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Long-term fire activity under the East Asian monsoon responding to spring insolation, vegetation type, global climate, and human impact inferred from charcoal records in Lake Biwa sediments in central Japan

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ABSTRACT

Records of sedimentary charcoal provide fire histories for assessing the relationship between fires and climate conditions, vegetation, human impact, and other factors. We analyzed charcoal particles in sediments from Lake Biwa in central Japan, dating back to 150,000 years ago. The sediments are well dated, homogenous, and had a constant sedimentation rate, making them ideal for assessing the long-term fire history through charcoal concentration analysis. Low charcoal concentrations in the glacial periods of Marine Isotope Stage (MIS) 2 and 6 indicate that few fires occurred in the periods under the cold climatic conditions. Variations in the microcharcoal concentration between 40,000 and 130,000 years ago, with a periodicity of 21,000–23,000 years, correspond to variations in the spring insolation in central Japan, vegetation type, and global climate, suggesting that the long-term fire activity in central Japan was determined mainly by spring insolation and vegetation type under the influence of global climate change. This finding suggests that insolation changes induced by precession cycles could influence a long-term phenomenon in an area as a direct local effect. Between 16,000 and 3000 years ago, sediments were characterized by an extraordinarily high concentration of large charcoal particles (>50 μm) and the predominance of elongated charcoal particles, suggesting that grassland fires (presumably anthropogenic) occurred frequently in the lakeside area. The frequent fire occurrence presumably contributed to the inflow of a large amount of organic materials, resulting in changes in the aquatic environment of Lake Biwa and/or its adjacent area.

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1. Introduction

Fire often threatens human life and plays an important role in most ecosystems. Because fire activity has been shown to alter significantly with climate change (e.g., Gillett et al., 2004; Kasischke and Turetsky, 2006; Westerling et al., 2006), many people are concerned about how climate change may alter fire activity in the future. Many previous studies predict future fire activity on Earth using fire–climate models (e.g., Scholze et al., 2006; Pechony and Shindell, 2010; Moritz et al., 2012). Paleorecords in sediments help aid the understanding of interactions between fire and factors such as climate change, vegetation type, and human activity (e.g., Power et al., 2008; Daniau et al., 2012), which could enable prediction of future fire activity.

In regions affected by the East Asian monsoon, such as Japan, present-day wildfires are mostly anthropogenic and are controlled because of the dense population; most fires occur by human carelessness and are extinguished soon (e.g., The Forest Fire Control Association, 2007). The anthropogenic nature of present-day fires prevents us from precisely evaluating the climatic effect on fire activity, so the climatic effect is still unclear in these regions, especially over the long term. Thus the aims of this study are: (1) to show when fires have occurred frequently or infrequently since the glacial period of Marine Isotope Stage (MIS) 6; (2) clarify what factors determined long-term fire regimes under natural conditions, e.g., vegetation type, precipitation, and temperature; and (3) assess how past human activity may have affected fire regimes.

To evaluate the climatic effect on fire activity and interaction between fire and other factors under natural conditions with the

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East Asian monsoon, we examined charcoal in sediments from Lake Biwa in central Japan (Fig. 1) that were deposited over the last 150,000 years, including periods before clear evidence of the earliest human presence in central Japan (40,000 years ago). Furthermore, comparison between fire activities in the periods before and after human occupation would aid in understanding human effects on fire activity.

Lake Biwa, the largest lake in Japan, is in the central part of Honshu Island (Fig. 1). The north basin is estimated to contain muddy sediments up to approximately 250 m thick that have been continuously deposited during the last ca. 400,000 years (Meyers et al., 1993; Yoshikawa and Inouchi, 1993). In addition, the sediments are composed of homogeneous mud and the sedimentation rates are almost constant. Therefore, Lake Biwa sediments contain continuous high-quality environmental records from the middle Pleistocene to the present. Studies of various proxies in Lake Biwa sediments show that the records represent changes to the regional environment related to global climate variation. Such records include pollen assemblage (Miyoshi et al., 1999; Hayashi et al., 2010a,b; 2017), diatom assemblage (Kuwae et al., 2002, 2004; Nagayasu et al., 2014), biogenic silica (Xiao et al., 1997a), eolian quartz (Xiao et al., 1997b), fluvial quartz (Xiao et al., 1999), lignin composition (Ishiwatari et al., 2009; Ohira et al., 2014), and branched tetraether lipids (Ajioka et al., 2014). Thus, Lake Biwa sediments are ideal for analysis of charcoal concentration to assess fire history. Variation in charcoal concentration in the sediments likely represents fire activity within the watershed area and its adjacent area.

