**Article**

**Speleothem stable isotope records from Eastern Europe & Turkey**

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**Abstract:** The region of Eastern Europe & Turkey contributed to the SISAL (Speleothem Isotopes Synthesis and AnaLysis) global database with stable carbon- and oxygen isotope time-series from 18 entities from 14 cave systems. The currently available oldest record from this region is the ABA-2 flowstone record (Abaliyet Cave; Hungary) reaching back to MIS 6. The temporal distribution of the compiled 18 entities points out a ~20-kyr-long period, centering around 100 ka, lacking speleothem stable isotope record in the region. The regional subset of SISAL_v1 records displays a continuous coverage for the past ~90 kyr for both δ¹⁸O and δ¹³C, with a mean temporal resolution of ~12 yr for the Holocene, and >50 yr for the pre-Holocene period. The highest temporal resolution both for the Holocene and the pre-Holocene was achieved in the So-1 record (Sofular Cave; Turkey). Assessing the data, an important split was found regarding the climatic interpretation of speleothem δ¹⁸O. While the oxygen isotope composition of more continental formations is thought to reflect mainly temperature variations and changes in moisture transport trajectories, it may strongly reflect fluctuations of precipitation amount in the southern part of the region. Variations of δ¹³C primarily interpreted as humidity changes reflecting dry/wet periods across the region. Elevation gradients from three non-overlapping time periods from the region – for the last 5kyr - indicated systematically prevailing elevational gradients around ~0.26‰ 100m⁻¹ in δ¹⁸O. The regional comparison of SISAL_v1 speleothem δ¹⁸O and the temporal distribution of coarsely crystalline cryogenic cave carbonate occurrences back to 45ka does not appear to confirm the finding that occurrence of the latter coincides with the warming from stadial to interstadial conditions.

**Keywords:** Carpathians, Balkan Peninsula, Holocene, hydroclimate, cryogenic cave carbonate, carbon, oxygen

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1. **Introduction**

South-eastern Europe is the cradle of karst research [1-3]. The Kras Mountains in Slovenia gave their name to the entire discipline, and the very first karst research [4] and speleological [5] institutes were established in this region. Eastern Europe and Turkey has a very diverse karst landscape, and wide range of geochronological and geochemical investigations targeted the cave deposits in this region, aiming to infer information about past environments.

Radionetric dating of submerged speleothems from the Dalmatian Coast helped to constrain periods of sea-level low - [6-8] and high-stands [9] during the Quaternary.

Trace element variability in speleothems from the region provided basis for paleohydroclimate implications [10-12], supported the identification of historical flood events [13]. Siklósy et al. [14] associated a sudden rise in rare earth elements with the Middle Bronze Age eruption of Santorini. In
the meanwhile, changes in U concentration and δ²³⁴U changes associated with an increase in detrital material (e.g. Al, Si, Th) in the younger part of the same flowstone were used to detect pollution from historical mining activity [15]. Geochemical imprint (e.g. peaks in Br, Mo, S) was found to be indicative for the Minoan eruption studying the trace element profile in the So-1 record from Sofular Cave [16].

