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Palynological evidence for a warmer boreal climate in the Late Pliocene of the Yukon Territory, Canada

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Abstract

The Late Pliocene (3.6 – 2.6 Ma) was a period of significant global warmth, considered a potential analogue for future anthropogenic climate change. Newly discovered fine grained sediments from between the gold bearing lower and upper White Channel Gravels show the presence of a wetland or lake within Bonanza Creek, Dawson Mining District, Yukon. This environment was surrounded by a diverse Pinaceae dominated boreal forest with significant stands of angiosperms in favourable sites. Quantitative climate reconstructions derived from pollen and spores reveal a mean annual temperature at least 6°C warmer than today with warm summers and relatively mild winters. Finally, the new pollen assemblage is used to discuss the age of the White Channel Gravels.

1. Introduction

Global mean annual temperature of the Late Pliocene is estimated to have been 2 – 3°C higher than today (e.g. Lunt et al. 2010). Late Pliocene atmospheric CO_2-concentrations close to or even higher than modern values along with a near-modern palaeogeography, ocean bathymetry and palaeobiology, suggest that the warm Pliocene climates may provide plausible comparative scenarios for interpreting the path of future climate warming during the 21st century (e.g. Meehl et al. 2007; Dowsett et al., 2010; Salzmann et al. 2011; Haywood et al., 2013). The early Late Pliocene (3.3 – 3.0 Ma) represents one of the warmest climates of the last four million years and has been intensively studied to understand the feedbacks, processes and impacts of a climate significantly different from today (Dowsett et al. 2013; Haywood et al. 2013; Salzmann et al. 2013; Pound et al. 2014).

The global biome distribution for the Late Pliocene reflects this warmer than modern world. The warming was particularly accentuated at high latitudes of the northern hemisphere where cold needleleaf taiga forests reached the Arctic Circle and tundra vegetation was largely absent (e.g. Ballantyne et al. 2010; Andreev et al. 2013). A global data-model hybrid biome reconstruction suggests that during the Late Pliocene the Yukon was located on the eastern margin of extensive taiga forests; to the east a more continental climate meant that there were regions of extensive grasslands (Salzmann et al. 2008). However, the construction of the Late Pliocene global biome map used a mechanistic vegetation model to fill in regions with no palaeobotanical data and the extensive high-latitude grasslands, to the east of the Yukon, are one such model predicted region with high uncertainty due to a lack of data (Salzmann et al. 2008).

The Klondike Mining region is located on the Klondike Plateau within western central Yukon. Recent fieldwork has revealed a Late Pliocene organic rich horizon, which provides an opportunity to better constrain this region of the Late Pliocene global biome reconstruction (Salzmann et al., 2008). Today the Klondike Plateau ecoregion experiences a subarctic continental climate with long cold winters and short mild summers (Smith et al., 2004). This climate supports a boreal forest dominated by *Picea glauca* and *P. mariana*, with rivers and fire disturbance creating areas of greater diversity and more variable habitats (Smith et al., 2004). The Klondike plateau has also been a significant source of gold and the palaeoenvironmental information from the organic rich horizon will contribute to the understanding of this economic deposit (Lowther et al., 2014). The Klondike placer (mineral deposit concentrated through mechanical action) gold district attained global prominence with the gold rush of 1896 and the rich and geographically constrained placers (Burke, 2005, Chapman et al. 2010), which continue to support a regionally important mining industry. Placer gold was initially collected from the modern drainage of the region, but economically valuable resources were subsequently discovered at the base of thick gravel sequences which formed raised benches (McConnell 1905; 1907). The bench gravels became known as the 'White Channel Gravels' (the sediments currently do not have a formal name) as a consequence of the appearance of freshly mined sections. The White Channel Gravels continue to be exploited, which involves the removal of overburden to access the auriferous basal layer. Consequently, these mining activities have generated excellent stratigraphic sections which permit sedimentological study at multiple points in the Bonanza Creek drainage, (Lowther et al. 2014). The White Channel Gravels are an informal name for the deposits and a future publication will formally define them as a stratigraphic unit. The White Channel Gravels represent a braided river system and the gravels have traditionally been subdivided into a lower and upper gravel, based on colour, lithology and clast preservation (McConnell 1905; 1907). However, the gravels have also been considered to be a single unit, with the difference in colour being post-depositional staining (Morison 1987). The recent discovery of a fine grained organic rich mud, dividing the upper and lower gravels and representing a period of system shutdown, has confirmed that the traditional sub-division is valid (Lowther et al. 2014).

