Millennium-scale volcanic impact on a superhumid and pristine ecosystem

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ABSTRACT

Ecosystems damaged by distal volcanic ash and sulfur deposition usually recover within decades. However, sediment, stalagmite, and pollen records from the southernmost Andes indicate a 2000 yr impact on forest and aquatic ecosystems after deposition of a thin tephra layer. SO_2 released from altering pumice produced intense soil and lake acidification in a >150,000 km^2 area. Acidification led to nutrient leaching and affected soil microorganisms, causing plant decay and increased soil erosion in an area larger than 8000 km^2. We conclude that weakly buffered soils in humid environments are extremely vulnerable to volcanic and anthropogenic acidification, causing long-lasting ecosystem damage and perturbations of paleoclimate proxy records.

Keywords: volcanic impact, acidification, ecosystem.

INTRODUCTION

Distal deposition of tephra leeward of volcanic centers usually causes little mechanical destruction of vegetation. Pollen records in Iceland (Caseldine and Hatton, 1994), New Zealand (Giles et al., 1999), and central Europe (Schmincke et al., 1999) document perturbations lasting only decades after large prehistoric eruptions. After the historic Laki eruption in 1783, acid deposition damaged the vegetation far from the center of eruption in Europe for only several years (Thordarson and Self, 2003). Sites with less than 50 cm tephra fall, investigated after the eruption of Mount St. Helens (USA) in 1980 (Antos and Zobel, 1986) and after the eruption of Hudson volcano in Chile (Vogel, 1998) in 1991 (Fig. 1), show tree recovery and normal growth rates after just a few years. These observations suggest that distal volcanic fallout produces only short-term environmental impacts. However, the extent of impacts on ecosystems attributed to volcanic fallout depends on various factors such as climatic conditions, soil characteristics, tics, as well as grain size and structure of the tephra. The acid-buffering capacity of soils (Ugolini and Dahlgren, 2002), climate conditions, as well as volatile composition and structure of the volcanic glass, are of key importance for intensity and duration of the impact on soils and vegetation.

Here we present an example of the effects caused by volcanic fallout from Mount Burney (Fig. 1A), a stratovolcano situated in the southernmost Andes (Fig. 1A) in an area with more than 6000 mm annual precipitation (Schneider et al., 2003). After a large Mid-Holocene eruption (4290 ± 90 cal. yr B.P.; Kilian et al., 2003), the tephra fan was distributed leeward of the center, toward the southeast over an area covered by an interlocked mosaic of superhumid evergreen *Nothofagus* forest and cushion bogs (Figs. 1B and 1C). The isopach map of the tephra layer (Fig. 1B), reconstructed from sediment and peat core data, indicates a tephra volume of 2.8 km^3 (Kilian et al., 2003), comparable to that of the Hudson eruption in 1991 (3.6 km^3; Sacasso et al., 1994), larger than that of Mount St. Helens in 1980 (1 km^3; Sarna-Wojcicki et al., 1981), but smaller than that of the Late Glacial Laacher See eruption in central Europe (6 km^3; Schmincke et al., 1999). Around 60 km southeast of Mount Burney, in the central section of the eruption fan (Fig. 1B), profiles from soils, peat cores, as well as lake and fjord sediments (Figs. 1B and 1C) show a 5–12-cm-thick tephra fall layer (Fig. 2). It consists of vesicle-rich (>80 vol%) pumice with a grain size of 0.2–2 mm (Fig. 2, inset). Mortified tree trunks and coarse plant relicts were found above the tephra layer in soil profiles and sediment records in an extended area of the eruption fan (Figs. 1B and 1C).