Although it has been long recognized that stable isotope analysis of inclusion-hosted water has a great potential in speleothem-based paleoclimate reconstructions [17], the relatively large sample amount required for classical dual inlet mass spectrometry and the sophisticated technique for O isotopic analysis (using fluorine compounds as reagents) precluded wide application. With the advent of continuous flow mass spectrometry and laser spectroscopy, the required sample volume has decreased significantly and coupled analysis of H and O isotopes compositions of inclusion-hosted water became easily available, for details see [18]. Despite the potential of inclusion fluid research, stable isotope compositions of fluid inclusions have only been gathered from Turkish and Hungarian speleothems from the Eastern Europe & Turkey region. Hydrogen isotope compositions of inclusion-hosted water, analyzed by the continuous flow technique [19] for a stalagmite from SE Hungary was interpreted as a sign of drip water composition variation in the Bronze Age [14]. Although the analytical precision and post-deposition exchange processes precluded precise paleotemperature calculations, the co-variation of δ¹⁸O for speleothem calcite and inclusion-hosted water analyzed in a stalagmite from Eastern Turkey were used to infer past variations in seasonal precipitation distribution [20]. Mid-Holocene changes in moisture transport trajectories were inferred from the H isotope compositions of inclusion-hosted water analyzed by conventional dual inlet mass spectrometry [21]. An important methodological recognition is that hydrogen isotope compositions provide reliable paleoclimate records, while δ¹⁸O data are compromised due to post-deposition recrystallization and calcite-water isotope exchange [22]. As a result, δH values were used for paleotemperature calculations either applying local δH-temperature relationships, or combining the δH data with calcite δ¹⁸O values [11,18]. These procedures yielded paleotemperature estimates in agreement with independent methods both for the last interglacial [18] and the Middle Bronze Age [11].

Although the longest history of karst research leads back to this region [1], stable isotope investigations of calcareous speleothems began relatively late, at the very end of the 20th century [23,24]. Stable isotope ratios of certain non-calcareous cave deposits, such as cave ice [25,26] and guano deposits [27-29], have a pronounced paleoclimatological potential in the region, however stable carbon and oxygen isotope ratios of carbonate deposits became the most frequently investigated and most abundant geochemical parameter in speleothems studies in Eastern Europe and Turkey.

The first studies aimed to infer paleoenvironmental reconstructions based on stable isotope composition of Late Pleistocene speleothems were carried out in Wierna Cave, Southern Poland [23] and Ceremosnja Cave (Serbia) [30]. Nevertheless, this aim was first achieved in Bear’s Cave (Pestera Ursilor), Romania [31]. Several other records followed these within a short time from the same area (e.g. [14,32,33]); including the iconic So-1 record from Sofular Cave, Northern Turkey [34] which provided the first speleothem-based climate record covering the Holocene and the Last Glacial in SE Europe.

The Eastern Europe & Turkey SISAL region is an important hydroclimatological transition zone. The study area lies in the temperate climate zone [35], but is characterized by a highly diverse precipitation regime. The extreme humid conditions along the coastal areas of the Dinaric Karst (annual precipitation >4000 mm) to the arid conditions in central Anatolia (annual precipitation <300 mm) both hosting extended karstic terrains. Accurately dated and robust terrestrial hydroclimate records, such as those provided by speleothems offer an excellent way to reconstruct the changes in hydroclimate on decadal to orbital time scales. Moreover, a long-term perspective of (hydro)climate variability for the Eastern Europe & Turkey SISAL region provides an important context for evaluating potential shifts in large-scale atmospheric moisture-flux conditions, since this
is the only region of the continent where the contribution of Mediterranean sourced moisture year-round exceeds ~20% [36].

The present paper describes and evaluates the spatiotemporal coverage of the speleothem derived stable isotope records for the last 160,000 yrs as available in the SISAL_v1 database [37]. The paper highlights the areas and periods lacking data and how these might be mitigated taking additional identified records into consideration for the Eastern Europe and Turkey region. The number of overlapping records is low in general, except for 1-6 ka (5<n<8), when the spatial distribution and the temporal coverage provided the opportunity to explore the spatial pattern of stable oxygen isotope composition of speleothem calcite ($\delta^{18}O_{w}$). In addition, the negative extremes of $\delta^{18}O_{w}$ are compared to the cumulated probability of the ages of coarsely crystalline cryogenic cave carbonates (approx. 10-45 ka) to gain excess knowledge about the paleoenvironment, because the two types of secondary cave carbonates have totally different origins.

