Stable carbon isotopes in speleothems from temperate areas

Carl Österlin

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Författaren är ensam ansvarig för uppsatsens innehåll.

Stockholm, den 29 juni 2010

Clas Hättestrand
Studierektor
Abstract
Speleothems are considered a reliable proxy for paleoclimatic reconstructions and analysis of stable carbon isotopes in speleothems is used for paleoclimatic reconstructions. However, in temperate areas that lacks C4 vegetation there are uncertainties in how to interpret changes in the δ¹³C signal. The aim of this study is to increase the understanding of how the δ¹³C signal in speleothems from temperate areas can be interpreted. The study was divided in two parts, first a literature study that focused on interpretations of the δ¹³C signal in speleothems from temperate areas and a case study in which a comparison of seven δ¹³C records from similar environments in the Scandes Mountains and the Alps are made. The results from the literature study were used in the case study to draw conclusions on tree line and vegetation changes during Holocene in central northern Scandinavia. The study showed that trends in interpretation of the δ¹³C signal in speleothems from temperate areas are that low δ¹³C values are interpreted as wetter, warmer conditions with higher bio productivity, and high δ¹³C values are interpreted as colder, drier conditions with lower bio productivity. Further it was found in the study that vegetation changes seen in Holocene pollen data are also seen in δ¹³C records from Scandinavia. The δ¹³C signal in temperate speleothems therefore appears to be related to changes in vegetation density and to tree-line changes.
STABLE CARBON ISOTOPES IN SPELEOTHEMS FROM TEMPERATE AREAS
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1. Introduction

Calcium carbonate speleothems are formed in limestone caves by drip water originating from precipitation. They are a valuable natural archive for paleoclimatic research since they can contain information on how the climate has varied throughout history. A number of different methods are being used to track climate signals, one of these is analysis of stable isotopes of oxygen and carbon. Stable oxygen isotopes ($\delta^{18}O$) are more commonly used than stable carbon isotopes ($\delta^{13}C$), since the former are generally easier to interpret. The reason for this is that stable carbon isotopes are influenced and dependent by far more processes than the stable oxygen isotopes (Lauritzen & Lundberg 1999). CO$_2$ from the soil layer and dissolved carbon derived from bedrock contributes to establish a $\delta^{13}C$ signal in the speleothem (Genty et al. 2003, McDermott et al. 2006). The variations in $\delta^{13}C$ are then governed by several different processes, such as; vegetation density (Baldini et al. 2005) percolation pathway, drip rate (Linge et al. 2001), amount of meteoric precipitation, residence time for water in the soil layer, degassing, kinetic fractionation (Baker et al. 1997).

In areas with vegetation using both C3 and C4 photosynthetic pathway the $\delta^{13}C$ signal is easier to interpret and have been related to changes between these two types of vegetation. However in temperate areas lacking C4 vegetation the interpretation is more difficult (McDermott et al. 2006) and there is no clear consensus of how $\delta^{13}C$ should be interpreted due to the complex variations influencing the $\delta^{13}C$ signal (Lauritzen & Lundberg 1999). That is why this thesis will focus on interpretations of $\delta^{13}C$ in speleothems from temperate areas.

Paleoclimatic reconstructions are today made from several archives such as tree-rings, ice cores, ocean and lake sediments. Speleothems provide an addition to the terrestrial archives, which gives us the possibility to reconstruct terrestrial climate in areas where other archives are not available. Better knowledge on how to interpret the $\delta^{13}C$ signal in speleothems from temperate areas may help improving paleoclimatic reconstructions that is a crucial part in developing more accurate climate models.

1.1 Aim and main questions concerning the study

The aim is to increase the understanding of how the $\delta^{13}C$ signal in speleothems from temperate areas can be interpreted. The thesis consists of two parts; the first part is a literature study aiming to analyze how the $\delta^{13}C$ signal in speleothems from temperate areas has been interpreted. The second part is a case study exploring if it is possible to relate the $\delta^{13}C$ signal in speleothems from northern Scandinavia, to changes in vegetation from the same area during Holocene (~last 10 000 years).

Questions that I aim to answer in this thesis;
- Are there any general trends in how the $\delta^{13}C$ signal in speleothems from temperate areas has been interpreted?
- Can the $\delta^{13}C$ signal in speleothem from northern Scandinavia be related to changes in vegetation density and/or tree-line?
1.2 Background

Speleothems are depositional cave features such as stalactites, stalagmites and flowstones that form primarily in limestone, dolomite and marble caves and are made up of calcium carbonate (CaCO₃). Speleothems form by carbonate saturated groundwater dripping in the cave and deposits its contents. This can give the speleothem a layered character (McKnight & Hess 2002; Ruddiman 2008).

