Earth and Planetary Science Letters 375 (2013) 291–302

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Moroccan speleothem and tree ring records suggest a variable positive state of the North Atlantic Oscillation during the Medieval Warm Period

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ARTICLE INFO

Article history:
Received 31 July 2012
Received in revised form
10 May 2013
Accepted 28 May 2013
Editor: G. Henderson
Available online 10 July 2013

Keywords:
North Atlantic Oscillation
medieval climate anomaly
speleothem
prior calcite precipitation
aragonite
trace elements

ABSTRACT

We present a magnesium (Mg) and strontium (Sr) record from an aragonitic speleothem (Grotte de Piste, Morocco, 34°N; 04°W) providing a reconstruction of effective rainfall from 619 to 1962 AD. The corresponding drip site was monitored over 2 yr for drip water Mg/Ca and Sr/Ca ratios. Results show evidence for prior aragonite precipitation, which can explain negative correlations between speleothem Mg and Sr concentrations. The data shown here have important climate implications concerning the evolution of the North Atlantic Oscillation (NAO). A comparison of the stalagmite data from Grotte de Piste with an updated tree ring based drought reconstruction from Morocco and other NAO related proxy records confirms that the Medieval Warm Period (MWP) was dominated by NAO+ conditions. The stalagmite record and multiple proxy records from the Iberian Peninsula, however, suggest that considerable rainfall variability occurred during the MWP. This implies that the NAO has been more variable during the MWP than formerly suggested.

1. Introduction

The North Atlantic Oscillation (NAO) represents the dominating atmospheric pressure mode of the North Atlantic/European area (Hurrell, 1995; Wanner et al., 2001) and has a large effect on winter surface air temperatures and precipitation in the Northern hemisphere (Hurrell, 1996; Hurrell and Van Loon, 1997). The NAO affects the strength and the course of the westerlies and can be described by the NAO-index, which is defined as the difference in normalized sea level pressure between the Icelandic low and the Azores subtropical high. In order to gain understanding of its natural variability, proxy based NAO reconstructions over the last hundreds to thousands of years are a necessity (Cook et al., 2002; Luterbacher et al., 1999; Olsen et al., 2012; Trouet et al., 2009). Trouet et al. (2009) suggested that the Medieval Warm Period was characterized by persistent NAO+ conditions, whereas the Little Ice Age (LIA) was characterized by dominantly NAO− conditions. Lehner et al. (2012), however, demonstrated that the persistence of NAO+ during the MWP and the MWP–LIA transition could not be reproduced by the climate models. The NAO reconstruction from Trouet et al. (2009) thus needs to be verified by other proxy records.

The NAO reconstruction from Trouet et al. (2009) is based on a rainfall sensitive speleothem record from NW Scotland (Proctor et al., 2000) and a tree ring based PDSI reconstruction from Morocco (Esper et al., 2007). Here, trace element compositions of an aragonitic speleothem from the north-western part of the Middle Atlas in Morocco have been investigated. The speleothem record covers the time period 619–1962 AD and is from a cave located in an area sensitive to droughts, which is affected by the NAO. This is evident from the strong decrease in the amount of winter rainfall after the 1970s, which was linked to predominantly positive NAO conditions (Ward et al., 1999).

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http://dx.doi.org/10.1016/j.epsl.2013.05.048

Speleothems are well established archives of continental paleoclimate (Cruz et al., 2005; Drysdale et al., 2009; Kanner et al., 2012; Wang et al., 2008; Zhang et al., 2008). To date, most studies rely on calcitic stalagmites and flowstones (Cai et al., 2010; Neff et al., 2001; Spötl et al., 2002; White, 2004). In this study, however, an aragonitic stalagmite has been used.

Aragonite speleothems are common in dolomite host rock caves and in (seasonally) arid settings (Bertaux et al., 2002; Frisia et al., 2002; Railsback et al., 1994; Wassenburg et al., 2012). In general, aragonite is diagenetically less stable under atmospheric conditions compared to calcite and may therefore recrystallize to calcite (Frisia et al., 2002; Martin-Garcia et al., 2009). However, well preserved aragonitic speleothems provide excellent archives for climate reconstruction (Cosford et al., 2008; Li et al., 2011), because they are – due to their often high U content – well suited for U–Th dating. Whereas most studies of aragonite speleothems have focussed on oxygen isotopes (Cosford et al., 2008; Holmgren et al., 1999; Holzkämper et al., 2009; Li et al., 2011 and others), trace element compositions remain largely unexplored (Finch et al., 2003; 2001; McMillan et al., 2005; Wassenburg et al., 2012). Therefore, understanding the processes affecting speleothem aragonite trace element abundances is a necessity in order to explore their full potential.