2. Study Region and Climate

Karst areas occupy ~50% of the Eastern Europe & Turkey SISAL region (3.03×10⁶ km²). These karst areas can be categorized into three types based on relief and climate characteristics [38]:

- High range mountains, including the Dinarides and Hellenides, the high elevation areas of the Carpathians, and the northern and southern mountains of Anatolia (Taurides, Pontides),
- Mediterranean medium range mountains, in some parts of southern Dalmatia and surrounding the Aegean Sea and extending to central Anatolia,
- Humid hills and plains. This is the dominant karstic landscape of the Carpathians, NW part of the Dinarides, N and W part of Black Sea coast areas and all the karst NW from the Carpathians up to the Baltic Coast.

The southern regions, from the Dalmatian Coast through the Peloponnesus and large part of Anatolia are dominated by Mediterranean climate characterized by dry, hot summers (minimum precipitation < 40mm, mean temperature of the warmest month (Tmax) ≥ 22°C) and warm (Tmax<22°C and at least 4 monthly avg. temperature (T) ≥ +10°C) summers ([35]). Most of the region is characterized by wet continental or boreal climate (Figure S1). Continentality increases eastwards. Warm temperate/continental climate (monthly mean temperature of the coldest month (Tmin) is between -3 and 18°C) with warm summers and no dry season prevails over the elevated terrains of the Balkan Peninsula stretching northward to the Baltic Coast. In the meanwhile, areas with warm temperate hot summers occur in the Central Balkan region and the south-eastern part of the Eastern European Plains.

Boreal climate with warm summers without a dry season prevails over large part of the mountainous area (Carpathians, Dinarides, and Trachian Massive) and the northeastern parts of the Eastern European Plains up to the Gulf of Finland. The appearance of its counterpart with cool summers and cold winters (Tmax< +22°C, the 4 monthly avg. T < +10°C and Tmin > -38°C) is restricted to the highest regions of the Carpathian Range (Figure S1).

From a seasonal perspective, warm season cyclones reach the Baltic countries originating from the Mediterranean- and Black seas, as well as from the North Atlantic. Cold season cyclones, however, originate almost exclusively from the North Atlantic [39]. Mediterranean moisture is the dominant source for precipitation in the Balkan Peninsula [40,41]. The Black Sea acts as an important moisture source for the surrounding coastal region and for Northern Turkey [34,42].

The highly elevated mountainous areas show the largest recharge volumes (700-800 mm a⁻¹), however in percentage recharge rate is higher in the Mediterranean regions (from ~20% to ~65%) than in the high range mountains (from ~5% to ~65%). The recharge rate of the humid hills and plains varies between ~5% and ~60% with a mean of ~30%, being lower than in the Mediterranean medium range mountains and high range mountains [38]. Overall, it can be said that in the Eastern Europe & Turkey SISAL region, the maximum recharge can be observed in the Dinaric karst and Western Anatolia, while the Eastern Balkan and central-east Anatolia has the driest karstic areas [38].
3. “Eastern Europe & Turkey” Records in SISAL_v1

3.1 Distribution of speleothem isotopic records in space and time

The Dinaric Karst is underrepresented in the SISALv1 database (Figure 1; Table 1), despite its richness in caves and cave sediments. There is a 54-yr-long modern speleothem from Postojna Cave [24] and a ca. 1700-yr long stalagmite from the Modrič Cave [43] from the Dinaric region. There are three records in the SISALv1 from two caves located in the Peloponnesus (Mavry Trypa Cave [44]; Kapsia Cave [13]) and another one from the Aegean Thasos Island (Skala Marion Cave [45]).

Additional records are from the northern (Sofular Cave [34] and southern margins of Anatolia (Dim Cave [46]). The Carpathian karst regions is relatively better represented with records from Ceremonija- [30], Ascunsă- [47], and Ursilor caves [31] and two records from Baradla Cave [18].

There are three entities from the relatively small karstic area in the Southern Transdanubia, the Mecsek Hills, two from the Abaliget- [48] and one from the Trió Cave [11,14].

![Figure 1](image.png)

**Figure 1.** Map indicating the location of speleothem records included in the SISAL v1 and others not yet in the database from Eastern Europe & Turkey showing the karst aquifers (data provided by The World Karst Aquifer Mapping Project [49]).