In paleoclimatic research only the speleothem features stalagmites and flowstones are used. Hence, only these features are included in the use of the term speleothem in this thesis.

For using speleothem as a paleoclimatic proxy there are today a number of methods (e.g. Fleitmann et al. 2008 and reference therein). Growth intervals, based on uranium datings or lamina counting, give indications of when the climate has been drier/wetter or warmer/cooler. Annual band thickness of the speleothem can be used to interpret the mean annual temperature and rainfall. Trace elements (as Mg, P, U, Sr, Ba and Na) can also be interpreted to reflect growth rates, meteoric precipitation and/or vegetation. Stable oxygen isotope analysis yields interpretations of precipitation and temperature throughout the past. Stable carbon isotopes are used for interpretations of vegetation density or vegetation changes (Fleitmann et al. 2008).

Stable carbon isotopes found in speleothem are derived from plants by photosynthetic release of CO₂ to the soil and also through the decay of dead plants in the soil, as well as from dissolved carbonate bedrock in the cave drip water (Kacanski et al. 2001). Depending if the plants use C₃ or C₄ (found in arid environments) photosynthetic pathway their signatures in stable carbon isotope record will appear different (Kacanski et al. 2001). According to Ruddiman (2008) all trees use C₃ photosynthetic pathways and also cool climate shrubs and grasses. Plants using the photosynthetic C₄ pathway that has a distinctively different δ¹³C signature are shrubs and grasses that grow in areas with hot summer climates.
Besides the biological activity there are a number of other factors and processes affecting the δ^{13}C signal of speleothems. Four factors are pointed out as being the most important ones namely; the isotopic composition of atmospheric CO₂, inorganic carbon derived from the bedrock, production of CO₂ from plants and by processes in the soil, and degassing of CO₂ during precipitation of calcite (Williams et al. 2004). Higher biological activity in the soil layer leads to an increase in the proportion of light biogenic CO₂ in comparison to the amount of heavier carbon from the bed rock (Baldini et al. 2005).

In areas where it is and has been both C3 and C4 vegetation, and with a proportion of those which may be determined independently by pollen data, interpretations of signals from carbon isotopes are relatively easy to do. But in temperate areas with no C4 vegetation this is difficult and interpretations have been done from case to case (McDermott et al. 2006). According to McDermott et al. (2006) it is sometimes possible in environments without C4 vegetation to relate the δ^{13}C signal directly to the paleoclimate, but interpretations are tentative.

Vegetation density and microbial activity in soil above caves are known to be recorded in speleothems and the δ^{13}C signal in European speleothems are suggested to be directly linked to climate. Lower δ^{13}C is thought to be a consequence of higher vegetation density and also a more dense microbial activity, driven by an improved climate (warmer/more humid). A cold and dry climate hampers the microbial activity in the soil and thereby reduces vegetation density (Wainer et al. 2009). The δ^{13}C signal is therefore by Wainer et al. (2009) considered to be a valid proxy indicating either warm and wet, or cold and dry conditions in a cave located in southern France. The δ^{13}C signal has been used to interpret paleoclimate. It has been suggested that high δ^{13}C values is a reflection of cooler conditions and that low δ^{13}C a reflection of warmer conditions (Linge et al. 2001), thus, yielding more vegetation that governs the δ^{13}C signal. But also very local conditions as percolation path and drip rate affects the δ^{13}C signal too (Linge et al. 2001).

Baldini et al. (2005) states, in a study of speleothem from a temperate area with only C3 vegetation (British Isles), that they have the first empirical evidence for that vegetation density actually can govern the δ^{13}C signal. The recentness of this statement marks the lack of understanding and importance of further research to be conducted in the field of δ^{13}C interpretations in speleothem from temperate and subarctic areas.

Other explanations have also been done to the variations in δ^{13}C values. Elevated δ^{13}C in speleothem from British Isles have been interpreted to be a reflection of the residence time for water in the soil layer. If the residence time in the soil layer is too short equilibrium between the water and the soil CO₂ will not be reached, thus elevating δ^{13}C values (Baker et al. 1997).

2. Methods

This study consists of two parts. In the first part, the literature study, interpretations of δ^{13}C signals in speleothems from relevant literature have been analyzed. This was done to answer the first question of the thesis; Are there any general trends in how the δ^{13}C signal in speleothem from temperate areas has been interpreted? The results are summarized in a table since this is effective and understandable. Most important for
this type of analysis is how the literature was chosen, which is described below in 2.1. Also maps were constructed to see if there are any spatial patterns or trends in the interpretations of the $\delta^{13}$C signal.