METHODS AND AGE CONTROL

Based on Innomar-SES 96 echo-sounding profiles, sediment cores were taken with a 5-m-long Uwitec piston corer in Lake Chandler (CH1 core with 6.5 m length; 52°49′S, 72°54′W; Fig. 1), in Lake Martillo (LM1 core with 8.6 m length; 52°43′S, 72°56′W), in a

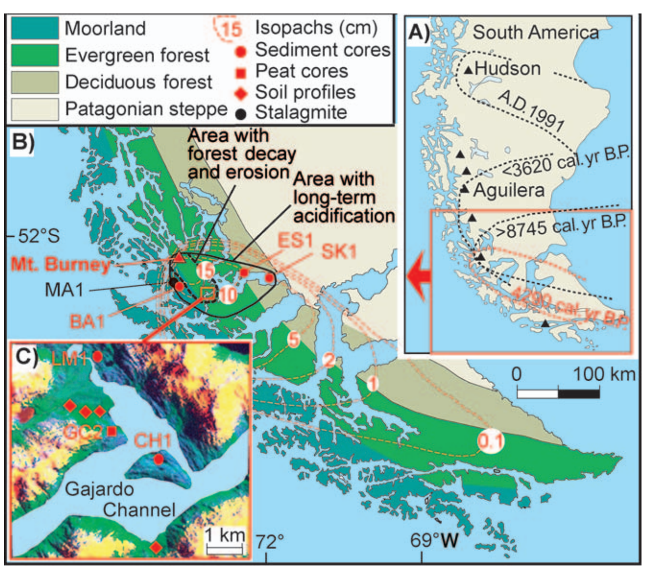

Figure 1. A: Southernmost South America with Hudson, Aguilera, and Mount Burney volcanoes and their major Holocene eruption fans. B: More detailed map of southernmost Andes with vegetation zones, isopachs (cm) of tephra fall deposits from the 4289 cal. yr B.P. Mount Burney eruption, and locations of fjord sediment cores ES1, SK1, and BA1 and stalagmite MA1. C: Gajardo Channel area with locations of the investigated soil, peat (GC2), and lake (CH1, LM1) sediment profiles.

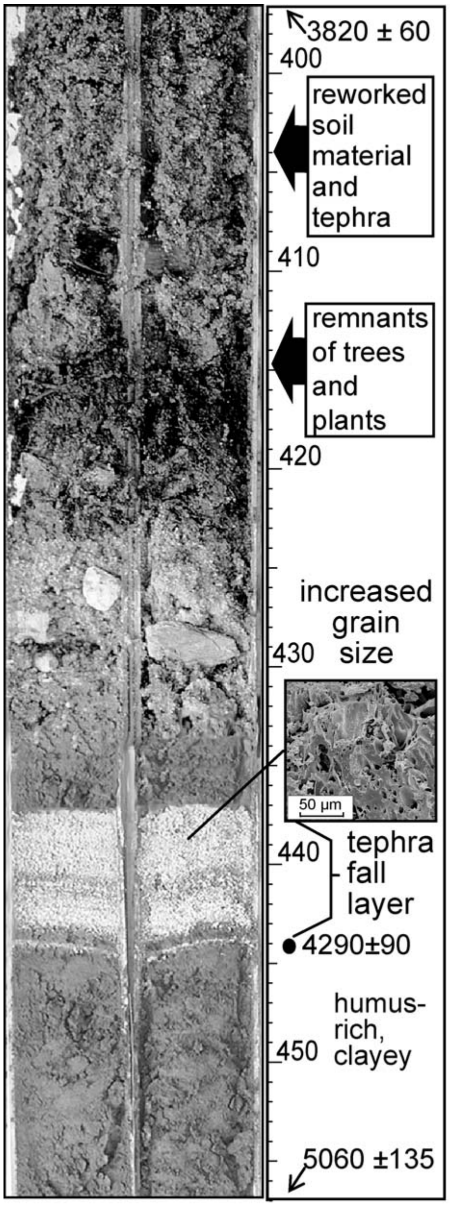

Figure 2. Sediment core retrieved from Lake Chandler with locations of ^{14}C ages (in cal. yr B.P.), an SEM picture of a pumice from the tephra layer, and specifications of the kind of accumulated sediments in the pre-, syn-, and posteruption phases (compare Fig. 3).

fjord to the west of Gran Campo Nevado (BA1 core with 8.8 m length; 52°41.6′S, 73°23.6′W), in the northern part of Seno Skyring (ES1 core with 4.1 m length; 52°42′S, 72°18′W), and in the eastern section of Seno Skyring (SK1 core with 4.7 m length; 52°37′S, 71°42′W). Overlapping (30–50 cm) of discontinuously drilled core sections was controlled by tephra layers.

