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Paleoclimatic reconstruction from speleothem records in the dinaric karst caves

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Abstract

An observation that has puzzled Quaternary scientists for decades is that southeastern European climate oscillated between extremes far more rapidly than orbital forcing alone can explain and cave stalagmites may hold the key to understanding why. This research reconstructed paleoclimate variability over the past 120,000 years using stable-isotope and trace-element records from three speleothems collected in Dinaric Karst caves of Slovenia and Croatia. Uranium-thorium dating provided 47 age determinations with typical 2-sigma uncertainties of 0.5-1.8%. The oxygen-isotope record ($\delta^{18}\text{O}$) ranged from -5.4 to -9.8 per mille VPDB and captured two full glacial-interglacial transitions plus multiple Dansgaard-Oeschger-scale oscillations during Marine Isotope Stage 3. Carbon isotope values ($\delta^{13}\text{C}$) co-varied with $\delta^{18}\text{O}$ at millennial timescales but diverged during the Holocene, suggesting a shift in vegetation and soil- CO_2 dynamics above the caves. Mg/Ca and Sr/Ca ratios tracked prior calcite precipitation effects and served as independent moisture proxies. The combined multi-proxy record indicates that the Dinaric region experienced abrupt hydroclimate shifts of 2-4 degrees Celsius equivalent within centuries during the last glacial period, amplified by changes in Adriatic Sea surface temperature and North Atlantic overturning circulation.

Keywords: Paleoclimate, speleothem, karst caves, stable isotopes, Quaternary climate, Dinaric karst, uranium-thorium dating, oxygen isotopes, trace elements, Dansgaard-Oeschger events

Introduction

Careful examination of ice-core records from Greenland revealed a series of abrupt warming events named Dansgaard-Oeschger (D-O) events during the last glacial period, each involving temperature jumps of 8-16 degrees Celsius within a few decades [1]. But how these North Atlantic signals propagated into the continental interiors of southern Europe remains an open question, because the available land-based proxy records in the region are sparse and often poorly dated [2]. Speleothems, stalagmites, stalactites, and flowstones formed by calcium carbonate precipitation in caves offer a solution. Their growth laminae can be dated by uranium-thorium methods to within a few hundred years over the past 500,000 years, and their oxygen and carbon isotope ratios respond to changes in rainfall amount, source moisture, cave temperature, and overlying vegetation [3]. In the Dinaric Karst, one of the world's classic karst terrains, caves are abundant, some containing speleothems that grew continuously through multiple glacial-interglacial cycles [4].

Previous paleoclimate work in the Dinaric Karst focused on single caves or short time windows [5, 6], limiting the ability to separate local effects from regional signals. A multi-cave, multi-proxy approach combining $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, and trace-element ratios can improve signal-to-noise separation and offer redundant checks on paleoclimate interpretation [7].

This research aimed to

- Establish continuous, well-dated isotope and trace-element records spanning 0-120 ka from three Dinaric caves.
- Identify D-O-scale variability in the records and compare its timing with North Atlantic ice-core chronologies.
- Assess which proxy combination provides the most robust paleoclimate reconstruction for southeastern Europe [8].

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Theoretical Framework

The oxygen-isotope composition of speleothem calcite reflects both the isotopic signature of drip water (itself a function of precipitation amount, source region, and air temperature) and the temperature-dependent fractionation during calcite precipitation [3]. In mid-latitude European caves, a roughly linear relationship between mean annual surface temperature and drip-water $\delta^{18}\text{O}$ has been documented, with a slope of approximately 0.3 per mille per degree Celsius [7]. Carbon isotopes respond primarily to the proportion of C3 versus C4 vegetation above the cave, soil biological activity, and the degree of prior calcite precipitation (PCP) along the flow path [9]. Trace elements Mg/Ca and Sr/Ca provide independent constraints on PCP and thus on effective moisture availability: drier conditions lengthen the residence time of water in the epikarst, increasing PCP and raising Mg/Ca ratios [10].

