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The significance of chemical, isotopic, and detrital components in three coeval stalagmites from the superhumid southernmost Andes (53°S) as high-resolution palaeo-climate proxies

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ABSTRACT

Stalagmites are important palaeo-climatic archives since their chemical and isotopic signatures have the potential to record high-resolution changes in temperature and precipitation over thousands of years. We present three U/Th-dated records of stalagmites (MA1–MA3) in the superhumid southern Andes, Chile (53°S). They grew simultaneously during the last five thousand years (ka BP) in a cave that developed in schist and granodiorite. Major and trace elements as well as the C and O isotope compositions of the stalagmites were analysed at high spatial and temporal resolution as proxies for palaeo-temperature and palaeo-precipitation. Calibrations are based on data from five years of monitoring the climate and hydrology inside and outside the cave and on data from 100 years of regional weather station records.

Water-insoluble elements such as Y and HREE in the stalagmites indicate the amount of incorporated siliciclastic detritus. Monitoring shows that the quantity of detritus is controlled by the drip water rate once a threshold level has been exceeded. In general, drip rate variations of the stalagmites depend on the amount of rainfall. However, different drip-water pathways above each drip location gave rise to individual drip rate levels. Only one of the three stalagmites (MA1) had sufficiently high drip rates to record detrital proxies over its complete length. Carbonate-compatible element contents (e.g. U, Sr, Mg), which were measured up to sub-annual resolution, document changes in meteoric precipitation and related drip-water dilution. In addition, these soluble elements are controlled by leaching during weathering of the host rock and soils depending on the pH of acidic pore waters in the peaty soils of the cave's catchment area. In general, higher rainfall resulted in a lower concentration of these elements and vice versa. The Mg/Ca record of stalagmite MA1 was calibrated against meteoric precipitation records for the last 100 years from two regional weather stations. Carbonate-compatible soluble elements show similar patterns in the three stalagmites with generally high values when drip rates and detrital tracers were low and vice versa. $\delta^{13}C$ and $\delta^{18}O$ values are highly correlated in each stalagmite suggesting a predominantly drip rate dependent kinetic control by evaporation and/or outgassing. Only C and O isotopes from stalagmite MA1 that received the highest drip rates show a good correlation between detrital proxy elements and carbonate-compatible elements. A temperature-related change in rainwater isotope values modified the MA1 record during the Little Ice Age (~0.7–0.1 ka BP) that was ~1.5 °C colder than today. The isotopic composition of the stalagmites MA2 and MA3 that formed at lower drip rates shows a poor correlation with stalagmite MA1 and all other chemical proxies of MA1. 'Hendy tests' indicate that the degassing-controlled isotope fractionation of MA2 and MA3 had already started at the cave roof, especially when drip rates were low. Changing pathways and residence times of the seepage water caused a non-climatically controlled isotope fractionation, which may be generally important in

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ventilated caves during phases of low drip rates. Our proxies indicate that the Neoglacial cold phases from ~3.5 to 2.5 and from ~0.7 to 0.1 ka BP were characterised by 30% lower precipitation compared with the Medieval Warm Period from 1.2 to 0.8 ka BP, which was extremely humid in this region.

1. Introduction

Stalagmites represent important palaeo-climatic archives due to a precise U/Th age control and the possibility of sub-annual resolution of their climate-related isotopic and geochemical signals (Henderson, 2006). However, palaeo-climate interpretations are often based on a single stalagmite record from one cave. Only a few case studies have reported variations of proxies of multiple stalagmites from a given cave (e.g. Dorale et al., 1998; Williams et al., 2004; Vollweiler et al., 2006). The variability of chemical and isotopic proxies between different stalagmites and/or their dependence on individual drip rate characteristics has rarely been investigated. Changes of the drip-water pathways may produce chemical and isotopic signals which are not directly related to climate, especially in caves with enhanced evaporation due to ventilation.

Here we present data from three Late Holocene stalagmites (MA1, MA2, and MA3) that grew close together in a small non-karst cave in the fjord region of the southernmost Andes (Chile, 53°S, Fig. 1). The location represents the core section of the Southern Hemispheric Westerlies (SHW). To our knowledge, this is the first study of speleothem records from this region. The aim of this study is to evaluate the climatic sensitivity of chemical and isotopic tracers in these stalagmites and calibrate them against instrumental data (temperature and precipitation) over the past 100 years. Furthermore, we monitored the cave for five years. A major aim is to resolve extreme short-term climate events in our high-resolution proxy record, such as three-day 1000 mm precipitation periods that have been documented to be associated with extreme storms in the area (Schneider et al., 2003). We analysed the stable isotopes of C and O, and the concentrations of the carbonate-compatible elements Mg, U, and Sr as palaeo-environmental proxies. Elements like Y, Al, Ti, Zr, and HREE are usually not dissolved in the cave drip water and are fixed in siliciclastic particles, or sometimes adsorbed on colloidal particles (Borsato et al., 2007). In non-karst caves, such detrital minerals can be transported with the drip water onto the stalagmite. The variations of the detritus-indicating trace elements in the stalagmites were investigated in order to detect their sensitivity to drip rate and precipitation changes. Our new speleothem-based high-resolution temperature and precipitation records from southern Patagonia are compared with other palaeo-climatic reconstructions from the southern Andes, which is a key region for understanding past variability of the SHW and their forcing mechanisms.