Tephra assignment to volcanic eruptions of the Austral Andes Volcanic Zone (Kilian et al., 2003) is based on mineral and glass major element chemistry of the tephra, which was determined by electron microprobe (Cameca SX51, University of Heidelberg). ^{14}C measurements of terrestrial macrofossils were performed with an HVEE Tandetron accelerator mass spectrometer at the Leibniz Laboratory of University of Kiel. $^{13}C/^{12}C$ ratios were measured simultaneously by accelerator mass spectrometry (AMS) and used to correct mass fractionation. Conventional ^{14}C ages were calibrated using the CalPal 2005 (see http://www.calpal.de for further details). All depicted ages are means of one-sigma values.

Fifteen Th/U ages (^{230}Th-^{234}U disequilibrium method) were obtained from the 26-cm-long stalagmite MA1 (52°41.7′S, 73°23.3′W; Fig. 1) from a cave 12 km northwest of Gran Campo Nevado. Th/U measurements were performed on a MAT 262 RPQ mass spectrometer with a double-filament technique at Forschungsstelle Radiometrie, Heidelberg University (see Frank et al., 2000). Ages were corrected for initial detrital ^{230}Th under the assumption of an activity ratio of $^{230}Th/^{232}Th$ like average crust. Corrected ages show a nearly constant growing rate of 60–72 μm/yr throughout the past 4500 yr.

The particle size analyses were conducted each 10 cm of the cores with a Galai CIS-1 laser particle counter, with an analytical range between 0.5 and 150 μm. The texture of tephra and minerogenic and biogenic components were determined each 10 cm of core section with the scanning electron microscope (SEM) LEO 435 VP at the Geology Department of Trier University.

Carbon and sulfur concentrations in sediments were determined by means of a C/S analyzer (ELEMENTAR) burning 10–20 mg sample aliquots in a tin capsule. Mean relative standard deviations were 2.2% for C and 2.1% for S. Estimated detection limits were 0.01 wt% for C and 0.02 wt% for S. Sulfur content in volcanic glass was determined by electron microprobe. Sulfur content and trace element contents of bulk tephra and glass separates were performed by ICP-MS analyses from Act-Labs, using international standards and methods described at http://www.actlabs.com.

RESULTS

Lake Chandler and Lake Martillo (CH1 and LM1, Fig. 1C) and fjord sediment cores (SK1, ES1, and BA1 in Fig. 1B), taken across the eruption fan, document the sedimentation of the past 6000 yr. The stratigraphy is based on AMS-^{14}C ages and a tephra chronology, which includes a very thin tephra layer of Aguilera volcano (younger than 3620 ± 230 cal. yr B.P.; Kilian et al., 2003) and a further small tephra layer of Mount Burney (2020 ± 90 cal. yr B.P.; Kilian et al., 2003). All sediment cores show strongly increased (up to four- to fivefold) S accumulation rates during at least 2000 yr after the 4290 cal. yr B.P. eruption of Mount Burney (Figs. 3A–3C).