McConnell (1907) considered the White Channel Gravels to be Pliocene and Morison (1987) used the presence of *Corylus* pollen to support this hypothesis. Froese et al. (2000) provided two hypotheses for the age of the upper and lower White Channel Gravels based on palaeomagnetic data. The first of these proposed that the upper White Channel Gravels were Early Pleistocene (2.58 – 1.95 Ma) and the lower White Channel Gravels were latest Pliocene (3.33 – 2.58 Ma) (Froese et al. 2000). The second postulated that the whole sequence was older, placing the upper White Channel Gravels in the latest Pliocene and the lower White Channel Gravels were as old as the early Piacenzian (3.58 Ma) (Froese et al. 2000). The presence of a tephra layer inter-bedded with the upper White Channel Gravels has provided a radiometric age of 3.59 – 2.7 Ma (Westgate et al. 2002) and around 3 Ma using glass fission track dating (Lowey, 2004). Based on the dating of this tephra layer the second palaeomagnetic age hypothesis is considered more likely (Westgate et al. 2002). Furthermore, the overlying Klondike Gravel has been dated to around 2.64 Ma, showing that the upper White Channel Gravels have to be older than this further supporting the second palaeomagnetic age hypothesis (Hidy et al. 2013).

Palynological data from the Klondike Mining District have been previously reported from Dago Hill and Jackson Hill (Westgate et al. 2002; Schweger et al. 2011). These samples have come from the gravels of both the upper and lower White Channel Gravels. In the lower White Channel Gravels the pollen indicates the dominance of a dense Pinaceae forest with little evidence for herbaceous plants (Schweger et al. 2011). There is also evidence for a slightly more open forest community with a low diversity understory component (Schweger et al. 2011). Taxonomic diversity increases in the upper White Channel Gravel with a dominance of *Pinus* and Poaceae, and a greater diversity of herbaceous pollen (Schweger et al. 2011). In this paper we present a new Late Pliocene pollen assemblage from four sites in Bonanza Creek (Fig. 1). This pollen flora shows a higher diversity from those previously reported and a previously unreported environment in the White Channel Gravels. We apply the Co-existence Approach and the Mutual Climatic Range techniques to reconstruct climate parameters from the pollen. Finally, the new pollen assemblage is used to discuss the age of the lower and upper White Channel Gravels. The data presented in this paper further our understanding of high-latitude vegetation during a significantly warmer geological interval and contribute to filling gaps in global databases used in climate studies.

2. Methods

Samples for pollen analysis were collected in the summer of 2012 from four different gold mines (Adams Hill, Cheechako Hill, French Hill and Gold Hill) in Bonanza Creek (63.924N, 139.324W), south of Dawson City (Fig. 1). Samples were collected from a fine grained horizon located between the lower and upper White Channel Gravels. Samples were also taken from the gravel and sand layers, but these proved unproductive. The fine grained sediment is poorly consolidated and varies from a black organic rich mud to a brown coarser grained mud (full details can be found in Lowther et al. (2014)).

One gram of the five samples was processed using the standard HCl – HF acid technique, before being mounted in silicon oil for study (e.g. Faegri & Iversen 1989). A minimum of 300 grains were counted for each site with the exception of the Gold Hill locality, which yielded a very low pollen concentration. To gain information on the palaeoclimate during the deposition of the White channel Gravels we use the Co-existence Approach (CA) of Mosbrugger and Utescher (1997) and the Mutual Climatic Range (MCR) described by Thompson et al. (2012a, b). Pollen and spores have been identified using Bassett et al. (1978), Beug (2004) and the pollen reference collection held at Northumbria University. Both of these techniques use the nearest living relative of a fossil plant to reconstruct bioclimatic ranges within which all plants in a fossil assemblage could have survived (Mosbrugger & Utescher, 1997; Thompson et al. 2012a, b). We use the Palaeoflora Database (Utescher & Mosbrugger, 2010) to calculate Mean Annual Temperature (MAT) for the flora recovered from the White Channel Gravels. However, as the Palaeoflora Database is primarily for use on Eurasia we also use the datasets for North America published by Thompson et al. (1999a, b; 2000; 2006) to not only reconstruct MAT, but Mean Annual Precipitation (MAP), Mean Temperature of the Coldest Month (MTCM), Mean Temperature of the Warmest Month (MTWM), Mean Precipitation of the Coldest Month (MPCM) and the Mean Precipitation of the Warmest Month (MPWM). The MCR is used to produce ranges of MAT, MAP, MTCM, MTWM, MPCM, MPWM, the Growing Degree Days on a 5°C base (Newman 1980) (GDD5) and the ratio between Actual Evapotranspiration and Potential Evapotranspiration (AE/PE), which can be considered a moisture index (Thompson et al. 2012a, b).

