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Multi-proxy dating the 'Millennium Eruption' of Changbaishan to late 946 CE

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ABSTRACT

Ranking among the largest volcanic eruptions of the Common Era (CE), the 'Millennium Eruption' of Changbaishan produced a widely-dispersed tephra layer (known as the B-Tm ash), which represents an important tie point for palaeoenvironmental studies in East Asia. Hitherto, there has been no consensus on its age, with estimates spanning at least the tenth century CE. Here, we identify the cosmogenic radiocarbon signal of 775 CE in a subfossil larch engulfed and killed by pyroclastic currents emplaced during the initial rhyolitic phase of the explosive eruption. Combined with glaciochemical evidence from Greenland, this enables us to date the eruption to late 946 CE. This secure date rules out the possibility that the Millennium Eruption contributed to the collapse of the Bohai Kingdom (Manchuria/Korea) in 926 CE, as has previously been hypothesised. Further, despite the magnitude of the eruption, we do not see a consequent cooling signal in tree-ring-based reconstructions of Northern Hemisphere summer temperatures. A tightly-constrained date for the Millennium Eruption improves the prospect for further investigations of historical sources that may shed light on the eruption's impacts, and enhances the value of the B-Tm ash as a chronostratigraphic marker.
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1. Introduction

The 'Millennium Eruption' of Changbaishan volcano (also known as Mt. Paektu and Baegdusan), is so-called because it has been thought to have occurred approximately 1000 CE. The volcano is located on the border between China and the Democratic People's Republic of Korea (Fig. 1a and b). The Millennium Eruption disgorged an estimated 24 km^3 of dense magma (Horn and Schmincke, 2000), mostly as rhyolitic (comendite) tephra but with a subordinate quantity of trachyte. Stratigraphic relationships demonstrate clearly that the rhyolitic magma was erupted before the trachytic magma. Based on pumice clast size distributions, Horn and Schmincke estimated that the eruption column easily passed the tropopause. The tephra fallout associated with the rhyolitic

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stage of the eruption extends across northeast China (Sun et al., 2015), the far-east costal region of Russia (Andreeva et al., 2011) and the Korean peninsula. It is found in deep-sea sediment cores from the Japan Sea (Machida and Arai, 1983), as well as in lacustrine and peat sedimentary archives from Japan (e.g., Hughes et al., 2013; Chen et al., 2016; McLean et al., 2016, Fig. 1c). Known as the Baegdusan-Tomakomai ash (B-Tm layer), it represents a key stratigraphic marker in palaeoenvironmental and archaeological contexts (Chen et al., 2016). Millennium Eruption tephra have also been identified in a high-resolution ice core (NEEM-2011-S1) from northern Greenland (Sun et al., 2014a). Despite substantial efforts to date the paroxysm, mostly using radiocarbon techniques, the resulting estimates span at least the tenth century CE (Fig. 2; Sun et al., 2014b). Attempts to date the eruption have also prompted searches of mediaeval texts for reports suggestive of volcanic phenomena (Hayakawa and Koyama, 1998).

Among more recent attempts to date the Millennium Eruption are two works based on wiggle-matched radiocarbon ages of trees (*Pinus* and *Larix*) that were engulfed (alive) by pyroclastic density currents during the eruption (Xu et al., 2013; Yin et al., 2012), and another based on Greenland ice core stratigraphy (Sun et al., 2014a). These studies pointed to an eruption date sometime in the period between the 920s and 950s CE.

We set out here to calculate an accurate date of the Millennium Eruption by making new radiocarbon measurements of the same subfossil larch stem from China, for which previous wiggle-matching (Xu et al., 2013) yielded a model age of 940–952 CE (2σ) for the outermost ring before bark (*waldkante*). Since the tree was 264 years old when killed by the eruption, we reasoned that it was alive in 775 CE, the year of an ephemeral burst of cosmogenic radiation. The signature of this event has been recognized in annually-resolved ^{14}C measurements made for trees from Japan (Miyake et al., 2012), Europe (Büntgen et al., 2014), and New Zealand (Güttler et al., 2015), as well as in ^{10}Be abundance in ice cores from Greenland and Antarctica (Sigl et al., 2015). We hypothesized that locating this absolute time marker would enable simple annual increment counting to date the last ring formed by our tree before it was killed by the Millennium Eruption. A secure date for the Millennium Eruption would permit us to investigate the magnitude and extent of any climate response using Northern Hemisphere summer temperature proxies.

