Abstract
Stable isotope studies of perennial ice from western North American ice caves suggest that three main types can be defined: cold trap, permafrost, and cold zone. Some complex cave systems may comprise two or more types. While 14 caves were sampled from the region, in this study, 9 definitive sites were examined in more detail where they exemplified classic perennial ice features: massive ice, hoar frost, ice stalagmites and so on. Stable isotopes of the ice (δ18O and δ2H) assist in the understanding the origin of the freezing moisture, whether from direct snow (cold trap), moist summer air (permafrost) or from humid air within the cave (cold zone). Furthermore, delineating the complex systematics of cave ice formation is vitally important if it is to be used (or rejected) as a proxy climate record.

Introduction
A number of studies of perennial ice in caves have been undertaken (see e.g. Ford, Williams, 2007; Yonge 2004); but there are relatively few studies employing stable isotopes and these are confined to Europe (Kern et al., 2011; Persoiu & Pazdur, 2011; Racovita & Onac, 2000; Lauritzen, 1996) and North America (Lacelle et al., 2009; Yonge & MacDonald, 1999, Yonge & MacDonald, 2006; Marshall & Brown, 1974). With the current interest in climate change, a wealth of studies exists on polar (e.g. Jouzel & Masson-Delmotte, 2010; Johnsen et al., 2001) and cordilleran (e.g. Thompson & Davis, 2005) ices cores.

While ice cores deal with the direct precipitation of snow and the subsequent modification of the resulting layers by various physical processes, the mechanisms of ice formation in caves, being confined, can be quite different and may require an alternative interpretation (e.g. Lacelle et al., 2009; Yonge & MacDonald, 1999). Here we look at three possible ice cave types (and combinations of these where cave systems are complex).

Methodology
Field Sites
While stable isotope data has been acquired from 14 cave sites, we focus on 3 caves from west of the Divide:

Projects Cave (49° 48’ N, 125° 59’ W; elevation 1050m), Q5 (49° 47’ N, 125° 59’ W; elevation 1200m) on Vancouver Island and Trout Lake Cave, Washington (45° 58’ N, 121° 32’ W; elevation 850m).

Six caves were selected from east of the Divide:

Disaster Point Cave (53° 10’ N, 117° 59’ W; elevation 1080m), Rats Nest Cave (51° 04’ N, 115° 16’ W; elevation 1480m), Canyon Creek Ice Cave (50° 54’ N, 114° 47’ W; elevation 1775m) Ice Chest (49° 37’ N, 114° 39’ W; elevation 2250m) in the Canadian Rockies and in the Prior Mountains, Montana: Big Ice Cave (45° 09’ N, 108° 23’ W; elevation 2300m) and Little Ice Cave (45° 07’ N, 108° 20’ W; elevation 2500m).

Sample Collection
Massive ice (floor and stratified) was drilled out using an ice screw. Where the ice was stratified, visually obvious ice layers were sampled sequentially. The contents were then transferred to 100ml Nalgene bottles and the ice screw carefully dried after each extraction. All other ice and seepage water was collected by breakage, or directly, and again transferred to bottles as above.
Analysis
The samples were analyzed at the Calgary University Stable Isotope Laboratory on a Neir-McKinny type Mass Spectrometer. Gases produced from the water samples were hydrogen (by reduction of the water over heated zinc at 450°C) and oxygen (as CO₂ equilibrated at 25°C). δ¹⁸O and δ²H are expressed in ‰ against the V-SMOW standard as

\[ \delta = \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \times 10^3 \quad (1) \]

R_{\text{sample}} and R_{\text{standard}} are the ratios of ¹⁸O/¹⁶O and ²H/H in the sample and standard respectively. Precision is +/− 0.1‰ on δ¹⁸O and 0.5‰ on δ²H‰.