The relative data scarcity in the mid-Balkans (Figure 1) could be reduced since studies have been recently published from Macedonia [50], Croatia [51] and Bosnia [52] (Table 1). Recently published records from Demânovska Valley [53]; Closani Cave [10]; Tausoare and Ascunca caves [54] are also expected to expand the data coverage for the Carpathian region.

There are karst regions in the northern part of the studied area (Figure 1), but only a few speleothem stable isotope records have been identified e.g. [23,55]. One explanation for this is that the permafrost conditions which existed around [56] and beneath the former Fennoscandian Ice Sheet which covered this area [57] very likely prevented speleothem formation (see also [23]).
because there was no water movement in the frozen ground. This hypothesis is indirectly supported by a recent study showing flowstone deposition in the Kraków-Częstochowa Upland at 975-470 ka [58], predating the major glaciations of the region. The thawing of this frozen ground could be a prolonged process after deglaciation [57,59], maintaining unfavorable conditions for speleothem formation. Moreover, the flat terrain means that the current karstwater table is near to the surface, which does not favor subaerial speleothem formation in the sub-terrain cavities.

Additional identified records (Table 1) e.g. from the Romanian Carpathians [32,33] the Low Tatras [60] or the Pontides [20,61,62] may help in increasing the spatiotemporal coverage of the region. These records were not included to the SISAL database yet, either due to difficulties in obtaining data developed and published decade(s) ago or because they did not meet SISAL quality criteria [37]. For example, although a single radiometric age broadly constrains the beginning of speleothem formation from Slowianska Drwali Cave (southern Poland) to 12±6 ka [55], it is insufficient to achieve an age-distance model to assign ages to the small set of randomly collected isotope measurements made on the speleothem, rendering this record unsuitable for the SISAL database (Table 1).

Table 1. Metadata of the speleothem records of the Eastern Europe & Turkey SISAL region, included in the SISAL v1 database [37] and records identified but not yet included. Column headings in italics represent field names that can be queried in the SISAL database. Min/Max year the date corresponding to the ultimate/first stable isotope data of the entity respectively. Entities without an entity_id are not in SISAL_v1.

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<th>longitude (E)</th>
<th>elevation m amsl</th>
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</tbody>
</table>

*minimum and maximum date of the stable isotope record were rounded to integer

From a temporal perspective, the oldest record in the region is the ABA_2 entity from the Abaliget Cave (Figure 2; Table 1). The period from ~108.8 to ~160.6 ka is represented by only four
records with two overlapping segments. The first overlap can be seen between the Abaliget records from ~140.2 ka to 143.5 ka and the second one between Baradla records and ABA_1 from ~123.3 ka to 129 ka. This is followed by a cca. 20-kyr-long hiatus up to ~89.7ka (Figure 2). This period is only scarcely represented in certain part of the region [67], although radiometric ages from a couple of speleothems have been reported from this period from the Carpathian karstic regions (e.g. [68,69]). Moreover, a recent compilation of radiometric ages from more than 90 speleothems and flowstones from the Croatian karst show an even temporal distribution back to the onset of MIS5 [7], suggesting there is a good opportunity to develop speleothem stable isotope records for this period.

From ~90 ka onwards, there is continuous coverage for both δ¹⁸O and δ¹³C for the records from Eastern Europe & Turkey, although most of the period is characterized by low replication of records. The Dim-E3 record stretches from 89.7 ka to 12.6 ka overlapping with the So-1 record from 50.3 ka (Table 1). These two speleothems are the only records from the region until 10.5ka when the Leany record starts (Figure 3).

The Holocene is the best represented period in the region (Figure 2, 3, 4). The period from ~1.42 ka to ~2.05 ka with its 7 records is the most represented in the region: PU-2, GK-09-02, MAR_L, POM2, CC-1, So-1 and S1. Before this date, a coinciding hiatus characterizes the time series of the Ursilor- and Skala Marion Cave entities; from ~2.2 ka to ~3 ka, which may suggest a sub-regional pattern with conditions unfavorable for speleothem formation.