2. Site description

The "Marcelo Arévalo" cave (location MA in Fig. 1; 52°41.7′S/73°23.3′W) was unofficially named after its discoverer in 2002. It is located 15 km NW of the centre of the 200 km^2 large Gran Campo Nevado (GCN) ice field, which represents the highest elevation and a significant climate divide in this section of the Andes (Schneider et al., 2007). The cave is situated about 20 m above sea level on the shore of a small bay in a fjord system along the Pacific coast (Fig. 1). This extremely windy and superhumid area in the western range of the Andes is unpopulated and can only be reached by ship.

South of 40°S the Andes represent one of the most pronounced climate divides in the world since this mountain range is located perpendicular to the SHW belt. Southernmost South America is the only continental landmass within the SHW core. Hence, the southernmost Andes are the only barrier to these winds that would otherwise blow nearly unimpeded around the globe. The very cold Antarctic continent causes a steep temperature and pressure gradient between the high latitudes and the subtropics giving rise to stronger westerly winds than at similar latitudes in the Northern Hemisphere (Schneider et al., 2003). The SHW belt stretches from 35° to 60°S and exhibits distinct seasonal as well as millennial-scale changes in its wind and precipitation patterns (e.g. Lamy et al., 2007, 2010). At the Southern Andes climate divide, precipitation is mainly controlled by the SHW intensities.

The MA cave is located in the core of the SHW (Fig. 1) where throughout the year strong winds and very high precipitation occur (up to 10,000 mm per year at the Gran Campo Nevado with maxima of up to 500 mm per day; Schneider et al., 2003). NCEP-NCAR[1] data between 1960 and 2000 indicate that precipitation and wind speed in the SHW core are higher in summer and lower in winter (Fig. 1a inset), whereas the northern margin of the SHW in central Chile (30–40°S) shows higher humidity in winter and significantly lower humidity in summer (Lamy et al., 2010).

The cave was formed by coastal weathering and erosion in a fracture zone during the Lateglacial or Early Holocene when the coastline was 20 m higher than today. The host rock consists of granite, granodiorite and gneiss; hence, karst dissolution did not play a role. The Ca in the drip water is derived from Ca-bearing silicate minerals (feldspar, hornblende, clinopyroxene) leached from the soil-weathering horizon in the cave catchment area and from sea spray. The restricted catchment area of the cave (less than 1 km^2) lies on a relatively flat crest that is covered by peat vegetation with acidic (pH 3–5) soil water. The well-drained steep slopes are overgrown by evergreen Magellanes rain forest (Fig. 1b and c). The MA cave is situated on a steep southeastern slope (no direct sunlight) and is 15 m deep, up to 6 m high and 2–3 m wide. Large trees (up to 20 m) cover the relatively wide cave entrance. Due to this and the cave's easterly exposure only very weak winds are noticeable inside. Thus, the cave is relatively well protected during the frequent and strong storms from mainly western directions. However, cave temperature and humidity are closely linked to the external atmospheric conditions (see Section 4.1).

The three stalagmites (MA1–MA3) grew less than 1 m apart from each other, approximately 7 m behind the cave entrance. Due to the very close distance between the stalagmites, we assume that they were probably fed by the same drip-water source. Given their location nearby the wide entrance, the speleothems are influenced by large humidity and temperature variations (comparison of inside and outside temperatures in Fig. 2c) and sea spray (Biester et al., 2002, 2004) which can enter the cave as fine drifts of mist. Salty encrustations near the rain-protected entrance confirm the occasional deposition of sea spray. Furthermore, mosses and algae grew locally on the surface of the stalagmites during periods of low drip rates.

Two Plinian eruptions of the Mt. Burney volcano, located about 40 km north of the cave (Fig. 1a, 1520 m asl, 52°20′S/73°23′W), occurred during the growth interval of the stalagmites: a major

[1] http://dss.ucar.edu/pub/reanalysis/.