Siberian trees: Eyewitnesses to the volcanic event of AD 536

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The AD 536 volcanic eruption caused a drastic decrease in tree-ring widths, cell wall thickness, carbon and oxygen isotopic values in larch tree cellulose, and frost-ring formation, effects which are without an analogue over the past 2000 years in Siberia.

The new annual ice-core chronologies for volcanic sulfate in Greenland and Antarctica (Larsen et al. 2008; Sigl et al. 2014) can be compared with the annually dated Siberian (Russian) tree-ring chronologies to investigate the impact of major volcanic eruptions that occurred around AD 536.

We discuss the effects of volcanic eruptions on trees growing in the permafrost zone in Siberia and the trees' physiological response to such extreme environmental events. Using multiple lines of evidence, we discuss how tree-ring width (TRW), cell wall thicknesses (CWT), and stable carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotopes in tree-ring cellulose of larch trees were affected by extreme climate conditions during the period AD 516-560. We analyze the response of Siberian trees growing at the high-latitude sites in northeastern Yakutia (YAK; Sidorova and Naurzbaev 2002), eastern Taimyr Peninsula (TAY; Naurzbaev et al. 2002), and at a high-altitude site in the Russian Altai (ALT; Myglan et al. 2009; Fig. 1) to climatic changes after the major volcanic eruption of AD 536, which has no analogue over the past 2000 years in Siberia (Churakova (Sidorova) 2014), with the aim of improving our understanding of the physiological adaptation of trees to extreme environmental impacts.

Many scientists have investigated the "AD 536 dust-veil or unknown event" (e.g. Stothers 1984). This volcanic event likely lead to one of the most severe cold episodes in the Northern Hemisphere high-latitudes during the last two millennia (Briffa et al. 1998; Larsen et al. 2008), is despite the fact that ice-core acidity records from Antarctica suggest that, globally, much stronger volcanic peaks occurred at other times (Plummer et al. 2012).

Tree-ring width and stable carbon and oxygen isotope composition ($\delta^{13}C$ and $\delta^{18}O$) are indicators for both temperature and moisture regime changes, where fractionation processes during CO_2 uptake are important for $\delta^{13}C$, while for $\delta^{18}O$ changes in the soil and leaf water isotope ratio are determining factors (McCarroll and Loader 2004). We hypothesized that the volcanic eruption of AD 536 would lead to strong decreases in tree-ring width and cell wall thickness as a result of the combined effect of reduced incoming solar radiation and related temperature decrease. In addition, we assumed that the temperature decrease and reduced vapor pressure deficit could have led to decreased stable carbon and oxygen isotopic ratios in tree rings for both high-latitude and high-altitude sites. To test our hypothesis, we examined our tree-ring width chronologies from 21 years before and 24 years after the AD 536 event. They showed a pronounced narrowing of tree-ring widths from well-replicated, >2000 year-long chronologies. TRW, CWT, $\delta^{13}C$, and $\delta^{18}O$ isotope chronologies were measured on four cross-sections of relict wood at each site (Fig. 2).

Differences in tree response among the study sites

At all three studied sites, we observed that the period AD 516-560 was characterized by the strongest decrease in tree radial growth over the past 2000 years (Churakova (Sidorova) et al. 2014). The strikingly low $\delta^{18}O$ values at ALT in AD 536 (Fig. 2) reflect a low condensation temperature of precipitation water supplied to trees. Furthermore, low temperatures lead to low vapor pressure deficit and thus to low needle water enrichment. This $\delta^{18}O$ leaf water signal is transferred to the cellulose, although part of the leaf oxygen isotope enrichment is lost in the stem during cellulose formation by the exchange with less enriched xylem water. Low $\delta^{18}O$ values in cellulose associated with thin cell walls and a low numbers of cells (in AD 536 only two cells were counted) indicate that reconstructed June-July air temperatures dropped by ca. 4°C relative to the mean June-July air temperature which was around 9°C at YAK for the last 2000 years (Sidorova et al. 2005; Churakova (Sidorova) et al., unpublished data).