3. Results

3.1. Palynology

Of the five fine-grained samples processed for palynomorphs only four yielded a countable flora (Fig. 2). The Gold Hill sample yielded a total of eight pollen grains representing: *Betula*, Cyperaceae, *Picea*, *Pinus* and *Taraxacum*-type. Of the remaining four samples, the two samples from the Cheechako Hill locality yielded the highest pollen concentrations and taxonomic diversity (Fig. 2). The pollen assemblages are described below; all percentages quoted in the text are of the total pollen flora for each site.

The Adams Hill organic rich layer was dominated by *Corylus* sp. (28.7%), *Pinus* sp. (24.6%), *Betula* sp. (12.6%) and *Picea* sp. (10.3%). Other tree and shrub taxa comprise a further 12.1% of the assemblage and include *Abies* sp, *Alnus* sp, Ericaceae, *Larix* sp, *Myrica*/*Comptonia*, cf. *Ostrya* sp. and *Salix* sp (Fig. 2). Herbaceous taxa make up 7% of the pollen flora, 5% of this is pollen of Poaceae and the remainder includes *Campanula*-type, Iridaceae, *Micropus*-type and *Urtica* sp. (Fig. 2). Wetland and aquatic taxa are represented by Cyperaceae, *Lemna* sp. and *Typha latifolia*-type, which form 4.4% of the total assemblage from Adams Hill (Fig. 2). The only spore recovered was of *Lycopodium annotinum* present.

The Cheechako Hill mud layer, which is stratigraphically below the Cheechako Hill organics layer, contains 44% wetland and aquatic taxa. This is mostly Cyperaceae pollen (26.8%), but also contains abundant *Sphagnum* spores (15.4%) and lesser amounts of *Lemna* sp., *Saxifraga* cf. *hirscula* and *Typha latifolia*-type (Fig. 2). Tree and shrub taxa comprise another 43.2% of the assemblage and are predominantly *Pinus* sp. (Fig. 2). Other tree and shrub pollen in the Cheechako Hill mud sample represent *Abies* sp., *Alnus* sp., *Betula* sp., *Corylus* sp., Cupressaceae, Ericaceae, *Fraxinus* sp., *Juniperus* sp., *Larix* sp., *Myrica*/*Comptonia*, cf. *Ostrya* sp., *Picea* sp. cf. *Quercus* sp. and *Salix* sp. (Fig. 2). Ferns form 7.6% of this assemblage and are mainly spores of *Pteridium*-type (6.1%), there are also spores of *Huperzia selago*, *Lycopodium annotinum*, and indeterminate monolete spores (Fig. 2). The herbaceous component of the Cheechako Hill mud layer represents 5% of the total assemblage and shows the presence of *Campanula*-type, Gentianaceae, Iridaceae, Poaceae and *Polygonum bistorta*-type (Fig. 2).