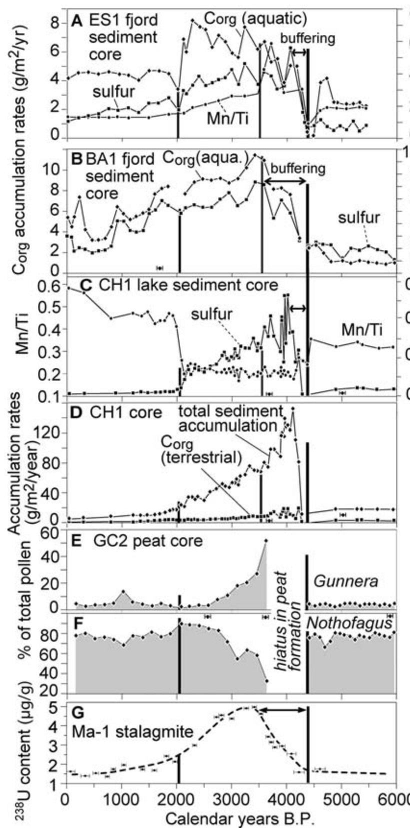

Figure 3. A–C: Sulfur and C_{org} accumulation rates, and Mn/Ti ratios for sediment cores ES1, BA1, and CH1 with identified tephra layers of Mount Burney (4290 cal. yr B.P.), Aguilera (3620 cal. yr B.P.), and Mount Burney (2020 cal. yr B.P.). Dots with error bars indicate additional calibrated ^{14}C ages. D: Accumulation rates for total sediment, terrestrial C_{org}, and reworked tephra in the Lake Chandler sediment core (CH1). E–F: Profile of peat core GC2 with *Nothofagus* and *Gunnera* pollen record with tephra layers and cal. ^{14}C ages (dots with error bars). G: ^{238}U content with Th/U ages (dots with error bars) in the stalagmite MA1.

However, there are differences between 150 and 350 yr until the maximum S accumulation is reached. The lake sediment core CH1 shows the fastest reaction, probably due to a restricted catchment area with restricted buffer capacity due to a granitic basement underlying the soil (SERGEOMIN, 2003). Pre-eruptive S accumulation rates are not reached again until ~2300 yr after the eruption. The BA1 fjord sediment core shows the slowest increase in the S accumulation, which may reflect some buffering due to the outcrop of some marble in the generally granitic catchment area. Pre-eruptive S levels reappear as late as 3500 yr after the eruption, and fjord sediment cores ES1 and SK1 (curve not shown here) show elevated S levels at present if compared to the pre-eruption levels. This reflects an ongoing process of S supply from the tephra in the less humid area to the east of the Andes where tephra alteration may be slower (Ugolini and

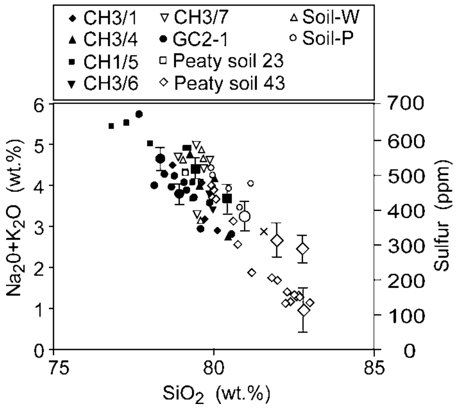

Figure 4. Total alkali (K_2O and Na_2O, left *y* axis) versus SiO_2 contents of glass of the 4289 cal. yr B.P. Mount Burney tephra layer from different sampling sites. Sulfur content (right *y* axis) is shown for selected samples (large dots with error bars). Note: Samples from peat cores show most pronounced leaching effects. Soil-W and Soil-P represent original field-book labelling of different soil outcrops.

Dahlgren, 2002). Based on the distribution of investigated core sites in the eruption fan, we estimate that an area of at least 150,000 km^2 was affected by the long-term S supply from the altering tephra (Fig. 1B).

Electron microprobe and ICP-MS analysis of volcanic glass from the 4289 cal. yr B.P. tephra fall layer indicate loss of S and other mobile elements (such as Na, K, and U; Fig. 4) by glass alteration. Smaller glass particles and tephra fall in peat cores, altered within an acid environment, show up to 60%–90% loss of the initial concentrations of K_2O, Na_2O, and S. Present-day S concentrations of the tephra are between 150 and 300 ppm, but the glass alteration trend allows us to estimate initial S contents of ~600–700 ppm (Fig. 4). As 20–25 vol% of the tephra layer consists of glass fragments, a deposition of 120 g/m^2 S for areas covered by at least 10 cm of tephra can be estimated (Fig. 1B).

