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An integrated carbon isotope record of an end-Permian crater lake above a phreatomagmatic pipe of the Siberian Traps

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ABSTRACT

The largest mass extinction in Earth history occurred at the end-Permian (~252 million years ago) and is marked by a global negative carbon isotope excursion and the onset of Siberian Trap volcanism, prompting diverse hypotheses on the link between flood basalt volcanism, carbon cycle perturbations, and mass extinction. Phreatomagmatic pipes associated with Siberian Trap volcanism have been proposed as conduits for the release of ^{12}C-enriched carbon gases from thermogenic and/or magmatic sources to the end-Permian atmosphere. Some of the pipes have preserved crater-lake sediments of volcaniclastic origin. This study examined the preserved evidence for ^{12}C-enriched carbon release into the Western Oktyabrsk crater in east Siberia from the underlying volcanic basin. We find that the $^{13}C/^{12}C$ ratio of the carbonate cement, organic matter, and long-chain n-alkanes in the lacustrine crater sediments support the hypothesis that ^{12}C-enriched carbon infiltrated the basal crater sediments and lake water immediately after crater formation. The values and trends of $\delta^{13}C_{Carb}$, $\delta^{13}C_{TOC}$, and $\delta^{13}C_{n\text{-alkanes}}$ in the crater sediments are consistent with ^{12}C-enriched carbon with isotopic values similar to that of carbon sourced from thermogenic and/or ^{12}C-enriched magmatic sources. This implies that carbon release through the pipes in the Tunguska Basin may explain the source of the global negative carbon isotope perturbations, and their coincidence with Siberian Trap volcanism, at the end-Permian.

1. Introduction

Understanding the cause of the end-Permian mass extinction requires identifying processes and mechanisms that can be tested in the rock record. A major feature of the end-Permian extinction event is a negative carbon isotope excursion observed globally in carbonate and organic matter (Korte and Kozur, 2010). This is accompanied by strong evidence for increased pCO_2 that resulted in global warming, ocean acidification, and increased terrestrial weathering rates (Clapham and Payne, 2011; Joachimski et al., 2012; Payne et al., 2010; Sun et al., 2012). Proposed sources of ^{12}C-enriched carbon include methane clathrates (Berner, 2002; Erwin, 1993), enriched magma (Sobolev et al., 2011), coal burning (Grasby et al., 2011), and contact metamorphically cracked petroleum or sedimentary organic matter (Svensen et al., 2009). Unlike most of the other sources, the volcanic source of ^{12}C-enriched carbon has a clear release trigger. Furthermore, work by Majorowicz et al. (2014) suggested that there were insufficient gas hydrate deposits left by the end-Permian to explain the observed carbon isotope excursion. This fact highlights the potential relevance of organic carbon degassing. The discovery of phreatomagmatic pipe structures in the Siberian Traps offer a geologic record, enabling testing of volcanic degassing hypotheses for the first time.

Svensen et al. (2009) first proposed the phreatomagmatic pipes as conduits for release of ^{12}C-enriched carbon, promoting a volcanic mechanism to explain the global carbon isotope excursion and source of increased pCO_2 at the end-Permian. In the case of Siberian Trap volcanism, two sources of ^{12}C-enriched carbon have been proposed. The first is thermogenic carbon, produced by contact metamorphic heating of Tunguska Basin petroleum and organic matter in the aureoles around Siberian Trap sills (Svensen et al., 2009). Ample reactive carbon existed in the form of mature hydrocarbon deposits in Neoproterozoic and Cambrian horizons by the end-Permian and immature organic matter throughout the basin in carbonates and marls of Cambrian to Silurian age (Frolov et al., 2011; Petrychenko et al., 2005; Zharkov, 1984). Although suggested in recent literature (Ogden and Sleep, 2012; Retallack and Jahren, 2008), coals of Devonian to Permian age were sparse and shallow in the southern portion of the Tunguska Basin and were unlikely to be major contributors of contact metamorphic carbon through the diatremes (Frolov et al., 2011). The second proposed source

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for ^{12}C-enriched carbon is recycled oceanic crust incorporated into Siberian Trap source magmas. Modeling studies by Sobolev et al. (2011) argue for the involvement of dense recycled oceanic crust in Siberian Trap plume generation, to explain the lack of observed uplift and rifting over the presumed plume head. This magma could have generated CO_2 enriched in ^{12}C compared to typical mantle carbon. The purpose of this project was to investigate to what extent the diatreme degassing hypothesis could explain the source of ^{12}C-enriched carbon at the end-Permian.