2. Material and methods

The borehole core BIW08-B (100.3 m long) was collected in 2008 by drilling in Lake Biwa (35°13′41.15″ N and 136°03′21.29″ E) at a water depth of 53 m (Fig. 1 after Takemura et al., 2010). The sediments are mainly composed of dark-gray massive silty clay from 0 to 89 m. This includes those deposited over the last 150,000 years (0–46 m) used in the present study. We based the age–depth model of the upper 46 m on the ages of eight volcanic ash layers, K-Ah (7.2 ka), U-Oki (10.2 ka), AT (30.0 ka), SI (46.3 ka), K-Tz (95.2 ka), Aso-ABCD (97.7 ka), Aso-3 (133.0 ka), and Aso-2 (145.8 ka), following Nagayasu et al. (2014; Fig. 2). The dates of K-Ah, U-Oki, AT, and SI were estimated from an age model of the Lake Suigetsu sediments constructed from radiocarbon data and varve counts (Smith et al., 2013). The SI age stems from the correlation between SI (BT-15) in the Lake Biwa sediments and SG06-3668 in the Lake Suigetsu sediments based on the similarity of their glass chemical compositions (Nagahashi et al., 2004; Smith et al., 2013). This age is consistent with the SI age derived using the thermoluminescence method (49 ± 10 ka; Shitaoka et al., 2013). The dates of K-Tz, Aso-ABCD, Aso-3, and Aso-2 were estimated primarily from the correlation between the marine oxygen isotope ratio (Bassinot et al., 1994) and beds including these volcanic ash layers based on their lithofacies (e.g., marine beds interbedded in terrestrial deposits), palynological data, diatom data, and the age model of the beds, with respect to their radiometric ages (Nagahashi et al., 2004, 2007). Based on the age–depth model of the BIW08-B core, we estimated an average sedimentation rate of 0.3 m/ky in this zone. The age–depth model correlates well with the radiometric ages of

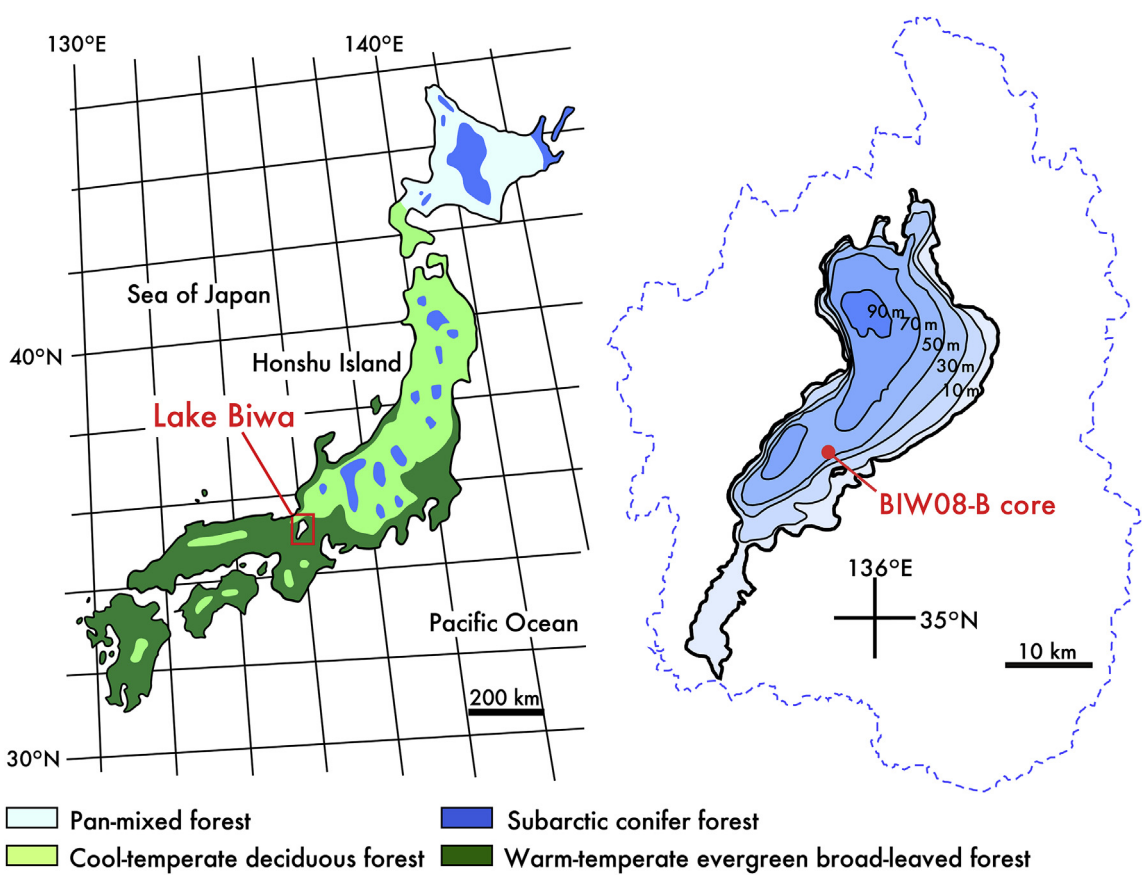

Fig. 1. Map of Japan showing modern vegetation type, compiled by Igarashi and Oba (2006). Map of Lake Biwa showing the coring site of BIW08-B (right). The dashed blue line indicates the lake's watershed area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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