For the second part, the case study, relevant $\delta^{13}$C records were digitized using the software *Plot digitizer 2.4.1*. The records were then plotted in diagrams for an overview and to be able to compare Holocene $\delta^{13}$C records to see if there are similarities in the records. The diagrams were compared also with pollen data from Scandinavia.

**2.1 Constraining the study**
The number of articles analyzed in the literature study has been limited by the following constraining factors:

- Only peer-reviewed articles have been used.
- Only $\delta^{13}$C interpretations from temperate areas have been used since this is where environments with only C3 vegetation are found.
- Third, no articles with a publication date older than 1990 was chosen to keep the study focused on contemporary research, and also because very little research on paleoclimatic reconstruction from interpretations of $\delta^{13}$C signals were conducted before this date.
- Articles describing speleothems deposited in equilibrium according to the “Hendy test” (Hendy 1971) were chosen. Speleothems that are not deposited in equilibrium face a larger number of processes, as kinetic fractionation and evaporation of the stable carbon isotopes, which affects and complicates the interpretations of the $\delta^{13}$C signal. Thus making comparisons with other speleothems deposited in equilibrium inappropriate as these conditions overshadow local conditions seen in the $\delta^{13}$C signal.

I am of the opinion that most of the literature concerning speleothem that falls under these constraining factors has been covered in this study. However, there is always the possibility that some literature within this definition has fallen out and therefore is not covered in this study. But even so, this should not affect the result of the literature study to point in any misleading direction since the aim is to see if there are any general trends in the interpretations of stable carbon from the defined area.

In order to make a general selection of what literature to study regarding $\delta^{13}$C interpretations, only speleothem from study areas located in environments that fall under subtropical-warm temperate and mid latitude cool temperate climatic zones of the five basic climatic zones were considered (McKnight & Hess 2002). These climate zones generally occurs from 40°N and pole ward in the northern hemisphere, and 40°S and pole ward in the southern hemisphere. For more detailed selection articles within these zones that stated a presence of C4 vegetation was not considered.
3. Results

5.1 Literature study

The results of how $\delta^{13}$C have been interpreted are presented in Table 1, which is a compilation of $\delta^{13}$C records from the speleothems that fell within the limits of the constraining factor presented in 2.1. Table 1 is based on a total of 28 speleothems, 21 of these are from sites located in Europe (figure 4), two in Australia (figure 5) and five in New Zealand (figure 5). Four of the five $\delta^{13}$C records (ENI, WSI, Waitomo, Paturau/Punakaiki from New Zealand) are composite records consisting of $\delta^{13}$C values from several speleothem samples. In table 2 the general trends of the interpretations from speleothems presented in Table 1 are concluded.
### Table 1: Speleothem from temperate areas with δ13C interpretations