There is a good chance to further extend the regional dataset beyond the MIS6, since entities predating the current dataset have already been identified from Turkish [62], Macedonian [50], Croatian [70] and Hungarian [71] localities. Moreover, calcareous cave deposits exceeding the current limit of applicability of U-Th dating method can be found in the region [58].
Figure 2. Temporal span of individual speleothem records in the Eastern Europe & Turkey SISAL region for (a) $\delta^{18}$O and (b) $\delta^{13}$C for the last 160 ka

The average length of the records is ~13.8ka and the median is 4.9ka, including hiatuses. The shortest growth period was 54yrs (POS-STM-4), the longest spanned ~77.1ka (Dim-E3). The temporal resolution of the SISAL archived speleothem stable isotope records of the Eastern Europe & Turkey region ranges from sub-decadal (So-1, [34], S1 [44]; Trió, [11] to >1000yr (Dim-E3, [46]). The characteristic temporal resolution of the available speleothem stable isotope records can be estimated to 12 yr for the Holocene, while it is usually >50 yr for the pre-Holocene period (Figure 3). The studies following the pioneering record of PU-2 [31], achieved characteristically finer temporal resolution (Figure 3).
3.2 Environmental controls on stable isotope composition of speleothem carbonate

Out of the 14 cave systems studied in the Eastern Europe & Turkey SISAL region (8.6% of the total number in the SISAL_v1 database [37]), 7 have been monitored.

Monitoring of key variables (e.g. cave temperature, ventilation) regulating dripwater hydrology and saturation conditions in caves provides a basis for the process-based understanding of environmental controls on stable isotope composition of speleothem carbonate and speleothem growth conditions at specific cave-settings (e.g. [72,73]). A weakness of the early period of speleothem-based paleoscience in the region is the previously presented relatively modest level of monitoring. Consequently, in the lack of site-specific information (site specific infiltration processes, calcite precipitation), most of the paleoclimatic inferences of these studies relied on general notions. However, recently this knowledge-gap began to be filled by speleological monitoring studies becoming abundant in the region [10,74-80]. This predicts that much more experimental experience is being made available to help the interpretation of the speleothem recorded geochemical signatures over the region in the forthcoming studies.

Thorough monitoring enabled a recent study to compare modeled and measured dripwater δ¹⁸O in Postojna Cave [81]. Monthly measured precipitation (amount and δ¹⁸O) and ratio of evapotranspiration were the input parameters, while the mixing and delay process taking place during infiltration were statistically simulated in the model. There was excellent agreement between the measured δ¹⁸O_{spe} and the modeled ones calculated using the modeled dripwater δ¹⁸O between 1984 and 2002. Such studies are to become more-and-more abundant as cave monitoring advances, thus providing an improved process-based understanding for the interpretation of speleothem archived isotope geochemical signatures.

3.2.1 Environmental controls on speleothem δ¹⁸O

Paleoclimatic interpretation of speleothem δ¹⁸O variations requires knowledge and quantitative estimation of processes that may affect the isotopic composition of water during the course of the
hydrologic cycle and during calcite deposition. For a general introduction to environmental controls on speleothem δ¹⁸O the reader is referred to (LEAD PAPER to be cited).

The stable isotope composition of precipitation correlates positively with temperature in the Eastern Europe & Turkey SISAL region [82-84] as generally seen in the extratropics [85].

A progressively stronger correlation between the water stable isotope content of monthly precipitation and local surface air temperature was registered moving inland across Europe [86]. A related pattern is seen dividing the warm Mediterranean coastal sites and the continental ones regarding the modern day δ¹⁸O/T slope (so-called “temperature effect”) (Figure 5). The temperature effect ranges from ~0.15‰ per °C for coastal sites (e.g. Figure 4, [87]) to ~0.35‰ per °C for most continental locations (e.g. Figure 5, [84]).