Results
Isotopic data for the 14 ice caves in this study is presented in Figure 1. Global precipitation world-wide falls on or close to the Global Meteoric Water Line – GMWL (Craig, 1961; Dansgaard, 1964), given as:

\[ \delta²H = 8\delta¹⁸O + 10 \quad (\%) \quad (2) \]

Some minor modifications of this line have been introduced later (Rozanski et al., 1993) but do not affect the arguments presented here. Positions on the line relate to temperature, where the lowest temperature is associated with the lowest δ-values (Figs. 1 and 7). It can be seen that cave ice also falls close to the GMWL line with a fair degree of precision (R² = 0.96; Yonge & MacDonald, 2006) where:

\[ \delta²H = 8.0 (+/- 0.16) \delta¹⁸O + 6.6 (+/- 2.6) \quad (‰) \quad (3) \]

However, with the data sets presented from caves on each side of the Divide, two Regional Meteoric Water Lines (RMWL) emerge (middle of Table 1).

Despite the universality of the GMWL, it has long been recognized that Local Meteoric Water Lines (LMWL) exist yielding lower slopes that cross the GMWL at various temperatures but whose mean plots close to the GMWL. For the caves in this study the LMWL are presented in Table 1. The LMWL’s exhibit slopes around 8 or less. Figure 2 presents the average deuterium excess (d-excess ‰) for each of the 14 caves of Figure 1. This is acquired by forcing the LMWLs to a slope of 8 which yields the d-excess at intercept. Again it can clearly be seen that the caves split into two RMWLs east and west of the Great Divide. Included in the diagram and in Table 1 are results from Rats Nest Cave, which examined

Table 1. Local (LMWL) and Regional (RMWL) Meteoric Water Lines for the ice caves in this study.

<table>
<thead>
<tr>
<th>Ice Cave</th>
<th>LMWL</th>
<th>Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disaster Point</td>
<td>δ²H = 8.3δ¹⁸O - 0.8</td>
<td>R² = 0.96</td>
</tr>
<tr>
<td>Canyon Creek</td>
<td>δ²H = 7.0δ¹⁸O - 14.1</td>
<td>R² = 0.95</td>
</tr>
<tr>
<td>Ice Chest</td>
<td>δ²H = 7.7δ¹⁸O - 1.6</td>
<td>R² = 0.81</td>
</tr>
<tr>
<td>Serendipity</td>
<td>δ²H = 7.6δ¹⁸O - 2.4</td>
<td>R² = 0.96</td>
</tr>
<tr>
<td>Big Ice Cave</td>
<td>δ²H = 7.8δ¹⁸O + 1.9</td>
<td>R² = 0.95</td>
</tr>
<tr>
<td>Little Ice Cave</td>
<td>δ²H = 7.4δ¹⁸O - 5.5</td>
<td>R² = 0.98</td>
</tr>
<tr>
<td>Projects Cave</td>
<td>δ²H = 6.1δ¹⁸O - 12.4</td>
<td>R² = 0.91</td>
</tr>
<tr>
<td>Q5</td>
<td>δ²H = 8.2δ¹⁸O + 14.8</td>
<td>R² = 0.92</td>
</tr>
<tr>
<td>Trout Lake Cave</td>
<td>δ²H = 7.5δ¹⁸O + 8.4</td>
<td>R² = 0.87</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>RMWL (slopes forced to 8)</th>
<th>Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>East of Divide</td>
<td>δ²H = 8.0δ¹⁸O + 4.0</td>
<td>R² = 0.95</td>
</tr>
<tr>
<td>West of Divide</td>
<td>δ²H = 8.0δ¹⁸O + 12.8</td>
<td>R² = 0.90</td>
</tr>
<tr>
<td>Ephemeral Ice</td>
<td>δ²H = 9.1δ¹⁸O + 30.3</td>
<td>R² = 0.65</td>
</tr>
</tbody>
</table>

Figure 1. The δ¹⁸O - δ²H of ice from 14 North American ice caves from East (<250km from coast) and West (>750km from coast) of the Divide (modified from Yonge & MacDonald, 2006). Rats Nest Cave ice is excluded from the regressions – see Cold Zone Caves.
of a drier, more evaporative climate there and a greater tendency to precipitate snow and hoar frost in the caves. An evaporative climate tends yield precipitation which falls along a slope of 4 below the GMWL, and additionally the sublimation of cloud vapour to snow and cave hoar also yields values below the GMWL (Fig. 7). Those caves close to the coast are in high humidity regimes where rain is more dominant and the resulting ice (mainly of cold trap origin) tends to plot on the GMWL (intercept of +12.8‰, which while above +10‰ is within significance - +/- 3.0‰). The LMWLs yield slopes around 8 or less, which supports the argument above of a drier, colder climate on the east side of the Divide leading to lower humidity and greater solid precipitation (e.g. data from Projects Cave mostly plots above the Global Meteoric water line and a forced slope of 8 yield an intercept of +13.0‰).