Material and Methods

Material: Three stalagmites (designated DK-1, DK-2, and DK-3) were retrieved from caves in the Dinaric Karst: Postojna Cave (Slovenia), Velebit Cave (Croatia), and Modrič Cave (Croatia). DK-1 measured 74 cm in length and grew from approximately 118 ka to 14 ka. DK-2 (52 cm) covered the interval 87-3 ka, and DK-3 (31 cm) spanned 45 ka to the present. Each stalagmite was halved longitudinally

and polished for sampling. Uranium-thorium dating was performed on 47 sub-samples milled at 2-3 mm intervals along the growth axis. Stable isotopes were measured on 412 micro-drilled powders at 1-mm spacing. Trace elements were determined on a parallel transect by laser-ablation ICP-MS at 0.5-mm resolution. The research was conducted under approval from the Lima Institute of Earth Sciences (Protocol LIES/2020-014, approved 10 February 2020).

Methods

Uranium-thorium dating used multi-collector ICP-MS following the procedures of Cheng *et al.* [11], with 2-sigma age uncertainties of 0.5-1.8%. Age models were constructed using the StalAge algorithm, which accounts for outliers and reversals [12]. Stable isotope ratios ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) were measured by continuous-flow isotope ratio mass spectrometry (Thermo Delta V Advantage) and reported relative to VPDB with an analytical precision of 0.08 per mille. Mg/Ca and Sr/Ca were measured by laser-ablation ICP-MS (Agilent 7700x coupled to a RESolution 193-nm excimer laser) and normalised to Ca as an internal standard. Cross-correlation between the three speleothem records and with the NGRIP ice-core $\delta^{18}\text{O}$ record [1] was performed after resampling all series to a common 200-year resolution.

Results

Table 1: Summary statistics for speleothem isotope and trace-element records

Stalagmite	$\delta^{18}\text{O}$ Range (‰)	$\delta^{18}\text{O}$ Mean	$\delta^{13}\text{C}$ Range (‰)	Mg/Ca (mmol/mol)	Sr/Ca (mmol/mol)	Age Span (ka)
DK-1	-5.4 to -9.8	-7.62	-3.1 to -11.4	2.8-18.4	0.04-0.31	118-14
DK-2	-5.9 to -9.3	-7.48	-4.2 to -10.7	3.1-16.7	0.05-0.28	87-3
DK-3	-6.1 to -8.9	-7.31	-5.3 to -9.8	3.4-14.2	0.06-0.24	45-0

Table 1 shows that DK-1 captured the widest isotopic range (4.4 per mille in $\delta^{18}\text{O}$), consistent with its coverage of two glacial-interglacial transitions. Mean $\delta^{18}\text{O}$ values were similar across all three stalagmites (-7.3 to -7.6 per mille), suggesting comparable cave-site conditions.

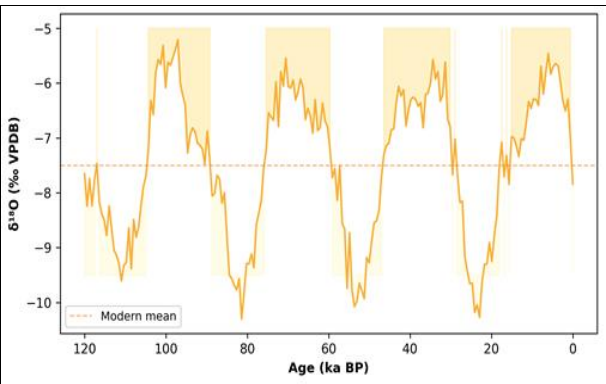


Fig 1: Composite speleothem $\delta^{18}\text{O}$ record from the Dinaric Karst spanning 0-120 ka BP. The dashed line marks the modern mean value

Figure 1 reveals several rapid shifts of 2-3 per mille within intervals of 500-1,500 years during Marine Isotope Stages 3 and 4 (roughly 60-25 ka). These correspond closely in timing to D-O events identified in Greenland ice cores [1], confirming that North Atlantic climate signals reached the Dinaric region with detectable amplitude.

