of a stalagmite from Wanxiang Cave in central China provide a paleoclimate record of the Penultimate Glacial Maximum (PGM) suggesting unexpectedly abundant non-monsoonal atmospheric precipitation at the nadir of the PGM. Eleven U–Th (^{230}Th) ages from 149 to 140 ka BP place the stalagmite in Marine Isotope Stage 6b, coincident with the greatest benthic marine $\delta^{18}O_{calcite}$ values of MIS 6. Carbon and oxygen stable isotope data, measurements of layer-specific width, positions of surfaces of non-deposition or dissolution, changes in the character and thickness of seemingly annual layers, changes in concentration of organic acids within the stalagmite's calcite, and patterns in the Mg concentration of that calcite all combine to give a coherent paleoclimate record. These data suggest that the stalagmite represents a wetter period than before or after its growth, with the wettest and coldest phase at 145 to 144 ka BP. This extreme in climate yields a striking correlation with the LR04 stack of oxygen isotope records from marine benthic forams, if the latter is subjected to a 4500-year chronological adjustment previously suggested by U–Th data from corals. The timing of the Wudu stalagmite's deposition combines with findings elsewhere to suggest that the PGM was the most extreme of later Pleistocene glacial maxima.

Petrography and U–Th age determinations suggest dramatic changes in climate during the PGM. At the beginning (149–146 ka BP) and end (143–140 ka BP) of the stalagmite's growth, abrupt (century-scale) drying caused lengthy hiatuses as dripwater to the stalagmite diminished. On the other hand, delivery of water to the stalagmite during the wettest phase (145–144 ka BP) caused dissolution of previous layers of the stalagmite.

Enhanced atmospheric precipitation during the cold of a glacial maximum is unexpected because, within the spectrum of Holocene climate, cooler conditions lessen the impact of the East Asian monsoon. Changes in the character of stalagmite layers indeed suggest weakened to negligible influence of the East Asian monsoon during the nadir of the PGM. However, data from the stalagmite are compatible with atmospheric precipitation from westerly winds that today reach only northwestern China but that may have been deflected southward in the PGM by southward migration of the Siberian High. This unexpected significance of the Westerlies during the PGM may be a result of the hypothesized extreme nature of the PGM relative to other glacial maxima of the later Pleistocene.

1. Introduction

The Penultimate Glacial Maximum (PGM) was the glacial maximum in Marine Isotope Stage 6 analogous to, but prior to, the Last Glacial Maximum in MIS 2. The Last Glacial Maximum and its deglacial transition to the Holocene (Termination I) have been the subject of much research, with a well-developed chronological nomenclature of numbered Dansgaard–Oeschger and Heinrich events and of named periods such as the Oldest Dryas, Bølling-Allerød, and Younger Dryas. By comparison, the PGM and its subsequent deglaciation (Termination II) have received much less attention and differentiation, with most effort

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focused on the timing and cause of Termination II (e.g., Spötl et al., 2002; Cheng et al., 2009; Drysdale et al., 2009). As a result, the timing and nature of the PGM remain largely unconstrained, limiting our understanding of the variability of glacial maxima as a group. Furthermore, because the PGM is beyond the range of radiocarbon age determination, determination of the timing of the PGM and of events within it has been hampered by non-decisive chronologies, with orbitally tuned chronologies providing no power to evaluate hypotheses about the significance of orbital effects and insolation (as pointed out by Drysdale et al., 2009). In addition, the PGM, like any of the Quaternary glacial maxima, represents global conditions markedly different from those of the Holocene, making straightforward uniformitarian inferences more challenging if not untenable.

With the significance but elusiveness of the PGM in mind, this paper reports on the paleoclimate record of a Chinese stalagmite that appears to have formed during the most extreme phase of climatic conditions in the PGM. The stalagmite's chronology is constrained by 11 U–Th (^{230}Th) ages that provide a precise chronology independent of orbital or other model assumptions. The stalagmite's record of climate change is derived from C and O stable isotope data, measurements of layer-specific width, positions of surfaces of non-deposition or dissolution, changes in the character and thickness of seemingly annual layers, changes in concentration of organic acids within the stalagmite's calcite, and patterns in the Mg concentration of that calcite. The result is a PGM record from 149 to 140 ka BP, with its most extreme conditions or nadir at 145 to 144 ka BP.

2. Setting

The stalagmite described here, which has been identified simply as “Wudu” in our work, comes from Wanxiang Cave in Wudu County in southeasternmost Gansu Province of north-central China (Fig. 1). Wanxiang Cave is large, with a length of approximately 1100 m (Johnson et al., 2006), and it is developed in Silurian limestones that are overlain by Quaternary loess, at an elevation of 1200 m a.s.l. (Zhang et al., 2004). Modern spelean carbonates in the cave are precipitated in isotopic equilibrium with cave dripwaters and reflect the mean annual temperature outside the cave (Zhang et al., 2004), but the significance of this modern relationship during the present interglacial to processes during past glacial maxima is unclear.