The Cheechako Hill organic rich layer from above the mud layer contains the most diverse pollen assemblage (Fig. 2). Like the mud layer, the organic layer is also dominated by wetland and aquatic taxa (52%). Cyperaceae comprise 42.5% of the pollen assemblage; other wetland/aquatic taxa include *Lemna* sp., *Myriophyllum* sp., *Saxifraga* cf. *hirculus*, *Sphagnum* sp. and *Typha latifolia*-type (Fig. 2). Tree and shrub taxa comprise a further 35.3% of the total pollen assemblage; this is mostly *Pinus* sp. with smaller amounts of *Abies* sp., *Alnus* sp., *Betula* sp., *Corylus* sp., Cupressaceae, Ericaceae, *Fraxinus* sp., *Ilex* sp., *Juniperus* sp., *Larix* sp., cf. *Ostrya* sp., *Picea* sp., cf. *Quercus* sp. and *Salix* sp. (Fig. 2). The herbaceous component of the organic layer makes up 8.2% of the pollen assemblage and is mostly Poaceae pollen (5.7%). There is also pollen representing *Aster*-type, *Campanula*-type, Caryophyllaceae, Gentianaceae, Iridaceae, *Polgonum bistorta*-type and Ranunculaceae (Fig. 2). Ferns only comprise 4.5% of the total assemblage, but show a greater diversity than in the underlying mud layer. Most spores are of *Pteridium* sp. (3%), but there are also examples of *Cryptogramma* sp., *Huperzia selago*, *Lycopodium annotinum*, indeterminate monolete spores, Polypodiaceae and *Selaginella* sp. (Fig. 2).

The French Hill organic rich layer yielded a less diverse flora than Adam Hill or Cheechako Hill. The pollen assemblage is dominated by tree and shrub taxa, with *Pinus* sp. (65%) and *Picea* sp. (21.5%) being most numerous. There are also small amounts of *Abies* sp., *Betula* sp., *Corylus* sp., Ericaceae, *Fraxinus* sp., *Larix* sp. and *Salix* sp. (Fig. 2). Wetland/aquatic taxa are only represented by small amounts of Cyperaceae, *Sphagnum* sp. and *Selaginella* sp., whilst the herbaceous component comprises *Campanula*-type, cf. *Cephalanthera* sp., Iridaceae and Poaceae (Fig. 2)

3.2. Palaeoclimate

We have reconstructed the climate within which the flora of the White Channel Gravels existed using the CA and MCR (Fig. 3). As field relationships suggest that the sampled mud to organic-rich layers from each of the gold mines were deposited at the same time, we utilize the whole flora of the region for our climate reconstructions. However, we also present climate reconstructions where taxa with uncertain identification in this study (e.g. their identification to an individual genus is not certain, such as: *Myrica*/*Comptonia* and *Ostrya* sp.) and taxa only identified in the Cheechako Hills organic rich sample (due to it being a distinct layer only found at Cheechako Hills) are excluded; we do this to show that the results of the analysis are comparable even when issues of uncertainty are taken into account (Fig. 3). For all climatic parameters we present the widest possible ranges from our reconstructions and then the ranges produced in individual analysis.

During the Late Pliocene we reconstruct a MAT in the range of 1 to 12°C for the White Channel Gravel flora (Fig. 3A). Using the CA we produce a range of 2.5 to 10.8°C using the dataset of Utescher and Mosbrugger (2010) and 1.4 to 11.2°C with the Thompson et al., (1999a,b; 2000; 2006) data (Fig. 3A). Using the MCR we reconstruct a warmer MAT range of 8.3 to 11.6°C (Fig. 3A). Taking into account the uncertainties mentioned previously the CA produces a MAT of 1.2 to 11.2°C and the MCR reconstructs a MAT of 1 to 12°C (Fig. 3A). The MTCM is reconstructed as a range of -20.3 to -0.1°C, with the MCR producing a warmer range of -0.5 to -0.2°C and the CA a range of -12.8 to -1°C (Fig. 3B). Taking into account our identified uncertainties the MCR then reconstructs a MTCM range of -14.5 to -2.2°C and the CA a range of -20.3 to -1°C (Fig. 3B). The flora produces a MTWM range of 14.1 to 24.4°C; once again the MCR reconstructs a warmer range of 16.3 to 23.5°C, whereas the CA range is 15.1 to 17.9°C (Fig. 3C). Excluding our uncertain taxa the MCR produces a MWTM range of 15.8 to 23.5°C and the CA reconstructs a range of 14.1 to 17.9°C (Fig. 3C).

