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Magnitude and consequences of volatile release from the Siberian Traps

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ABSTRACT

The eruption of the Siberian Traps flood basalts has been invoked as a trigger for the catastrophic end-Permian mass extinction. Quantitative constraints on volatile degassing are critical to understanding the environmental consequences of volcanism. We measured sulfur, chlorine, and fluorine in melt inclusions from the Siberian Traps and found that concentrations of these volatiles in some magmas were anomalously high compared to other continental flood basalts. For the ten samples for which we present data, volatile concentrations in individual melt inclusions range from less than the detection limit to 0.51 wt.% S, 0.94 wt.% Cl, and 1.95 wt.% F. Degassing from the Siberian Traps released approximately ~6300–7800 Gt S, ~3400–8700 Gt Cl, and ~7100–13,600 Gt F. These large volatile loads, if injected into the stratosphere, may have contributed to a drastic deterioration in global environmental conditions during the end-Permian.

1. Introduction

Almost two decades have passed since the eruption of the Siberian Traps was first proposed as a trigger for the end-Permian mass extinction (Campbell et al., 1992; Renne and Basu, 1991), the largest loss of floral and faunal diversity in Earth's history (Erwin, 1994; Sepkoski et al., 1981). The Permian–Triassic boundary was preceded by an ~1.5 Myr episode of ocean euxinia (Cao et al., 2009) and followed by ~5 Myr of suppressed biological diversity and large fluctuations in the $\delta^{13}C$ record (Lehrmann et al., 2006; Payne et al., 2004). Degassing and atmospheric loading of volatiles is one of the critical mechanisms that links mafic volcanic eruptions with global environmental change (Devine et al., 1984; Thordarson et al., 1996). We seek to quantify volatile flux throughout the evolution of the Siberian Traps large igneous province and to evaluate the potential climatic impact.

The Siberian Traps magmas were erupted through the Tunguska sedimentary sequence, which reaches 12.5 km in thickness (Meyerhoff, 1980). The thickness of Cambrian evaporitic sequences alone can exceed 2.5 km (Fig. 1); Zharkov (1984) estimates that the East Siberian Basin hosts a total volume of ~585,000 km^3 of rock salt. Additional Siberian salt deposits are found in Ordovician through Carboniferous strata (Zharkov, 1984).

Evidence from trace elements (Lightfoot et al., 1990; Wooden et al., 1993), $\delta^{34}S$ (Li et al., 2009b; Ripley et al., 2003), ε_{Nd} (Arndt and Christensen, 1992), magmatic sulfides (Li et al., 2009a), and drill cores through pipe structures (Svensen et al., 2009) provides strong support for widespread interaction between crustal rocks (including evaporites and carbonates) and magmas. Contact heating and metamorphism related to sill intrusion may have led to direct, potentially explosive gas release from the Tunguska sediments (Svensen et al., 2009). In addition to this direct degassing, we suggest that Siberian Traps magmas may have extensively assimilated these volatile-rich sedimentary rocks, increasing their concentrations of dissolved volatiles.

Outcrops of the Siberian Traps stretch from the Taimyr Peninsula in the north of Russia as far south as Bratsk (Fig. 1). With an estimated volume of ~4×10^6 km^3 (Fedorenko et al., 2000), the Siberian large igneous province ranks among the largest known continental flood basalts. Volumetrically, it is roughly three times as large as the Deccan Traps (Jay and Widdowson, 2008), and twenty times as large as the Columbia River Flood Basalts (Coffin and Eldholm, 1994). Although mafic lava flows are most abundant, volcaniclastic and intrusive units also account for large fractions of the total volume. The maximum cumulative thickness of the dolerite sills, which most frequently intrude the Paleozoic sedimentary rocks, has been estimated as 1200 m (Kontorovich et al., 1997).

The precise temporal relationship between the onset of eruption and the main pulse of extinction remains unclear, despite geochronological advances (Bowring et al., 1998; Kamo et al., 2003). Zircon-bearing rocks are rare at the base of all exposed Traps sections,