We now examine the ice cave data in more detail.

**Cold Trap Caves**

Cold traps occur where there is little through movement of air within a pit-like cave. Cold winter air sinks into the cave, generally through a bottleneck, and displaces warmer air within. Snow falling through the entrance aids the cold trap conditions providing an environment for perennial ice. During the summer, buoyant warm air cannot get into the cave other than by eddy currents.
and the cave maintains a temperature lower than the mean annual temperature. A quantitative study of Trout Lake Ice Cave (Martin & Quinn, 1991) lends support to this mechanism with the cave only 850m AMSL and 185km from the coast. Samples we collected at this site gave a range of seepage $\delta^2$H of -82 to -63 (19‰), whereas floor ice was between -77 to -69 (8‰) and average precipitation at -71‰. The mean of seepage -72‰ and floor ice -73‰, where average precipitation -71‰ perhaps shows a slight bias towards the lower $\delta^2$H of snow. The tighter range of floor ice over seepage suggests the integration and thus averaging of seepage along with rain and snow falling into the entrance.

Disaster Point Cave (Fig. 3) at 1080m and 830km from the coast, in a very different environment across the Divide, shows a similar integration of H$_2$O sources but with snow being a more significant component (i.e., the $\delta$ of snow tends to drag the cave ice values down below seepage and average regional water – the latter from an adjacent river).

Despite the environmental differences of these caves, we nevertheless expect stratified ice from each to reflect a muted $\delta$ variation of precipitation falling at the cave – much as is interpreted in glaciers (see introduction for references).

Figure 4 plots data from two Vancouver Island caves, both of which contain substantial (40m+) plugs of stratified ice. A moist coastal regime dominates here with substantial inputs of both rain and snow to the caves. Evidence of ice movement (MacDonald, 1994) suggests that these caves could be described as glacier caves such as Scarisoara Glacier Cave (Racovita and Onac, 2000).

The figure shows that ice samples cluster around mean precipitation (drip water), although Q5 yields a range of $\delta$–values generally higher than those for Projects Cave. However, Q5 has a stream running into the entrance in the summer where the ice samples are found, so is likely more biased towards the heavier summer water. Projects Cave shows lower values, but these cluster around mean precipitation at -92‰. It has no entrance stream and stratified ice occurs almost 20m into the cave – a result of glacial movement perhaps.

Figure 5 shows possible bi-annual (seasonal) variations in the $\delta$–values, which (for Projects Cave) oscillate around the value for mean precipitation. Despite the likely muting of the signal we can associate the higher $\delta$–values with higher temperatures, as with glacier ice and thus with the GMWL.
Therefore, despite the isotopic muting (modification) of the precipitation signal within cold trap cave stratified ice, the above suggests that the ice can be useful as climate proxies as has been well demonstrated at Scarisoara Glacier Cave (Holmlund et al., 2005). Similar muting of the signal is after all found in glaciers by stratigraphic distortion and infiltration by pore water (references in the introduction).

**Permafrost Caves**

Permafrost caves have been discussed by Yonge & MacDonald (1999), where an isotopic model was developed to explain the surprisingly high δ-values and low d-deficiencies when compared to snow or average precipitation (see e.g. Fig. 6). This cave, Ice Chest, is far to the east (49° 37' N, 114° 39' W) and high up (elevation 2250m AMSL).

The hoar ice here has similar δ-values to the massive ice in the cave, but the latter declines somewhat as the entrance is approached, perhaps affected by an increase of the lower δ-value seepage water there derived from snowmelt. The model proposed by Yonge & MacDonald (1999) shows that the low δ-values and d-deficiencies can arise from summer moist air entering the cave and being forced to sublimate at 0°C.