The tree's response to decreased light intensity and low temperatures caused by volcanic dust veils is also visible in ring width, but with a delay of three years, which may be due to the ability of the trees to use

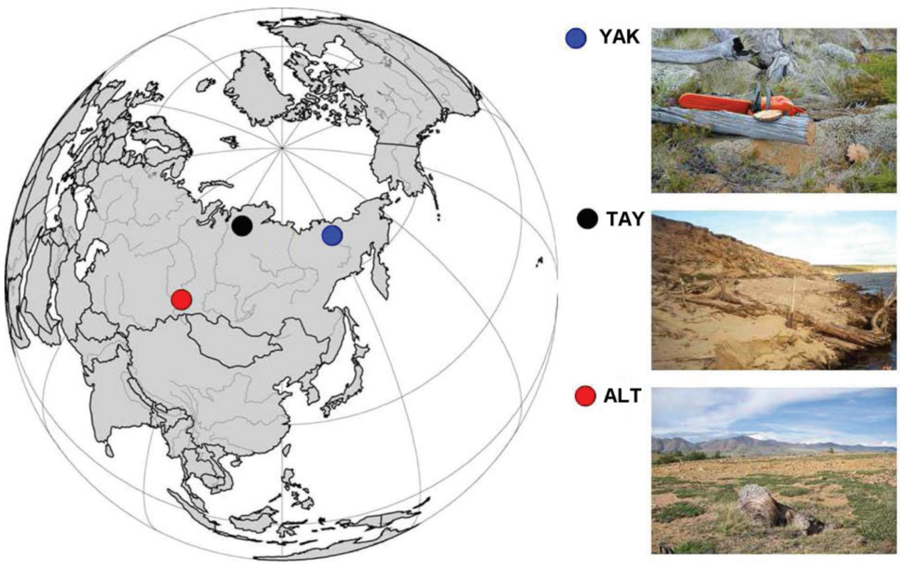

Figure 1: Map with locations and photos of the study regions in the high-latitude sites in northeastern Yakutia (69°N, 148°E; YAK), Taymir Penninsula (70°N, 103°E; TAY), and high-altitude site in the Russian Altai (50°N, 89°E; ALT).