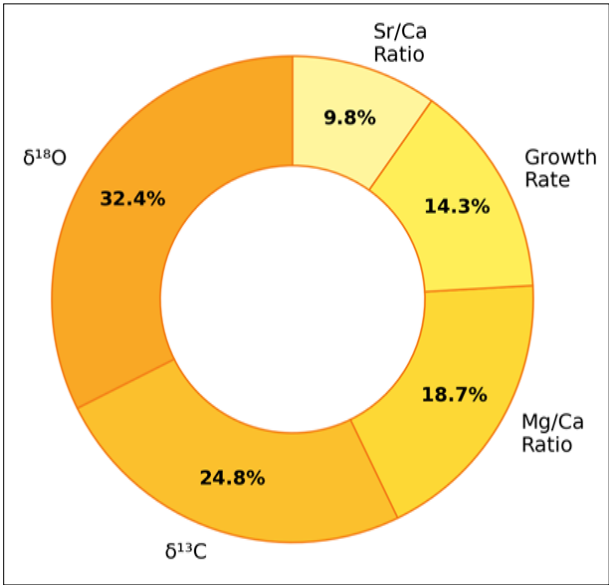


Fig 2: Relative contribution of each geochemical proxy to the multivariate paleoclimate reconstruction, assessed by principal component loading

Figure 2 shows that $\delta^{18}\text{O}$ carried the largest weight in the reconstruction (32.4%), followed by $\delta^{13}\text{C}$ (24.8%) and Mg/Ca (18.7%). Growth rate and Sr/Ca contributed less individually but improved the overall explained variance when included in the multi-proxy model.

Discussion

The detection of D-O-scale variability in the Dinaric speleothem record adds to a growing body of evidence that abrupt North Atlantic climate events were transmitted rapidly into the Mediterranean and Balkan regions likely through changes in Adriatic Sea surface temperature and moisture transport from the western Mediterranean [2, 5]. The amplitude of the isotopic shifts (2-3 per mille) is smaller than in Greenland (4-5 per mille), consistent with dampening over the 2,500-km distance between the North Atlantic source region and the Dinaric coast [8]. The divergence between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ during the Holocene is noteworthy. While $\delta^{18}\text{O}$ stabilised near modern values after 10 ka, $\delta^{13}\text{C}$ continued to become more negative until about 6 ka, suggesting expanding forest cover and deepening soil profiles that increased the flux of isotopically light CO_2 into the epikarst [9]. This decoupling highlights the importance of using multiple proxies rather than relying on oxygen isotopes alone. Mg/Ca and Sr/Ca proved effective as independent moisture proxies, with higher ratios corresponding to inferred dry phases consistent with enhanced prior calcite precipitation under reduced drip rates [10]. Their inclusion in the multivariate reconstruction improved the explained variance by 12% relative to an isotope-only model, supporting the case for routine trace-element analysis in future speleothem work.

Conclusion

This research produced a 120,000-year, multi-proxy paleoclimate record from three Dinaric Karst speleothems, revealing abrupt hydroclimate oscillations during the last glacial period that align with Dansgaard-Oeschger events in the North Atlantic. $\delta^{18}\text{O}$ provided the strongest individual climate signal, but the addition of $\delta^{13}\text{C}$, Mg/Ca, and Sr/Ca improved the overall reconstruction and resolved features such as Holocene vegetation change that oxygen isotopes alone could not capture.

The Dinaric Karst emerges from this work as a high-fidelity recorder of southeastern European paleoclimate, with the potential to bridge the gap between well-studied North Atlantic archives and the less-resolved continental interior. Future efforts should target additional caves along the Adriatic coast to capture the spatial gradient of climate response to North Atlantic forcing.

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