The pre- and posteruptive element mobility and acidification were monitored by the amount of Fe and Mn leaching from acid soils and the pH-dependent precipitation of Fe/Mn hydroxides in either lakes or fjords. Mn hydroxides require a pH of at least 7 to precipitate (Skousen et al., 1994). Prior to the 4290 cal. yr B.P. Mount Burney eruption, Chandler lake sediments (Fig. 3C) show high accumulations of Fe/Mn hydroxides, which led to high Mn/Ti ratios in the sediment (Fig. 3C). The lowering of Mn/Ti ratios in the Chandler Lake sediment core (CH1) for more than 2000 yr after the tephra deposition indicates a significant drop in the lake pH, which hampered the precipitation of Fe/Mn hydroxides. The general acidification of soil and aquatic systems by release of S from altering tephra may have caused increased flux of nutrients and mobile elements from land to the fjord system (Fig. 1B). This process is monitored by an increased precipitation of Fe/Mn hydroxides in the buffered marine aquatic systems, which led to higher Mn/Ti ratios after the eruption (Fig. 3A). The fjord sediment cores BA1, ES1, and SK1 also show increased accumulation of marine organic C (C/N ratios <10) after the eruption, documenting the posteruptive increase in nutrient supply to the fjord system.

Soil acidification causes significant leaching of nutrients (Mulder et al., 1989) from soil and tephra after the eruption. This is recorded by the U concentrations of a U/Th-dated stalagmite record (loc. BA1 in Fig. 1B). The stalagmite grew continuously in a small cave associated with a localized marble occurrence in otherwise granitic bedrock, and overlain by forest with peaty soils. Uranium concentrations increase threefold after the eruption during a period of ~1000 yr (Fig. 3E), before most base cations (buffering capacity) of surrounding soils and rocks were consumed. Pre-eruption U concentrations reappear only >3000 yr after the eruption.

The sediment core from the small Lake Chandler (100–300 m diameter) with restricted catchment area of moderate topography (Fig. 1C) documents the posteruptive erosional history (Fig. 2). AMS-^{14}C ages of terrestrial plant macrofossils (leafs) and tephra chronology (Kilian et al., 2003) provide a time frame for the past 9000 yr. From 8745 ± 110 cal. yr B.P. until the 4290 cal. yr B.P. Mount Burney tephra layer, the sedimentation was characterized by constantly low accumulation of clayey, organic-rich sediment components (<20 g/m^2/yr; Fig. 3D). The tephra fall layer is overlain by 3–4 cm of clayey-silty sediments, which were deposited in the decades after the eruption (Fig. 2) and indicate at first an almost normal sedimentation after tephra deposition. Above these fine-grained sediments, a mixture of gravel and coarse plant material, root and tree remnants, and reworked tephra was deposited, indicating destruction of soils and vegetation, and high erosion rates. During the first 200 yr after the eruption, the sediment accumulation rates increase sevenfold (up to 150 g/m^2/yr; Fig. 3D). From 300 yr after the eruption onward, accumulation rates decrease very slowly until pre-eruption levels are reached after 2300 yr. Chemical and microstructural analysis by scanning electron microscopy shows that the increased sediment input is from organic and minerogenic components of eroded soils. Three upward-inverted ^{14}C ages (3990 ± 70, 4030 ± 50, 4790 ± 60 cal. yr B.P.; Fig. 3D) in this part of the profile represent mixed ages caused by influx of organic remains from continuously deeper eroded soils. The tephra is reworked until 1500 yr after the eruption (Fig. 3D).

A high-resolution pollen record of the pre- and posteruption phase of Mount Burney was obtained from a minerogenic peat core (GC2, Fig. 1C) (Fesq-Martin et al., 2004) from the same area. The 4290 cal. yr B.P. Mount Burney eruption appears between 42 and 48 cm core depth. Two ^{14}C ages (3630 ± 50 and 2750 ± 10 cal. yr B.P.) and the thin 2020 cal. yr B.P. Mount Burney eruption layer (Kilian et al., 2003) give an age control on the slower posteruptive peat accumulation (Figs. 3E and 3F). The pre-eruption pollen record shows a stable ecosystem dominated by *Nothofagus* forest and bog plant communities (Fesq-Martin et al., 2004). The ^{14}C age of 3630 cal. yr B.P., directly above the Mount Burney tephra layer, marks the end of an ~650 yr hiatus in peat growth and pollen record after the eruption (Figs. 3E and 3F). At that time, peat-forming species *Cyperaceae* and *Juncaceae* started to grow again. Immediately after the hiatus, the pollen of *Gunnera magellanica*, a pioneering plant, amounts to 54% of all terrestrial plant pollen, compared to only 2%–5% before the eruption (Figs. 3B and 3C). The *Gunnera* peak is accompanied by high incidences of *Cyperaceae* and *Juncaceae* pollen, which we interpret as markers of a primary succession. *Nothofagus* abundance shows a drastic decrease from 80% before the eruption to a post-hiatus level of 32%. Only ~2000 yr after the eruption, *Nothofagus* pollen percentages (and associated *Ranunculaceae* and *Myrtaceae* pollen) reach the pre-eruption values (Fig. 3B). Since Neoglacial cooling was only minor in the southernmost Andes (Koch and Kilian, 2005), the described pollen perturbations could not have been caused by climate fluctuations.