<table>
<thead>
<tr>
<th>Speleothem Name</th>
<th>High/tempered/heavy values interpreted to reflect</th>
<th>Low/tempered/light values interpreted to reflect</th>
<th>δ13C range (‰)</th>
<th>I (°C)</th>
<th>Growth interval (kyr BP)</th>
<th>Elev. (m)</th>
<th>Present vegetation</th>
<th>Location</th>
<th>Frontier</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sg95</td>
<td>Cooler conditions</td>
<td>Warmer conditions</td>
<td>-2.6 to -4.6</td>
<td>2.8</td>
<td>4.2 - 0</td>
<td>280</td>
<td>-</td>
<td>Norway</td>
<td>-</td>
<td>Linge et al. 2001</td>
</tr>
<tr>
<td>LP6</td>
<td>Warmer conditions, high biogentic activity.</td>
<td>-3.2 to -8.5</td>
<td>-</td>
<td>424 - 392</td>
<td>400</td>
<td></td>
<td>-</td>
<td>Norway</td>
<td>-</td>
<td>Lauterz and Lundberg 2007</td>
</tr>
<tr>
<td>Okiek2</td>
<td>Cold and wet</td>
<td>Balanced humidity</td>
<td>+4.5 to -6.5</td>
<td>3.2</td>
<td>10 - 0</td>
<td>165</td>
<td>Birch / Spruce forest, Heather and peat moss</td>
<td>Norway</td>
<td>Below</td>
<td>Linge 2009</td>
</tr>
<tr>
<td>L-03</td>
<td>Cool, wet, (mild). Reduction in soil activity or shortening of duration of soil activity. Linked to decreased surface temp and increased humidity</td>
<td>Mild, dry</td>
<td>-1 to -5</td>
<td>1.4(outside)</td>
<td>4 - 0.2</td>
<td>400</td>
<td>Alpine vegetation</td>
<td>Norway</td>
<td>Below</td>
<td>Linge et al. 2009</td>
</tr>
<tr>
<td>FM3</td>
<td>Cold / Wet</td>
<td>High biogentic activity</td>
<td>+0.13 to -7.56</td>
<td>3.1</td>
<td>8.5 - 0</td>
<td>160</td>
<td>-</td>
<td>Norway</td>
<td>-</td>
<td>Linge et al. 2009</td>
</tr>
<tr>
<td>L4</td>
<td>High soil production of CO2, due to increased veg.</td>
<td>-5.5 to -9.4</td>
<td>-0.5</td>
<td>9.6 - 7.4</td>
<td>730</td>
<td></td>
<td>Herbs and grasses</td>
<td>Sweden</td>
<td>Above</td>
<td>Sundquist et al. 2007</td>
</tr>
<tr>
<td>K1</td>
<td>Less biomass due to drier conditions</td>
<td>-6 to -10.8</td>
<td>2.4</td>
<td>8.9 - 5.9</td>
<td>540 - 600</td>
<td></td>
<td>Herbs, grasses, spruce, birch</td>
<td>Sweden</td>
<td>Below</td>
<td>Sundquist et al. 2007</td>
</tr>
<tr>
<td>K11</td>
<td>Reduction in meteoric precipitation. Possibly temp. decrease</td>
<td>-5.5 to -10.4</td>
<td>2.4</td>
<td>4 - 0</td>
<td>540 - 600</td>
<td></td>
<td>Herbs, grasses, spruce, birch</td>
<td>Sweden</td>
<td>Below</td>
<td>Sundquist et al. 2010</td>
</tr>
<tr>
<td>CC3</td>
<td>Dry conditions</td>
<td>-3.2 to -11.2</td>
<td>10.4</td>
<td>12 - 0</td>
<td>60</td>
<td></td>
<td>-</td>
<td>Ireland</td>
<td>Below</td>
<td>McFerron et al. 1999</td>
</tr>
<tr>
<td>BMF</td>
<td>Increased veg. density</td>
<td>+0.6 to -9.3</td>
<td>10 (outside)</td>
<td>1929 - 1998</td>
<td>600</td>
<td></td>
<td>Trees (Ash, Sycamore, Oak), Shrubs</td>
<td>England</td>
<td>Below</td>
<td>Baldini et al. 2005</td>
</tr>
<tr>
<td>BOSS</td>
<td>Increased veg. density</td>
<td>+0.5 to 9.6</td>
<td>10 (outside)</td>
<td>1918 - 1998</td>
<td>600</td>
<td></td>
<td>Trees (Ash, Sycamore, Oak), Shrubs</td>
<td>England</td>
<td>Below</td>
<td>Baldini et al. 2005</td>
</tr>
<tr>
<td>F2</td>
<td>Increased veg. density</td>
<td>+0.5 to -6.8</td>
<td>10 (outside)</td>
<td>1946 - 1998</td>
<td>600</td>
<td></td>
<td>Trees (Ash, Sycamore, Oak), Shrubs</td>
<td>England</td>
<td>Below</td>
<td>Baldini et al. 2005</td>
</tr>
<tr>
<td>JW62</td>
<td>Falling to low values - interpreted as rapid cooling</td>
<td>-7.9 to -10.9</td>
<td>28 - 18.9</td>
<td>-</td>
<td>-</td>
<td></td>
<td>-</td>
<td>Poland</td>
<td>-</td>
<td>Paszur et al. 1995</td>
</tr>
<tr>
<td>PC-2</td>
<td>Dry conditions</td>