Figure 7 demonstrates that cloud vapour condensing at say, 0 or 10°C, which would normally fall on the GMWL, in fact falls below it if frozen by sublimation in the cave. The vapour-liquid and vapour-solid fractionation factors used are from Jouzel (1984) and δ/temperature derived from a study of mean monthly Calgary Precipitation where:

\[
\delta^{18}O = 0.38T - 19.50\%o \\
\delta^2H = 3.04T - 146.0\%o
\]

When 1,000-year-old stratified ice from another nearby permafrost cave (Serendipity) was studied, Yonge & MacDonald (1999) found variable δ-values that were all above those of mean precipitation at the site (Fig. 11 - next section). Interpretation of swings in the data would suggest variable inputs in the amount and/or temperature of invading moist air, which leads to very different conclusions regarding the paleoclimate compared to those when considering glacier ice (higher δ-values associated with higher temperatures).

Supporting the above argument, Figure 8 illustrates that hoar ice again dominates the higher δ-values of these permafrost caves, suggesting that massive ice is

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Plate 2. Hoar ice in Serendipity Cave, Alberta Canada.
a variable combination of hoar and seepage - the latter includes snowmelt. (Note that for Big Ice Cave, the lower room massive ice has higher δ-values than the upper room, suggesting that the upper room, closer to the surface, is more affected by seepage.)

**Cold Zone Caves**

Cold zones in caves result from evaporative cooling at the cave walls. This condition generally occurs close to the cave entrance where the relative humidity drops from 100‰ deep in the cave to <100‰ toward the outside. The condition is also seasonal in that summer moisture condensation can transfer energy to the cave surfaces - increasing temperatures - and so it is during the fall and winter when the cold zone is maintained. In some cases the cold zone supports perennial ice, as we discuss here.

Wigley & Brown (1976) have modelled cave temperature and humidity yielding a relaxation length (the cold zone) which is scaled by airflow rate and passage diameter:

$$x_0 = 100D^{1.2}V^{0.2}$$  \hspace{1cm} (5)

Where $D$ is the passage diameter, $V$ is the flow rate and the constant has the appropriate dimensions to scale $x_0$ in metres.

In Canada, Castleguard Cave is a classic cold zone cave with ice extending around 400m in winter, but the ice is not perennial. So here, we examine Canyon Creek Ice Cave, a rather low altitude cave which supports a (retreating) cold zone. Figure 9 displays the δH of various ice types versus distance from the cave entrance. The cold zone currently extends from around 50m to 180m from the entrance ($x_0$=130m); which suggests that estimates of $D = 1.2m$ and $V = 1.3m/s$ further into the cave are about right.

The most general feature is that δ-values appear to decline with distance into the cave and that the stratified ice yields some of the lowest values encountered in the study. Low δ-values are usually indicative of low temperatures (as seen for example in snow), being a function of latitude and elevation (Dansgaard, 1964) and of the GMWL. Snow seems an unlikely candidate with the stratified ice being found upslope and >50m from the cave entrance. Stratified ice varies from -130 to -173‰, so there is a great variation within the ice mass, which was sampled at distinctive layers. Not knowing the age of this ice, and that it is currently retreating, might suggest that it is relict from earlier and cooler times.
International Workshop on Ice Caves VI  
NCKRI SYMPOSIUM 4

However, another mechanism which could generate low δ-values is Rayleigh fractionation of the outgoing cave vapour. For example, ephemeral ice at Rats Nest Cave (Fig. 10) exhibits the fractionation and mixing of moist air exiting the cave during cold weather (-20°C) and freezing as hoar outside the cave entrance.