In the coastal regions the modern day δ¹⁸O/T slope is below the water-calcite isotopic equilibrium fractionation factor (~0.24‰ °C⁻¹ [88]), while in the more continental locations it is above it (Figure).

This is an important split; it explains a major part why the oxygen isotope composition of more continental formations is thought to reflect mainly temperature variation and changes in moisture transport trajectories transferred via source water δ¹⁸O fluctuation, while δ¹⁸O_spel strongly reflects fluctuations of precipitation amount in the southern part of the region. The correspondence, for instance, between the interannual variability of total amount of late autumn–winter precipitation (October to January) and δ¹⁸O_spel from Akcacale Cave (not yet in the database Table 1) is sufficiently strong to permit to achieve the first quantitative reconstruction of October to January precipitation [61,89].

![Figure 4](image_url)

*Figure 4. Map of the Eastern Europe & Turkey SISAL region, with the modern day δ¹⁸O/T slopes indicated by circles shaded in greyscale proportionate to the slope (min 0.16‰/°C: white; max 0.36‰/°C: black). The numbers in brackets next to the circles indicate the references for the corresponding studies; Slovenia: [82,90], Serbia: [91], Hungary: [79,83], Slovakia: [84], Romania: [77], Crimea: [92], Turkey: [93].*
3.2.2 Environmental controls on speleothem δ¹³C

For a general introduction to environmental controls on speleothem δ¹⁸O the reader is referred to (LEAD PAPER to be cited). Variations of δ¹³C primarily interpreted by changes in paleohydrology, such as soil biological activity (Abaliget Cave [48], Ascunsă Cave [47], Baradla Cave [63]; Trio Cave [11], Skala Marion Cave [45], Mavri Trypa Cave [44], Kapsia Cave [13] related to humidity changes or simplified to corresponding low/high δ¹³C values with dry/wet periods (Ursilor Cave [31], Modrič Cave [43]. For instance, P contents of the Trio speleothem supported that the δ¹³C values reflect humidity-related changes in soil biological activity [11].

In Anatolian karst representing warm semi-arid environments, the secular changes in δ¹³C may track changes in the dominance of C3 vs C4 in the vegetation type (Dim Cave [46], Sotular Cave [34]).

The relatively enriched (δ¹³C > -5‰) carbon isotope compositions identified in Dim Cave and Leány caves (Figure 2) supposedly occurred due to changes in ventilation effect [21,46]. This degassing related kinetic fractionation cause an increase of the δ¹³C value partly overprinting the paleohydrological signals, although, minima in speleothem δ¹³C curves can be regarded as largely unaffected by such kinetic processes [48].

4. Regional patterns in oxygen and carbon isotope records through time

Conventionally stalagmite formation in isotopic equilibrium is assessed on the base of weak or no correlation between speleothem δ¹³C and δ¹⁸O values measured along the growth axis as well as along the same growth lamina (Hendy, 1971). The lack of significant correlation between the C and O isotope compositions suggests quasi-equilibrium, carbonate precipitation can be assumed with a minor kinetic effect in the case of the ABA_1 (p=0.044), PU-2 (p=0.251) Dim-E4 (p=0.089) entities (Figure S2, Table S1).

The highest positive slope (2.64) with a significant correlation (adj. R²=0.45; p<6.5E-15) between δ¹³C and δ¹⁸O was observed in the CC-1 record. However, this is because the samples were gathered along a radial transect [30], rather than along the growth axis of the entity so that the kinetic effect is exaggerated as sampling points getting closer to the edge. The strongest correlation (adj. R²=0.64) although with a less steep slope of 0.35 (p<0.003) is seen in the short dataset of Pos-STM-4 record (Figure S2, Table S1). The kinetic effect was not an issue in the original study, because its primary scope was the detection of the ¹⁴C activity increase due to nuclear tests in the atmosphere and modeling the dynamics of soil carbon pools producing soil CO₂ [24]. However, this has to be considered when querying the database for entries applicable in (paleo)climatological studies. In addition, in the Dim-E2, E3 and S1 records, δ¹³C also had a positive significant (p<1.7E-15) slope (>1.4) with δ¹⁸O. In such cases, major kinetic effect can be expected to have occurred during carbonate precipitation.