<td>-9.1 to -10.8</td>
<td>9.8</td>
<td>8 - 1</td>
<td>482</td>
<td></td>
<td>-</td>
<td>Romania</td>
<td>Below</td>
<td>Otac et al. 2002</td>
</tr>
<tr>
<td>Stal-Ifell-1</td>
<td>Atmospheric and bedrock derived carbon</td>
<td>Formation of soil and veg. cover</td>
<td>+5 to -2</td>
<td>3 - 4</td>
<td>143 - 0</td>
<td>1440</td>
<td>Grass/shrub and scattered trees</td>
<td>Germany</td>
<td>Above</td>
<td>Worth et al. 2004</td>
</tr>
<tr>
<td>WN1</td>
<td>Low soil bio-productivity</td>
<td>-1 to -3</td>
<td>1.8</td>
<td>2019**</td>
<td>2400</td>
<td></td>
<td>No soil or vegetation</td>
<td>Austria</td>
<td>Above</td>
<td>Meyer et al. 2009</td>
</tr>
<tr>
<td>ALL1</td>
<td>Low soil bio-productivity</td>
<td>-1 to -3</td>
<td>1.8</td>
<td>1710**</td>
<td>2489</td>
<td></td>
<td>No soil or vegetation</td>
<td>Austria</td>
<td>Above</td>
<td>Meyer et al. 2009</td>
</tr>
<tr>
<td>V99</td>
<td>Higher proportion of biogenic CO2</td>
<td>-5 to -11</td>
<td>11</td>
<td>83.1 - 31.8</td>
<td>-</td>
<td></td>
<td>-</td>
<td>France</td>
<td>Below</td>
<td>Genty et al. 2003</td>
</tr>
<tr>
<td>VH14</td>
<td>Dry, cool, sparser veg. cover</td>
<td>Warm, wet, higher veg. density</td>
<td>-3.74 to -10.23</td>
<td>12.4(approx. veg.)</td>
<td>11.6 (lower veg.)</td>
<td>1402.0 - 1152.0</td>
<td>Deciduous forest (junepe, oak, hornbeam)</td>
<td>France</td>
<td>Below</td>
<td>Wainer et al. 2009</td>
</tr>
<tr>
<td>BDinf</td>
<td>Dry, cool, low soil productivity</td>
<td>Warm, wet, high soil productivity</td>
<td>-9.41 to -12.6</td>
<td>11-12 (outside)</td>
<td>128.3 - 112.5</td>
<td>110</td>
<td>Deciduous forest (oak, hornbeam)</td>
<td>France</td>
<td>Below</td>
<td>Couchoud et al. 2009</td>
</tr>
<tr>
<td>CC1</td>
<td>Low input of biogenic CO2</td>
<td>Lag in development of post glacial soil above</td>
<td>+3.1 to -2.8</td>
<td>7.5</td>
<td>380 - 43</td>
<td>840</td>
<td>-</td>
<td>Italy</td>
<td>-</td>
<td>Drysdale et al. 2004</td>
</tr>
<tr>
<td>LYN</td>
<td>Likely reduced bio productivity / positive temp. effect on isotopically heavier limestone. Or both</td>
<td>High and stable / increased bio-productivity</td>
<td>-6 to -12</td>
<td>9.5</td>
<td>9.5 - 5.1</td>
<td>300</td>
<td>-</td>
<td>Australia</td>
<td>Below</td>
<td>Xia et al. 2001</td>
</tr>
<tr>
<td>BO</td>
<td>More moisture available during growing season</td>
<td>-5.8 to -9.2</td>
<td>15</td>
<td>13.23</td>
<td>60 - 180</td>
<td>-</td>
<td>-</td>
<td>Australia</td>
<td>-</td>
<td>Goede et al. 1996</td>
</tr>
<tr>
<td>MO3</td>
<td>Warmer, increased veg. productivity</td>
<td>Approx. +2 to -8</td>
<td>-</td>
<td>31 - 0</td>
<td>390</td>
<td></td>
<td>Forrestered</td>
<td>New Zealand</td>
<td>Below</td>
<td>Hellstrom &amp; McCollagh 2000</td>
</tr>
<tr>
<td>ENI*</td>
<td>Dey</td>
<td>Wet</td>
<td>-5 to -9.6</td>
<td>-</td>
<td>4 - 0</td>
<td>-</td>
<td>-</td>
<td>New Zealand</td>
<td>-</td>
<td>Lorry et al. 2008</td>
</tr>
<tr>
<td>WSI*</td>
<td>Dey</td>
<td>Wet</td>
<td>-6.5 to -10.4</td>
<td>-</td>
<td>4 - 0</td>
<td>-</td>
<td>-</td>
<td>New Zealand</td>
<td>-</td>
<td>Lorry et al. 2008</td>
</tr>
<tr>
<td>Waitomo*</td>
<td>Dey</td>
<td>Wet</td>
<td>-7.04 to -10.67</td>
<td>-</td>
<td>12 - 0</td>
<td>-</td>
<td>-</td>
<td>New Zealand</td>
<td>-</td>
<td>Williams et al. 2004</td>
</tr>
<tr>
<td>Paturau/Punakaiki*</td>
<td>Dry</td>
<td>Wet and little effect from increasing atmospheric CO2</td>
<td>3.9 to -9</td>
<td>13.7 - 12.3</td>
<td>23 - 0</td>
<td>+170</td>
<td>Podocarp and hard wood broadleaf species</td>
<td>New Zealand</td>
<td>Below</td>
<td>Williams et al. 2005</td>
</tr>
</tbody>
</table>