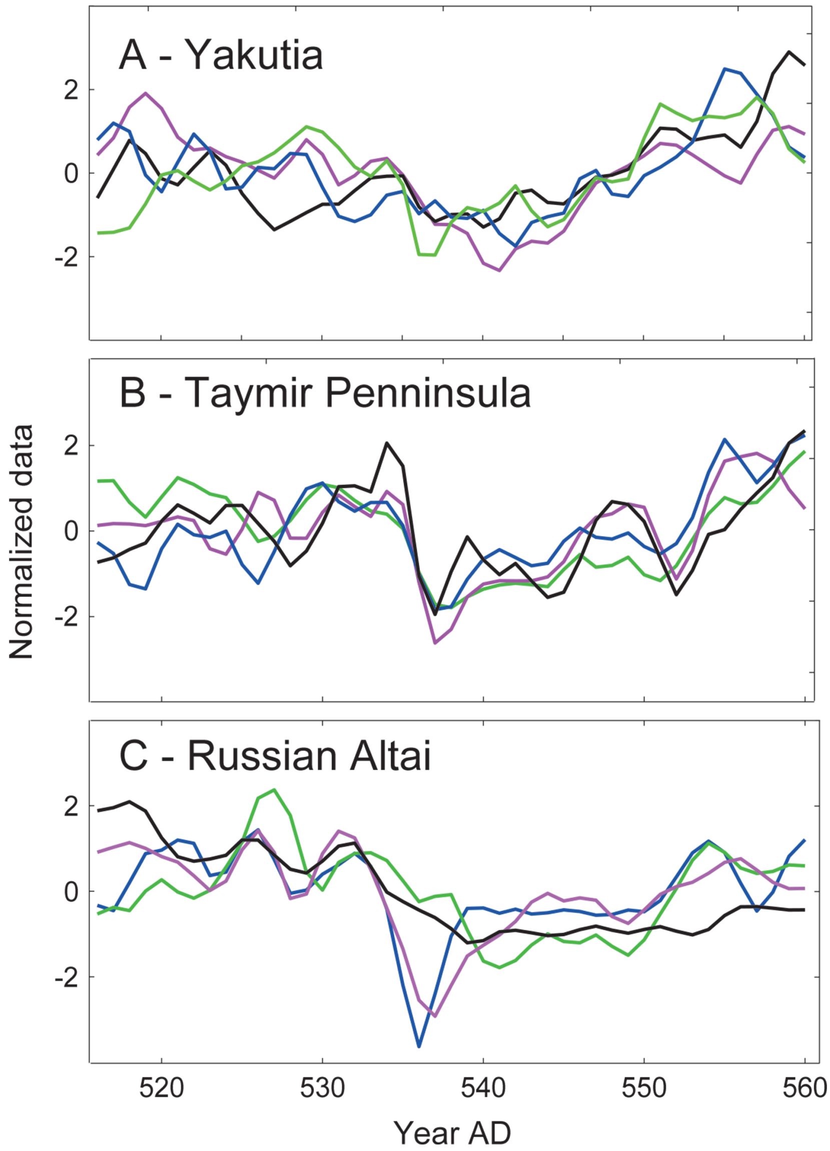

Figure 2: Normalized by 3-year smoothed δ^{13}C (green), δ^{18}O (blue), tree-ring width index (black), and cell wall thickness (pink) chronologies for the three study regions **(A)** Yakutia (YAK), **(B)** Taymir Penninsula (TAY), and **(C)** Russian Altai (ALT).

their carbohydrate reserves during early wood formation.

At the high-elevation ALT site, there was no clear reduction of TRW after AD 536, although the lowest values are observed in AD 539. There were reductions in CWT (AD 537) and, rather dramatically, in δ^{18}O cellulose for the year of AD 536, which rebounded strongly the next year. This is a clear difference between the sites near the northern tree limit, and the more southern, high-elevation site. Although the AD 536 event has not been recorded immediately in the TRW series at ALT, it would be associated with low maximum latewood density given the observed low cell wall thickness in AD 536 and AD 537 (Churakova (Sidorova) et al., unpublished data).

The advantage of multi-proxy studies

The study of multiple parameters like tree-ring width, latewood density, cell wall thickness and stables isotopes in tree rings from markedly different locations provides new insight into understanding the effects of volcanic eruptions in eco-physiological and climatological aspects. In particular, increased δ^{13}C indicates drought or high vapor pressure deficit, which is often coupled with limited water availability, while decreased δ^{13}C is an indicator for cold and moist conditions during the growing season. Reduced light intensity, as produced by a volcanic dust veil, can reduce photosynthesis, which will lead to an increase in the leaf intercellular CO_2 concentration, and thus also lower δ^{13}C (Farquhar et al. 1989). Therefore, if we take reduced δ^{13}C as an indication of stress in the trees, we can infer stressed growth conditions at both northern sites, but less so at ALT, in AD 536. This is consistent with the very low tree-ring widths in the North in those years, and frost rings at ALT in AD 536. The strikingly low cellulose δ^{18}O values (20‰, compared with the mean value 28.1‰ for the period from AD 520 to AD 560) at ALT in AD 536, associated with thin cell walls, strongly indicates a very cold or short growing season, even though the response in ring width is delayed by three years.

At the two sites closest to the northern limit of tree growth on the Taimyr Peninsula and in northeastern Yakutia, sharp declines of already small tree-ring widths, latewood density, and cell wall thickness occur in AD 536, and are accompanied by simultaneous drops in cellulose δ^{13}C. At the high-elevation, more southern Altai site, the reduction in TRW was delayed by three years, whereas very low values of δ^{18}O in AD 536, and reduced cell wall thickness in AD 536 and AD 537 (Churakova (Sidorova) et al. 2014).

Tree-ring parameters such as tree-ring width, cell wall thicknesses, and stable carbon and oxygen isotopes in tree cellulose, compared with other multi-proxy records such as ice cores and historical archives are useful proxies and complement each other perfectly. Using a multi-proxy approach would help to improve the quality of climate reconstructions in the past.

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