A weak correlation between δ¹⁸O and δ¹³C values is not a prerequisite of isotopic equilibrium; however, the replication test (i.e., a high degree of coherence between individual δ¹⁸O and/or δ¹³C profiles from different speleothems from the same cave over the common time period) is a more stringent test of isotopic equilibrium [94].

The SISAL database can provide the basis for regional replication tests. The pronounced enrichment signal expressed in the δ¹³C values prevailing in the older section of the CC-1 record and preceding the growth stops of S1 records is hardly replicated in the coeval records from the region (Figure S3b). This suggests that at least some sections of these records (e.g., S1) carry a strong kinetic effect and should be treated with caution.

4.1. Assessment of spatial patterns in the Holocene

The SISAL_v1 database contains 12 records from the past 11.6 kyr from Eastern Europe and Turkey. In the mid-Holocene, the relatively higher abundance of data (Figure S3a) provided a
glimpse on the spatial tendencies of δ¹⁸O_spe. The average δ¹⁸O_spe was calculated for contemporarily formed deposits from three separate semi-millennial periods from the Holocene. Unlike previous observations [95] latitudinal or continental trends could not be observed probably due to the limited spatial extent of the region (latitudinal extent <10°, longitudinal extent <12°). However, there are negative correlations between δ¹⁸O records from eastern and southeastern Europe and elevation, even though “site elevation” in the database [37] corresponds to the cave entrance rather than the elevation of recharge of dripwater (Figure 5). It can be assumed that the difference in site elevation is likely to properly reflect the difference in infiltration area elevations. Despite this uncertainty regarding the elevation of the actual recharge area, estimated δ¹⁸O_spe elevation gradients calculated for three non-overlapping semi-centennial periods (and excluding records with high risk of kinetic effects) during the past ~5 kyr suggests that this elevation trend is characteristic of the Holocene. Computed elevation gradients were significant (at p<0.1 level) in all but one cases and ranged between -0.25(±0.11) ‰/100m and -0.27(±0.08) ‰/100m.

Isotopic depletion of meteoric precipitation with elevation is expected [96] and has been measure in this region as ranging from -0.24 ‰/100m to -0.39 ‰/100m [73,87,97,98]. Slightly flatter elevation gradients are reported both for isotopic composition of (i) shallow groundwater (-0.24 ‰/100m, [99], interquartile interval: from -0.11 to -0.24 ‰/100m, [100] and (ii) dripwater (-0.11‰/100m, [73]).

Although it might be expected that the speleothem-derived gradient would be closer to that of shallow groundwater and of dripwater; interestingly, it in fact resembles that of precipitation most closely. Testing whether the found δ¹⁸O_spe gradient is prevailing over geological timescales especially under distinct climate settings, such as the LGM can be achieved with an increased entity numbers providing a much improved replication in this specific period. The robustness of this empirical δ¹⁸O_spe gradient can be further explored extending the region of towards nearby SISAL regions, e.g. [101].

![Figure 5. Elevation gradient of δ¹⁸O_spe for three semi-millennial time horizons for the past 5000 yrs for SE Europe](image-url)
4.2 Cryogenic cave carbonates, special calcareous speleothems from the region

Coarsely crystalline cryogenic cave carbonates (CCCcoarse) from Central Europe represent a novel archive to study the extent of permafrost in the past (e.g. [102-105]). CCCcoarse deposits are formed because permafrost thawing allows water to percolate through the epikarst and penetrate into the still-frozen cave system where it slowly freezes, becoming increasingly enriched in ions until the solution is supersaturated and carbonate precipitates [102]. Cryogenic carbonate has a very specific isotope composition [105,106].