* Composite speleothem record. ENI - three speleothems, north island, New Zealand. Waitomo - four speleothems, north island, New Zealand (GG1, GG2, RR-C, MAXX). WSI - four speleothems, south island, New Zealand. Paturau/Punakaiki -five speleothems south island New Zealand (WN4, WN11, CN1, TF1, TF2)

** Only one dating within the speleothems
Table 2. Tendencies in interpretations of $\delta^{13}$C from Table 1.

<table>
<thead>
<tr>
<th>Interpretations of $\delta^{13}$C values</th>
<th>High values</th>
<th>Low values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drier</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>Wetter</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Milder/Warmer</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Colder</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Increased bio productivity / vegetation density</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>Reduced bio productivity / vegetation density</td>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

The majority of the studies interpret high $\delta^{13}$C values as an indication of drier conditions, and low $\delta^{13}$C values as an indication of wetter conditions. It is also evident that low $\delta^{13}$C values have been suggested to reflect some form of increased biological activity. On the contrary, high $\delta^{13}$C is not as uniformly suggested as a decrease of biological activity, but still an apparent trend. It is worth noting that there is no reversed interpretation, none of the studies interpret high $\delta^{13}$C values as an increase in biological activity, and neither is low $\delta^{13}$C interpreted as decreasing biological activity. Interpretations that stand out are from the speleothems stal-hoel-1 and CC1 from the Alps. For these records low $\delta^{13}$C values are being interpreted as a formation of soil cover. The stal-hoel-1 speleothem is from a cave located at 1440 m.a.s.l. in southern Germany. Here, the soil formation is interpreted to occur during the late glacial until Boreal. This translates to a period of approximately 4000 years, from about 14 000 yrs Before Present (BP) to 10 000 yrs BP. For speleothem CC1 from a cave located 840 m.a.s.l. in northern Italy, the soil formation process was interpreted to occur during the period between 310 yrs BP to 340 yrs BP.

Another deviant interpretation is that from speleothem JWl2 from Poland (see table 1) where low $\delta^{13}$C values were suggested to reflect a cooling. This is a contradiction to the other interpretations, but the authors of the study only vaguely suggest this interpretation and no real explanation is being given to exactly what they base this suggestion on. The stal-hoel-1 speleothem is deviant in the interpretation of high $\delta^{13}$C values too, as it is suggested that elevated values are derived from atmospheric and bedrock carbon and not a reflection of climate related changes, which is the common suggestion in other speleothems.
Figure 4. Locations of European speleothems from Table 1

Figure 5. Locations of Australian and New Zealand speleothems from Table 1.
5.2 Case study

*Study area*

SG95 (Söylegrotta), L-03 (Larshullet) FM3 (Okshola), L4 (Labyrintgrotta), K1 and K11 (Korallgrotta) speleothem δ\(^{13}\)C records are located in the Scandes mountains, on both sides of the Swedish/Norwegian border not too far in latitude from the Arctic Circle (±3° latitude). The area is relatively close to the North Atlantic Ocean and the K1 and K11 speleothem from Korallgrotta cave are the ones located furthest away from it, at about 100 km. All caves but Labyrintgrotta are at present located below tree line, and have a subarctic climate. Mean annual temperature for the area, which often is the same as the cave temperature, is relatively similar. Labyrintgrotta is the coldest with -0.5°C (Sundqvist et al. 2007) and Okshola cave warmest with 3.1°C (Linge 2009b). The area is snow covered for a long part of the year, and growing season is therefore also limited. Labyrintgrotta is developed in folded and partly crystalline limestone, with a couple of centimeters thick soil cover and has a vegetation cover consisting of herbs and grass. Korallgrotta is developed in calcite limestone or marble, above the cave the soil layer is approximately 50 cm thick and vegetation consists of spruce, birch, herbs and grasses. Okshola cave is formed in marble with mica schist partings. The bedrock in which Söylegrotta was developed consists of calcite marble among rocks of ferruginous mica schist. Larshullet developed in carbonate consisting stripe karst.
5.3 Results from case study

In figures 8-9 the $\delta^{13}$C records of speleothem SG95 (Linge et al. 2001), FM3 (Linge 1999) K11 (Sundqvist et al. 2010), L4 (Sundqvist et al. 2007), Stal-Hoel-1 (Wurth et al. 2004), K1 (Sundqvist et al. 2007), L-03(Linge et al. 2001) and Oks82 (Linge et al. 2009b) are plotted. Stal-Hoel-1 from Hölloch cave, Bavarian Alps, was plotted together with the Scandinavian speleothem since the environment in which it was deposited resembles the Scandinavian with a low mean annual temperature, and also its location just above tree-line.