At 33°19′N, 105°00′E, Wanxiang Cave is located at the boundary between dry and wet climates in China, and precipitation decreases sharply north of its latitude. The area is near the modern (interglacial) northern margin of summer monsoon precipitation (Johnson et al., 2006), and it has a temperate monsoon climate with the marked transitional characteristics of a continental climate. During the summer, winds bring warm and humid air masses from the South China Sea, and the study area experiences its wet season. In the winter, cold and dry wind from the Gobi Desert dominates, and the area has its dry season. The seasonal march of the wet and dry periods is highly influenced by the strength of the monsoon wind (Domros and Peng, 1988). In warmer summers when there is a strong summer monsoon wind, the rain belt penetrates farther north and brings more rainfall to the study area (Kukla et al., 1988; An et al., 1990; Ding et al., 1992). During colder periods, the cold and dry westerly wind dominates, and the study area receives less rainfall. At time scales longer than 100 years, the summer monsoons generally are stronger during (globally) warmer periods, leading to wetter conditions in the study area. On the other hand, drier conditions prevail during global colder periods. Historically, the region has received about 480 mm of precipitation in normal years, but only about 400 mm in years of weak summer monsoons and about 600 mm in years of strong summer monsoons (Global Network of Isotopes in Precipitation (GNIP); <http://isohis.iaea.org/>). The temperature shifts greatly from day to night as well as from season to season. The average temperature is −14 °C to 3 °C in January, and 11 °C to 27 °C in July.

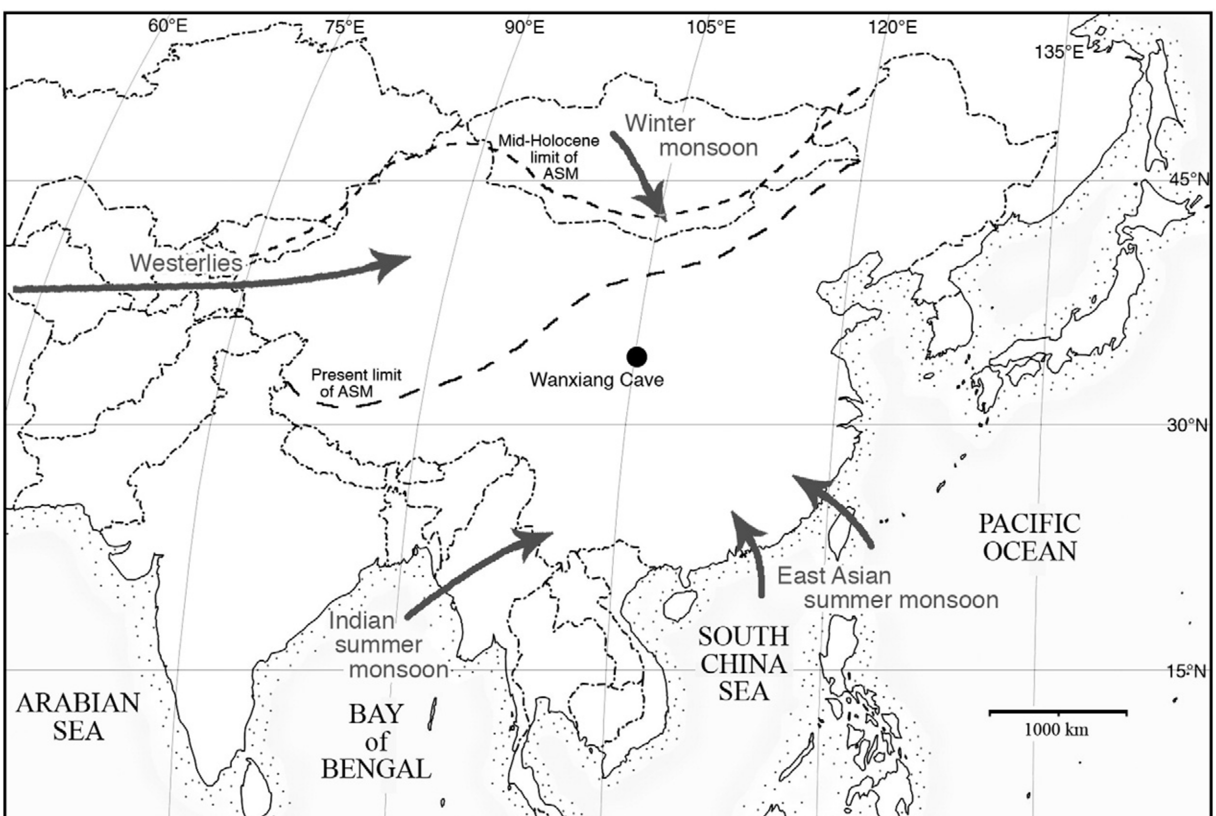

Fig. 1. Map of eastern Asia showing the location of Wanxiang Cave (filled circle) in central China. Arrows show modern (Holocene interglacial) wind patterns. Dotted lines for modern and mid-Holocene limits of Asian summer monsoon are from Winkler and Wang (1993).