DISCUSSION

Destruction of plant cover and forest was not abrupt, as indicated by the clayey sedimentation layer immediately above the pumice (Fig. 2). Therefore, mechanical or direct physical or chemical destruction by the fallout seems unlikely. Investigations on the critical loads of acidity for different types of soils and ecosystems in Great Britain indicate that acid soils, such as the peaty soils (pH of 3.5–5) in the superhumid part of the investigated area, are especially sensitive to acid input (Grattan and Gilbertson, 1994; Hornung et al., 1995). Furthermore, weathering of the quartz-feldspar–rich bedrock forms soils with low buffering capacity. In addition, well-drained soils on steep slopes in areas with high precipitation have very low critical acid-loading capacities (e.g., Hornung et al., 1995). In the investigated area (Fig. 1), forests are restricted to such well-drained sites on steep fjord slopes

(Young, 1972). On the Northern Hemisphere, a similar soil acidification was suggested to be responsible for the decline of the Scots Pine after the Hekla 4 eruption in Iceland ca. 4000 yr B.P. (Blackford et al., 1992) and the demise of Irish oak woodland after mid-Holocene volcanic eruptions (Pilcher, 1990).

Soil acidification increases leaching of base cations and nutrients, and replenishment takes decades (Mulder et al., 1989). This is important in the investigated moorland, where soils are extremely poor in nutrients (Godoy et al., 2003), and leaching is demonstrated in sediment and stalagmite records (Figs. 3A, 3C, and 3G). In forest sites, a drop of pH below the critical value of 3–4 could have also enhanced mobility of toxic Al (Gensemer and Playle, 1999) and/or damaged the microorganisms (*Mycorrhizae*) responsible for N supply of the plants (Smith, 1990). This combination of processes affected vegetation with distinct reaction times at individual sites over a period of more than 100 yr, before mortified trees collapsed and erosion of the soils started, as demonstrated by the Chandler Lake (CH1) sediment record (Figs. 2 and 3A). After destruction of the plant cover, extreme precipitation events (up to 480 mm/d; Schneider et al., 2003) accelerated erosion of soils until bedrock was exposed in an extended area. At many sites, a new primary succession of extremely slowly growing forest and bog species was needed. Soil profiles (Fig. 1C) and outcrops indicate that most present-day soils on steep slopes inside of the 10 cm tephra isopach (Fig. 1B) developed during the last 2000–3000 yr.

Our results emphasize the extreme sensitivity of ecosystems to any kind of acidification in superhumid and cold-climate mountain ranges with volcanic and/or granitic bedrock (Campbell et al., 2004). Volcanic fallout and related acidification specifically interact with soils and ecosystems, depending on microstructure and composition of erupted material as well as the rate of glass alteration. Our findings also have implications for the worldwide anthropogenic increase in deposition of acids from the atmosphere that may prompt similar effects. For the first time, we document long-lasting acidification and related nutrient leaching of soils by release of SO_2 from altering pumice, and the resulting impact on vegetation, erosion, and element mobility in proxy records. Understanding such effects may improve interpretations of Pleistocene-Holocene paleoclimate reconstructions, e.g., from pollen and lake sediment records, as we document that millennium-scale perturbations in environmental archives can be caused by deposition of only a small tephra layer far away from centers of volcanic eruptions.

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