Without considering absolute values in timescale or $\delta^{13}$C values, and just considering co-variance, the records show several similarities. The records of FM3, L4, Oks82 and Stal-hoel-1 all have a steep and quick drop towards more depleted $\delta^{13}$C values from the earliest parts of their records. All of these records also experience a period of (relative to the depletion phase) of stable values, followed by a phase of notable enrichment. The period of “stable values” varies though from a maximum of around 3 500 yrs BP (Stal-Hoel-1) to a minimum of around 1 500 yrs BP (L4). Worth noting is that K1 also experiences a phase of stable values followed by a phase of rapid enrichment just like the other records described above. It is interesting to see that both the Oks82 and L4 record experience the depletion phase at the same time period at around 10 000 yrs BP.

SG95, FM3 and Stal-Hoel-1 show some conformity with an enrichment phase starting around 4 000 yrs BP, followed by a depletion phase that reaches its maximum around 3 000 yrs BP. The Stal-Hoel-1 $\delta^{13}$C record covers the entire Holocene, thus it is comparable with all Scandinavian records. Besides the similarities it has with other records with its depletion phase and the co-variance with FM3 and SG95 between 4000 and 300 yrs BP it does not show much more conformity.

L-03, FM3 and SG95 all experiences enriched $\delta^{13}$C values at around 2 500 yrs BP. L-03 and SG95 co-varies with a dip in $\delta^{13}$C values at 1 000 yrs BP, when FM3 experiences elevated values. K11 is its general pattern fairly similar to FM3, but not exactly contemporary.
Figure 8. δ¹³C values over time from seven Scandinavian and one central European speleothem. The abbreviations in the figure are the names of the speleothems as shown in table 1.
Figure 9. δ13C values over time from seven Scandinavian speleothems, here shown in a higher time resolution. The abbreviations in the figure are the names of the speleothems as shown in table 1.
6. Discussion

The results from part one, the literature study, showed that there are clear general tendencies to interpret low $\delta^{13}C$ values in speleothems from temperate areas as increased bio productivity or vegetation density. And vice verse, high $\delta^{13}C$ values as reduced bio productivity or vegetation density. Another finding was the tendencies towards interpreting high values as dry conditions and low values as wet conditions. The tendencies were also to interpret high values as colder conditions and low values as warmer conditions. On the other hand, contradictions to these tendencies was also found. Wurth et al. (2004) interpreted high $\delta^{13}C$ values in the Stal-Hoel-1 speleothem to reflect atmospheric and bedrock derived carbon. However, excluding Wurth et al. (2004) the general trends in interpretation of $\delta^{13}C$ values in the literature study showed that most variations and changes reflected changes in water table, bio productivity and vegetation density. However, changes in either water table or temperature could actually be a reflection of the same thing. In general more moisture and higher temperatures yields a higher vegetation density. This means that interpretations of wetter and warmer conditions could also be seen as an interpretation of higher vegetation density.

The Stal-Hoel-1, FM3, Oks82 and L4 $\delta^{13}C$ records all show similar patterns with rapid depletion, stable values, and rapid enrichment of $\delta^{13}C$. Considering that this pattern in the $\delta^{13}C$ record from Stal-Hoel-1 was interpreted as a formation of a soil cover gives reason to believe that this could be the case for FM3, Oks82 and L4 too. With consideration to the similarity in location of Stal-Hoel-1 and L4 just above tree-line, this gives additional reason to believe that the pattern of the L4 $\delta^{13}C$ also could be a reflection of soil formation. On the other hand this phase with rapid depletion, stable values and rapid enrichment occurred 4000 years earlier for Stal-Hoel-1 than for the Scandinavian speleothems FM3, Oks82 and L4. Adding that Stal-Hoel-1 is located 47°N about 19° south of the Scandinavian speleothems, and with a continental climate as opposed to the oceanic climate at 66°N for the Scandinavian speleothems the comparison should be done cautiously.