From the flora preserved in the White Channel Gravels we reconstruct a MAP of 350 – 1800 mm/yr (Fig. 3D). Using the CA a MAP range of 930 – 1360 mm/yr is produced and a wider range of 350 – 1630 mm/yr when the uncertainty is taken into account (Fig. 3 D). The MCR reconstructs a MAP range of 795 – 1800 mm/yr using all taxa and a range of 465 – 1765 mm/yr when taxa are excluded (Fig. 3D). The MPCM is reconstructed as 9 – 159 mm, this widest range comes from the lowest estimate of the CA excluding uncertain taxa and the upper estimate from the MCR analysis using the whole flora (Fig. 3E). The MCR with the whole flora produces MPCM of 52 – 159 mm, the whole flora, the MCR excluding uncertain taxa provides a range of 34 –

157 mm, the CA reconstructs a range of 63 – 150 mm and the CA excluding uncertain taxa presents a range of 9 – 150 mm (Fig. 3E). The White Channel Gravel Formation had a MPWM in the range of 24 – 157 mm, this again reflects the lowest estimate of the CA excluding uncertain taxa and the upper estimate from the MCR analysis using the whole flora (Fig. 3F). Using the whole pollen assemblage the MCR produces a range of 48 – 146 mm, the MCR minus uncertain taxa a range of 24 – 143 mm, the CA a range of 71 – 157 mm and the CA without uncertain taxa a range of 35 – 157 mm (Fig. 3F). Using the MCR the GDD5 of the White Channel Gravels flora is reconstructed as 1.27 – 2.74 (x1000), when uncertain taxa are excluded the range expands to 0.99 – 2.71 (x1000). Using the MCR the AE/PE of the flora is reconstructed as 0.54 – 0.94 and this is widened to 0.42 – 0.94 when the identified uncertainty is taken into account.

4. Discussion

4.1. Palaeoenvironment of the fine grained sediments of the White Channel Gravels

The pollen and spores extracted from the fine grained layer of the White Channel Gravel show the presence of a diverse flora during the Late Pliocene (Fig. 2). The four samples that produced countable pollen show a comparable regional flora, but with some local variations (Fig. 4). The microflora extracted from the two Cheechako Hill samples were dominated by aquatics and wetland taxa, whereas the flora from Adams Hill and French Hill show proportionally more tree taxa. The organic rich layer from Adams Hill, Cheechako Hill and French Hill are all coeval, with the Cheechako mud layer being below the organic rich layer. We interpret the organic rich layer to indicate the presence of a wetland/lake in the vicinity of Cheechako Hill; the lower mud layer possibly represents an earlier stage of environmental development, although the pollen assemblage differences between the two layers at Cheechako Hill are minor (Fig. 2). Adams Hill is geographically very close to Cheechako Hill; it contains some of the wetland/aquatic taxa, but has a much greater proportion of tree and shrub taxa (Fig. 4). The Adams Hill locality was located in an area of marsh on the edge of the Cheechako Hill lake and may have had favorable growing conditions for broadleaf trees and shrubs (Fig. 2). French Hill, which is a greater distance from Cheechako Hill than Adams Hill is, lacks the majority of wetland/aquatic taxa, has a lower taxonomic diversity than the other samples and is dominated by Pinaceae pollen (Fig. 2). French Hill was deposited in a drier setting, towards the outer edge of the wetlands and reflects the regional Pinaceae dominated boreal forest. At the north of Bonanza Creek, at the modern junction with the Klondike River, Schweger et al. (2011) found a pollen flora in the White Channel Gravels at Jackson Hill that is comparable to that of French Hill. In neither the Jackson Hill nor the Dago Hill (situated to the east in Hunker Creek) localities did Schweger et al. (2011) find significant amounts of *Corylus*, Cyperaceae, *Salix* or *Sphagnum*, as well as many of the other taxa reported in this study, in the White Channel Gravels. This suggests that the flora from Adams Hill and Cheechako Hill is a unique local depositional environment, which has captured a diverse flora that was previously unknown from the region. The localized wetland/lake situated within a diverse boreal forest is also comparable to the reconstructed palaeoenvironment of the Late Pliocene sediments of the Lost Chicken gold mine, Alaska (Matthews 1970; Matthews et al. 2003).

The flora preserved in the fine grained layer of the White Channel Gravels represents a diverse boreal forest type vegetation and show differences with the plant communities found in this region today. The present day lowland vegetation of the region is boreal forest where fire disturbances create a mosaic of communities (Smith et al. 2004). *Picea glauca* and *P. mariana* dominate the forests, occasionally in mixed stands with *Betula papyrifera*, *Populus balsamifera* and *P. tremuloides* (Smith et al., 2004). On warmer slopes mid-successional communities of *Betula occidentalis, B. papyrifera*, *Picea glauca*, *Populus balsamifera, P. tremuloides* and *Salix* are found. Along rivers these mid-successional communities can be joined by *Alnus*, whereas poorly drained sites are characterized by *Picea mariana – Sphagnum* spp*.* communities (Smith et al. 2004). Understory shrub vegetation is comprised of Cyperaceae and Ericaceae, with Hypnaceae and lichens found beneath the shrubs (Smith et al. 2004).