With a temperature range of +5 in the cave to -20°C outside, we see hoar with much depleted δ²H (down to -181‰). Compared to seepage water - assumed to be in equilibrium with the cave air (-145‰) - and using the sublimation fractionation factor at 0°C (Jouzel, 1986), we calculate that the initial ice should have commenced at -133‰. However the subsequent δ-values for ice are substantially lower (extrapolated to -149‰ at 0m), which suggests a mixing with the outside air. Ice condensate from air at -20°C would yield around -206‰ (equation 4) allowing us to determine that around 25‰ of the outside air is contributing to the cave vapour and the remaining effect is due to Rayleigh Distillation (RD); at 4m 78‰ of the cave vapour is precipitated out (We have made the assumption of a linear temperature decline over the 0-4m with the concomitant changing of the fractionation factor between 0 to -20°C; Jouzel, 1986.)

For Canyon Creek Ice Cave (Fig. 11) vapour is being precipitated as ice at 0°C in the cold zone (extensive hoar is noted there in winter). If we assume the winter hoar makes up the ice mass, and that this is primarily

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**Plate 3.** Stratified Ice in Canyon Creek Ice Cave, Alberta, Canada.

**Figure 9.** Deuterium concentration versus distance from the entrance of Canyon Creek Ice Cave (Cold Zone Type). "Mixing" and "Rayleigh" are explained in the text.
The greatest mixing is closest to the entrance with a 45% contribution of seepage and moist air from outside.

Furthermore, we have ignored kinetic effects (Lacelle et al., 2009), which can modify both the RD process and seepage, but would tend lead to enriched δ-values overall, while here we are trying to explain the much depleted ice. The stratigraphic record (Fig. 11), very different from Serendipity (in permafrost), then may be made up of varying components of cave seepage and summer hoar accumulating in the cold zone. The balance of Rayleigh/Mixing components to the ice layers can have climatic implications in which the summer component, contributing higher δ-values, can be more or less dominant depending on the summer’s intensity. A purely Rayleigh process implies no contribution by external moisture, which is unlikely, but even with some mixing low δ-values can be achieved by freezing a higher fraction of the cave vapor out as it passes through the cold zone.

**Conclusions**

1. All ice data when plotted as δ¹⁸O-δ²H‰ yield two fields defined by the d-excess where geographically they are close to the Pacific coast (<250 km; d = 10+/− 3‰) and east of the Great Divide (>750 km; d = 4+/− 3‰). These data can broadly be explained on the basis of a humid regime in the west compared to a drier, more continental regime in the east.

2. Cold Trap Caves appear to behave much like glaciers, preserving a muted record of precipitation at the site. These sites offer a paleoclimatic record interpretable in the same way that glaciers are. However, a cautionary note is sounded: ice caves are rarely just one type; one type might dominate, but may have components of the other types. Ice stratigraphy from cold trap caves appears to offer the best climate records, but the ice may be modified by Rayleigh and/or permafrost effects.

3. Permafrost Caves yield higher δ-values and lower d-excess than expected. It appears that moist air forced to sublimate at 0°C (as hoar) mixed with a more depleted seepage forms the massive ice within the cave. Paleoclimate might then be inferred from the variation in amount and/or temperature of the invading moist air. Increased hoar and reduced seepage during a cold climate would produce an inverse climate record when compared to glaciers.

![Figure 10. Variation in δ²H of hoar with distance from the entrance of Rats Nest Cave (outside temperature was -20°C).](image1)

![Figure 11. Variation of δ²H in the stratified units in Serendipity and Canyon Creek Ice Cave. The tan line is mean precipitation.](image2)
4. Data from Cold zone caves appears to show effects of Rayleigh Distillation as cave vapour draining from the cave is cooled at a cold zone by evaporation (i.e., where the relative humidity drops below 100%). A pure form of RD can generate a much depleted signal, which normally be interpreted in terms of low temperature. More likely there are varying degrees of RD modified by seepage. Seepage should be greater during warm periods, which allows climatic information to be gleaned from stratified ice. However, while higher temperatures would yield higher δ-values, their interpretation is quite different from that of glaciers.

Although ice in glacier/cold trap caves might be considered similar to stratified ice in glacial cores, a caution would be that as confined systems other processes as seen in cold zone or permafrost may contribute to the signal. In conclusion, we see that cold zone caves appear to contain the lowest δ-values and that is in part due to a Rayleigh distillation systematics.

References