In calcitic speleothems, positive correlations between Mg and Sr have repeatedly been interpreted in terms of prior calcite precipitation (PCP). Prior calcite precipitation (Fairchild et al., 2000; Fairchild and Treble, 2009; McMillan et al., 2005; Sherwin and Baldini, 2011; Sinclair et al., 2012; Stoll et al., 2012; Wong et al., 2011) takes place if the water encounters a gas phase with a lower pCO_2 causing CO_2 degassing within the karst aquifer or at the cave ceiling. This leads to super-saturation of the water with respect to $CaCO_3$, and precipitation (Fairchild and Treble, 2009). Under dry climate conditions, PCP can increase because of the increasing abundance of gas-filled voids within the karst aquifer and decreasing drip rates. Nevertheless, changes in soil CO_2 production and cave air pCO_2 may be important as well (Sherwin and Baldini, 2011; Wong et al., 2011).

The interpretation of trace element records from aragonite speleothems differs from calcite speleothems due to (1) crystallographic differences (orthorhombic versus trigonal), (2) the possible presence of secondary calcite (Frisia et al., 2002; Martin-Garcia et al., 2009; Ortega et al., 2005), or (3) co-precipitation of both mineralogies (Holzkämper et al., 2009; Wassenburg et al., 2012). Crystallographic parameters (i.e. the space available for the cation within the crystal lattice) affect the absolute partitioning coefficients of trace elements. Therefore, PCP has a different effect on drip water trace element to Ca ratios compared to prior aragonite precipitation (PAP; Wassenburg et al., 2012).

The aims of this study are (1) to present and interpret an aragonite speleothem trace element record from the Middle Atlas in Morocco, supported by cave monitoring data; (2) to compare the speleothem record to an updated version of the tree-ring based PDSI reconstruction from Esper et al. (2007); (3) to assess the existence of the MWP-LIA transition in terms of NAO conditions and (4) to assess the persistence of NAO+ conditions during the MWP.

2. Case setting

2.1. Present day climate of the Middle Atlas

Morocco is bordered by the North Atlantic to the west, the Mediterranean Sea to the north-east and the Western Sahara to the south-east (Fig. 1). The cave investigated here is referred to as Grotte de Piste and is located in the north-western part of the Middle Atlas of Morocco (Fig. 1). According to Knippertz et al.

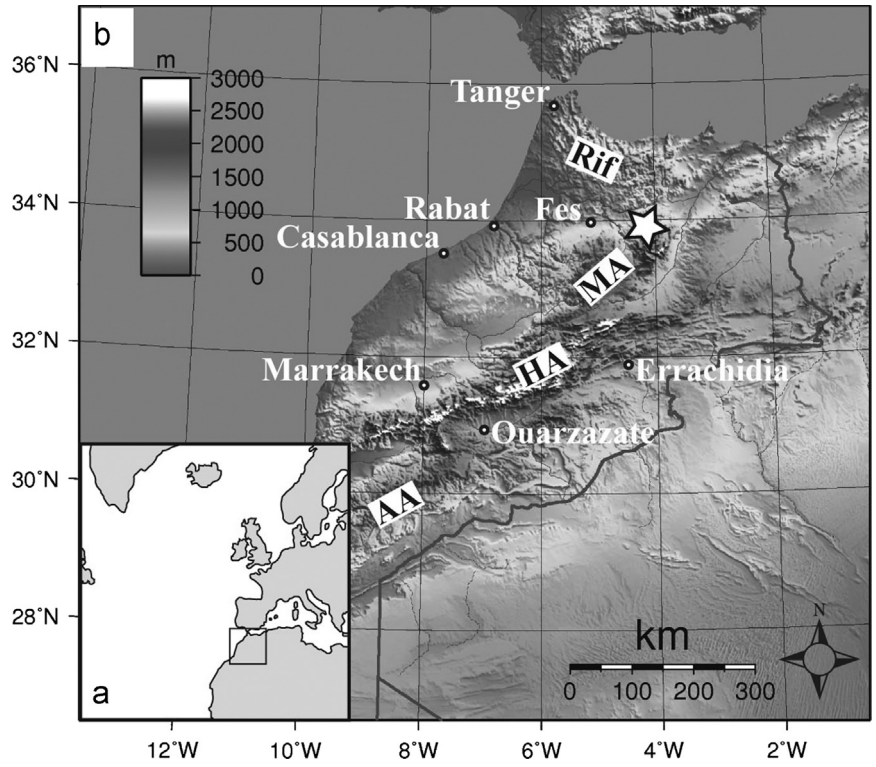

Fig. 1. (a) Regional setting of Morocco at the boundary between North Atlantic and Mediterranean Sea. (b) Cave position (indicated by the white star), with respect to the Rif, the Middle Atlas (MA), the High Atlas (HA), and the Anti Atlas (AA) mountain belts.