Hundreds of breccia-filled phreatomagmatic pipe structures associated with the Siberian Traps have been identified throughout the Tunguska Basin in East Siberia (Fig. 1A) (Von der Flaass and Naumov, 1995; Svensen et al., 2009). These relict hydrothermal vent structures are rooted at approximately 4 km depth and were formed by interaction between Siberian Trap sill intrusions and water–petroleum-bearing horizons of the Cambrian evaporite–carbonate sequence in the Tunguska Basin (Fig. 1B) (Von der Flaass, 1992). Iron ore prospecting in the 1980s led to extensive mapping and sampling of these diatremes via hundreds of boreholes. The diatremes exhibit complex multi-phase formation histories. They contain brecciated metasomatized country rock, volcaniclastic material, magnetite and celestine ore, collapse features, and veins, supporting an iterative explosive formation mechanism related to hydrothermal activity (Von der Flaass, 1997). Twelve are known to have preserved lacustrine-sediment-filled craters in their uppermost sections (Von der Flaass and Naumov, 1995). Structural and geological relationships show that the diatremes formed during the main emplacement stage of the Siberian Traps (Svensen et al., 2009; Von der Flaass, 1997). Field relations may further constrain the timing of diatreme formation to the initial stages of the main flood basalt eruption if the diatremes produced or formed contemporaneously with the thick tuff deposits observed in the southern Tunguska Basin stratigraphically beneath the main sequence lava flows (Black et al., 2012; Svensen et al., 2009). Palynological assemblages recovered from sediments in several craters are consistent with a latest-Permian age (Ankudimova and Naumov, 1995; Visscher et al., 2010).

This study is based on analyses of core material from the western crater in the Oktyabrsk vent complex in the southern Tunguska Basin (Fig. 1A). This is the only known preserved sedimentary system formed in the vicinity of the traps during volcanism. The preserved crater sediment deposits have a present-day surface dimension of approximately

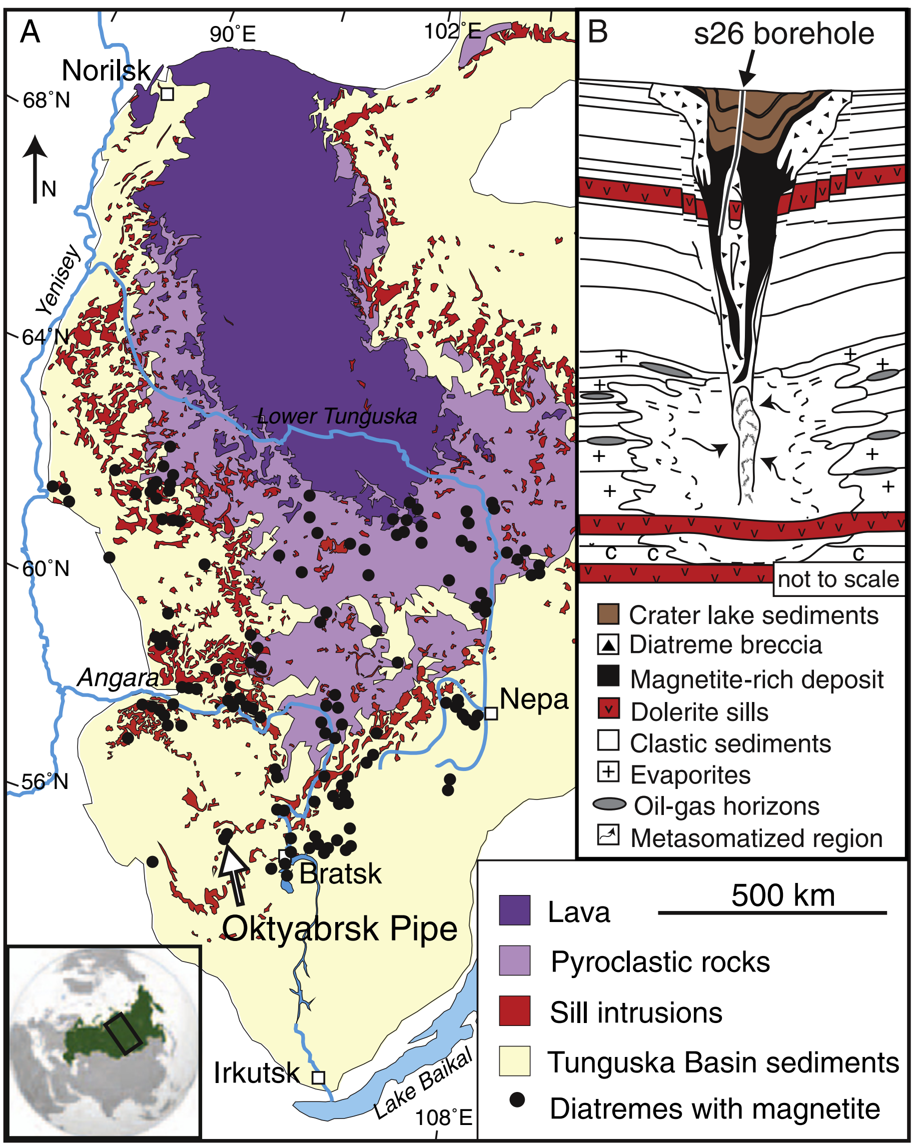

Fig. 1. A, geologic map of the Siberian Trap province highlighting the Oktyabrsk crater in the southern Tunguska Basin, East Siberia. B, schematic cross-section of the Oktyabrsk magnetite-bearing diatreme with potential for thermogenic gas production in the root zone due to contact metamorphic heating of sedimentary organic matter. The s26 core used in this study samples the middle of the Oktyabrsk crater sediments and the underlying breccia pipe.