CCCcoarse have been described in several caves in Europe [105] including karst areas from the Eastern Europe part of this SISAL region (Poland and Slovakia; [102,104,105,107]). U-Th dating of cryogenic minerals from the Last Glacial period typically suggest that most of the CCCcoarse deposits were formed between ~40 to 21ka BP, indicating the presence of a widespread permafrost zone extending beyond the southernmost limit of the Fennoscandian Ice Sheet [105].

There are seven peaks in the temporal distribution of the sum probability of CCCcoarse occurrences over the past 40 kyrs (Figure 6). Some of these peaks (at ~12, ~16, ~25 and ~36ka) correspond to regional minima of δ¹⁸Opel (So-1 and Dim-E4 records; Figure 6a), though these speleothems are from Anatolia. The CCCcoarse occurrences at ~12 and ~25ka correspond with regional minima of annual mean temperature inferred from branched glycerol dialkyl glycerol tetraethers (brGDGT; Figure 6b) from speleothems in the same region. However, there is no correspondence between interstadial transitions in the NorthGRIP ice core δ¹⁸O record [108] and CCCcoarse occurrences (Figure 6d) nor do the other CCCcoarse occurrences match δ¹⁸Opel or brGDGT-inferred temperature minima. Thus our regional assessment does not appear to confirm the hypothesis that the temporal distribution of CCCcoarse occurrences coincide with transitions from stadial to interstadial conditions [105], which otherwise is thought to be in agreement with the published model of CCCcoarse formation in ice filled cavities within the permafrost [103].

Linking the maxima of CCCcoarse occurrences and the minima of the regional paleotemperature proxies (Fig. 6) is a logical and straightforward interpretation, as viable as their formation explained with the thawing of the permafrost layer above the cavities [103]. The correspondence of CCCcoarse occurrence peak with locally more relevant temperature reconstructions could be scrutinized also in other SISAL regions, where radiometric ages for CCCcoarse occurrences are available.
Figure 6. Time series of (a) $\delta^{18}O$ speleothem records in the Eastern Europe & Turkey SISAL region, (b) annual mean temperature inferred from branched glycerol dialkyl glycerol tetraethers (brGDGT) calibrated with a global training set - MD04-2790 Black Sea core - (redrawn from [109]) and (c) probability distribution plot [110] of U-Th ages of coarsely crystalline cave carbonate from the Eastern Europe [102,105,107] and (d) 50-yr averaged $\delta^{18}O$ of the Greenland Ice Sheet (NorthGRIP ice core) [108] relative to V-SMOW for the last 45,000 yrs. The black vertical dotted lines indicate the coincidence of the probability peaks of the sum density functions, to the speleothem and ice core $\delta^{18}O$ records, and the regional mean annual temperature reconstruction.
5. Conclusions and outlook

There are comparatively few records from Eastern Europe and Turkey in the SISAL database, and most of these records only cover the Holocene. The Sofular Cave So-1 entity is the sole record in SISAL_v1 covering glacial cycles and extending back the Holocene. Thus, there is a strong need to gather such speleothems, since these provide a continuous record of the environmental response induced by a transition from cold glacial to warm interglacial climate regime.

Nevertheless, the diverse karst landscape of Eastern Europe & Turkey offer a great potential for reconstructing past environmental changes based on isotope records from speleothems. There is potential to expand the database by including recently published material, and exploration and exploitation of regions such as the Dinaric Karst [7] will yield more data in the near future.

The SISAL database can provide a solid basis for regional replication tests pointing out regionally incoherent variations from individual δ18O and/or δ13C profiles.

The regional subset, does not appear to confirm the existence of longitudinal trends in δ18Ospec across Eastern Europe during the Holocene. This likely reflects the relatively short distances involved. The existence of the SISAL database provides an opportunity to go beyond regional data syntheses to examine spatial patterns at a much larger scale [101]. Spatial scale is not an issue for the examination of elevation gradients, and here the data from Eastern Europe provide clear-cut evidence for elevational gradients in δ18Ospec during the Holocene (~0.26‰ 100m⁻¹). Comparative studies from other regions could provide insights into the stability of these gradients through time.

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