An elevation in tree-line is a consequence of more favorable conditions for establishment of vegetation. Thus yielding a higher vegetation density and gives a higher bio productivity, especially for sites previously situated above tree-line that is reached by the elevation.
Figure 10. Holocene pine tree-line fluctuations, Scandes Mountains, central Sweden. Reworked from Dahl et al. 1996

Notable is that the figure 10 shows that the pine tree-line in the Scandes mountains of central Sweden was at its highest during Holocene at 9 000 yrs BP, 225 m higher than today, with a rapid increase from 10 000 yrs BP and staying at high levels until 5000 yrs BP. This increase, peak and later decline of pine tree-line is contemporary with the phases of depletion, stable values and enrichment of $\delta^{13}$C in the Oks82 and L4 records. Except from the depletion phase, it is the same situation for the K1 record. The FM3 record do not experience the depletion, stable values and enrichment phases at the same time as Oks82 and L4, but still has low $\delta^{13}$C values when Holocene pine tree-line is peaking, and an enrichment in $\delta^{13}$C when the pine tree-line is falling. At 4 000 yrs BP the pine tree-line drops 50 meters rapidly, this takes place at the same time...
as the FM3 $\delta^{13}C$ records experiences notable and fairly rapid depletion of $\delta^{13}C$. Also the Oks82, L4 and FM3 have rapid depletion phases of $\delta^{13}C$ when the Holocene pine tree-line ascends rapidly.

L4 experiences the phases of rapid depletion, stable values and the rapid enrichment of $\delta^{13}C$ during the same period as a general elevation of tree-line in Scandinavia (Bjune 2005; Dahl et al. 1996) at around 10 000 - 4 000 yrs BP. The generally accepted view shown in the literature study that high $\delta^{13}C$ values is interpreted to reflect lowered vegetation density, and low $\delta^{13}C$ values reflects increased vegetation density gives reason to believe that the patterns in the $\delta^{13}C$ record from L4 is linked to changes in tree-line.

FM3 and Oks82 are today located below tree-line, and L4 above, but still they have similar patterns correlated with elevation of tree-line. This could thus be interpreted as a reflection of tree-line changes in their $\delta^{13}C$ record, which gives reason to believe that L4 was located below the tree-line between 9 200 and 7 800 yrs BP.

Since L4 should have experienced a higher vegetation density between 9 200 and 7 800 yrs BP when the tree-line also peaked, this could point to that elevations of tree-line gives a higher vegetation density which also could be seen in the $\delta^{13}C$ signal. Today's tree-line is lower than it was during early Holocene, hence FM3 and Oks82 that even today are situated below the tree-line would not reflect the tree-line fluctuations. But, the distinct pattern of rapid depletion, stable values and the rapid enrichment of $\delta^{13}C$ during the same period as the highest tree-line this pattern could indicate a period of higher vegetation density at these sites.

The K1 $\delta^{13}C$ record also show similarities with FM3, Oks82 and L4 except from the rapid depletion phase, which occur before the K1 record starts. Considering that K1 follows the fluctuations of pine and birch in Scandinavia gives further support to interpret the variations in $\delta^{13}C$ from Scandinavian speleothems as reflections of changes in tree-line. Only comparing the pine tree-line fluctuations in the Scandes Mountains in central Sweden from Dahl et al. (1996) with Scandinavian speleothem does not give enough support to interpret the $\delta^{13}C$ signal as a reflection of pine tree-line. But together with the birch and pine tree-line changes provided by Dahl (2005) and adding co-variance of FM3, Oks82, L4 and to some extent K1 with to this gives support that these speleothems reflects tree-line changes and thus vegetation density.
7. Conclusions

- The general trends in interpretation of the $\delta^{13}C$ signal in speleothem from temperate areas are that low $\delta^{13}C$ values are interpreted as wetter and warmer conditions, and high $\delta^{13}C$ values are interpreted as colder and drier conditions. Low $\delta^{13}C$ values are also interpreted to reflect higher bio productivity and an increase in vegetation density. High $\delta^{13}C$ values are interpreted to reflect a reduction in bio productivity and decrease in vegetation density.

- Vegetation changes seen in Holocene pollen data are also seen in $\delta^{13}C$ records from Scandinavia.

- The $\delta^{13}C$ signal can be related to tree-line changes.

- The $\delta^{13}C$ appears to be related to changes in vegetation density.

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Appendix 1.

The $\delta^{13}C$ signal for each speleothem in the case study, plotted individually for a higher resolution.