2. Materials and methods

The studied subfossil trunk (Fig. 3) belongs to a mature *Larix*, which would have had an estimated crown height of 20 m. The deposits containing the tree are located at Xiaoshahe on the northwest flank of Changbaishan volcano, about 24 km from the summit caldera (Fig. 1a). These deposits are of rhyolitic composition belonging to the first phase of the Millennium Eruption – the glass

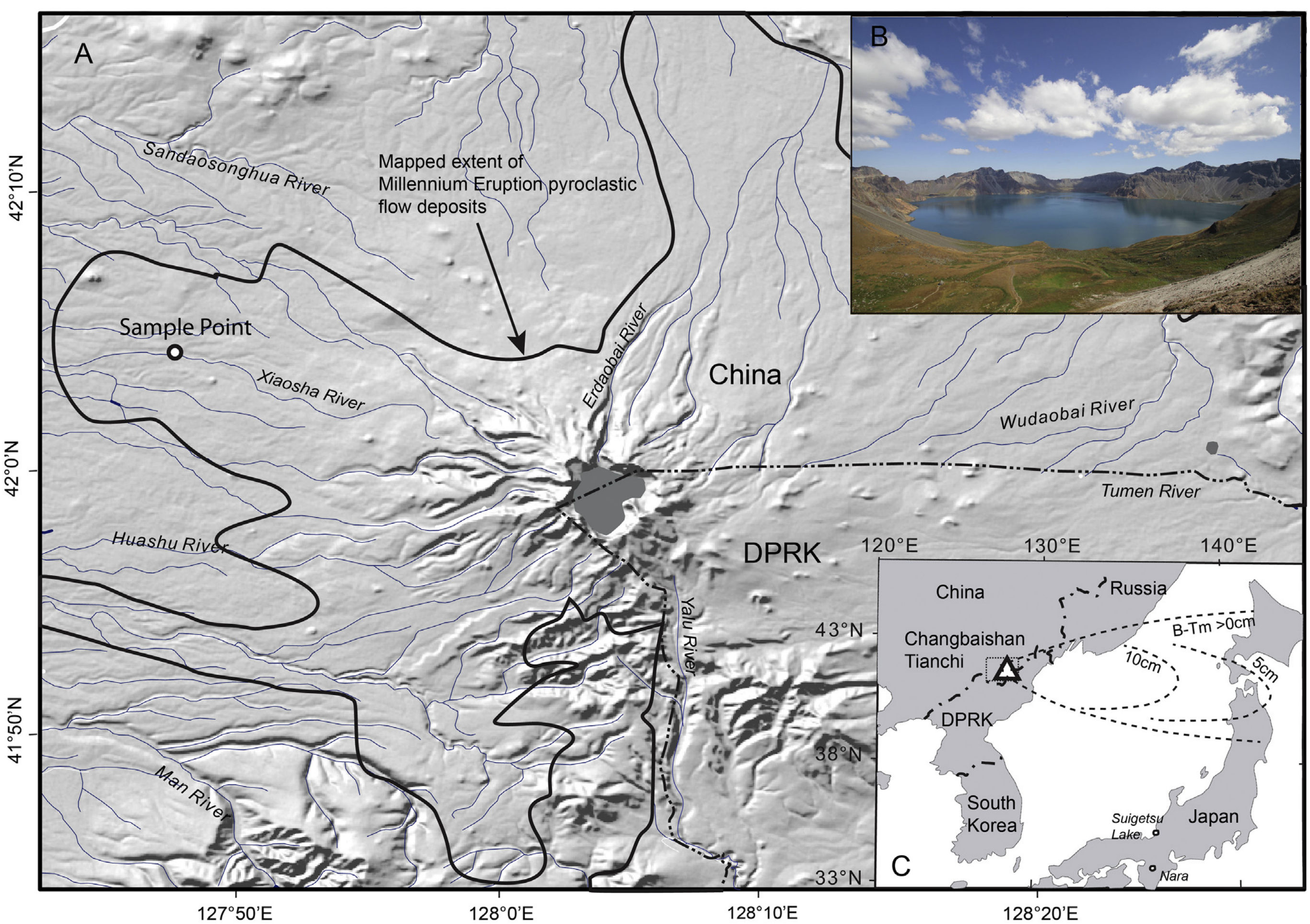

Fig. 1. Contextual information for the Millennium Eruption. (A) Location of the volcano and the tree sampling site (labelled 'Sample Point', 42°05.67′N; 127°47.87′E). (B) Photograph of the summit caldera and lake, taken from the Chinese side of the volcano. (C) Isopach map for the B-Tm layer (after Machida and Arai, 1983), showing sites in Japan discussed in the text.

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