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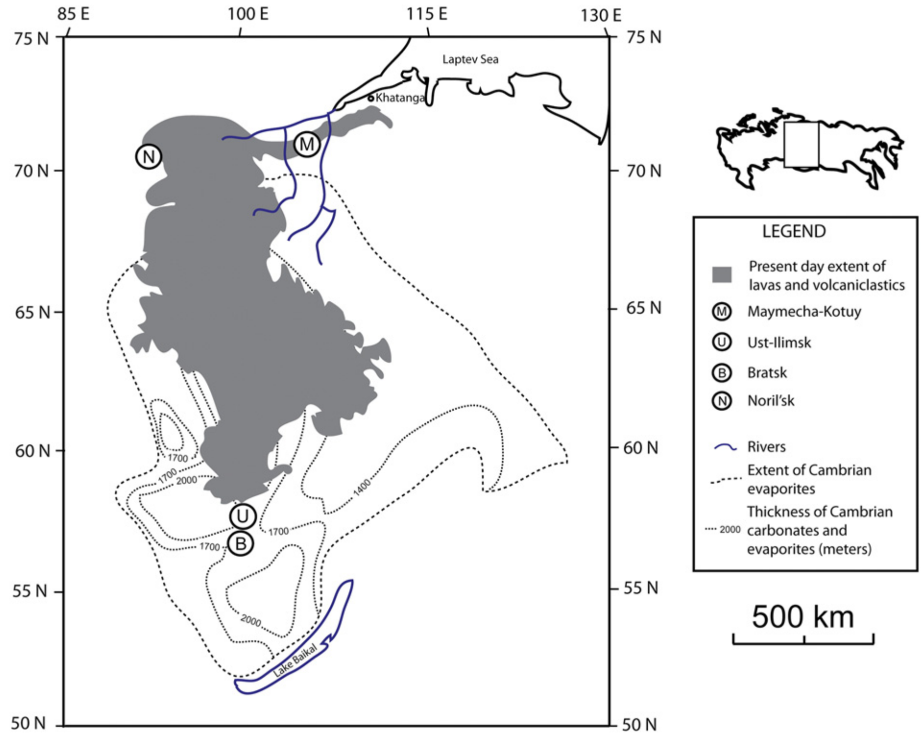

Fig. 1. Map showing present day extent of Siberian Traps lavas and volcaniclastics in the Tunguska basin based on Reichow et al. (2005). Thickness and extent of Cambrian evaporites, including limestone, halite, dolomite and anhydrite, are based on Zharkov (1984). As described in the legend, circled letters M, U, and B denote the three areas from which we obtained melt inclusion samples. N marks Noril'sk, the source of the inclusions reported in Sobolev et al. (2009). Reichow et al. (2005) have also argued that the distribution of intrusions and basaltic subcrop supports a much larger original extent of the Siberian Traps, reaching into the adjacent West Siberian Basin (not shown here).

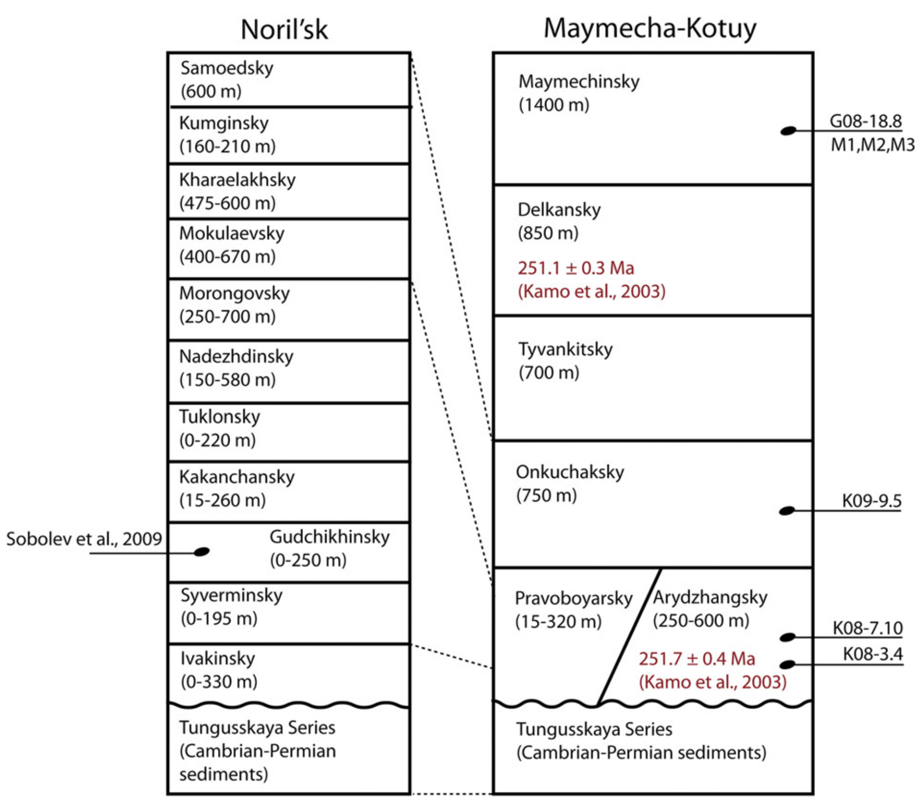

Fig. 2. Schematic stratigraphy of the extrusive suites in the Noril'sk and Maymecha–Kotuy regions of the Siberian Traps, marked with an N and M respectively in Fig. 1. U–Pb dates from Kamo et al. (2003) are given in red; stratigraphic positions of the samples from the Maymecha–Kotuy presented in this study are denoted on the right. The inclusions reported in Sobolev et al. (2009) come from the Gudchikhinsky picrites, as denoted on the left. Dotted lines show geochemical, paleomagnetic, and paleontological correlations between Noril'sk and Maymecha–Kotuy as proposed by Fedorenko and Czamanske (1997), Fedorenko et al. (2000), Kamo et al. (2003).