The Late Pliocene boreal forests of Bonanza Creek would have been dominated by members of the Pinaceae associated with smaller trees or shrubs of *Alnus*, *Betula*, *Corylus*, *Ostrya* and *Salix* (the inference of small angiosperm trees and shrubs is based on reports of Pliocene fossil wood of large trees in Wheeler and Arnette (1994) only representing members of the Pinaceae). This forest community is more diverse than those of the modern Klondike Plateau region, including those found on warmer slopes (Smith et al. 2004). The presence of large amounts of *Pinus* pollen in this region during the Pliocene has been highlighted as one of the significant differences with floras post 1.4 Ma (Schweger et al. 2011). Although *Pinus* pollen is probably over-represented in this assemblage (Webb & McAndrews 1976; Bradshaw & Webb 1985), it is a common fossil occurring in Neogene floras throughout northwest North America indicating it was an important component of the boreal forests during this time (Matthews & Ovenden 1990; Ager et al. 1994; Wheeler & Arnette 1994; Matthews et al. 2003; Schweger et al. 2011; Pound et al. 2012a). Conversely, *Abies* and *Larix* are likely under-represented in the pollen assemblages from Bonanza Creek (Webb & McAndrews 1976; Ager et al. 1994; Schweger et al. 2011), but macrofossils again show they were significant components in the regional flora (Wheeler & Arnette 1994; Matthews et al. 2003). The taxa list reported for Bonanza Creek is comparable to other Pliocene macro- and micro-floras reported from across north - west North America, with the exception of the tentative identification of *Ostrya* (Matthews & Ovenden 1990; Ager et al. 1994; White et al. 1999; Matthews et al. 2003; Duk-Rodkin et al. 2010). Today *Ostrya virginiana* reaches its northern limit in Canada at about 50°N, where it inhabits a climate with MTWM of around 16°C and MTCM of -17°C (Metzger 1990).

The climate of the Klondike Mining region today is subarctic continental with a MAT of -5°C, cold long winters of -23 to -32°C and short mild summers with temperatures between 10°C and 15°C (Smith et al. 2004). Annual rainfall is typically 300 – 500 mm/yr with low January precipitation (10 – 20 mm) and wetter summers with up to 90 mm a month (Smith et al. 2004).The reconstructed climate parameters from the Bonanza Creek flora are higher than modern. The Late Pliocene MAT was 6 - 17°C warmer than today, Pliocene summers were at or above the highest mean temperatures experienced today and MTCM was 3 - 31°C warmer than present day winters (Smith et al., 2004). Similar temperature reconstructions have been presented for the Pliocene localities near Circle Alaska (Ager et al., 1994) and further north on Ellesmere

Island (Csank et al. 2011). The Pliocene flora of the Circle region would have grown under a MAT of at least 3°C; with a MTWM of 12°C and a MTCM of -2°C (Ager et al. 1994). It is of note that our MTCM reconstructions do not all overlap (Fig. 3B). The MCR based reconstruction has a narrow range and is 0.5°C warmer than either of the CA reconstructions (Fig. 3B). This is likely a nuance of the techniques: the MCR approach ignores the extreme ends of the range; on the grounds that few species actually inhabit the edge of their climatic ecospace (Thompson et al., 2012a). Our reconstructed MAP range is large and covers the modern MAP to nearly four times present day MAP (Fig. 3 D). Comparing the reconstructed GDD5 with present day measurements shows that the Late Pliocene Yukon had a GDD5 more familiar to latitudes 5 - 10° further south (Thompson et al. 2012b). Comparing the bioclimatic parameters reconstructed for the White Channel Gravels to those of North American ecoregions presented in Thompson et al. (2007), shows that they are most similar to modern forest ecoregions found 5 - 10° latitude further south of Dawson City. In particular the MCR reconstructions for the Late Pliocene of the White Channel gravels are bioclimatically comparable to the modern forests of eastern Canada.

The warmer world of the Pliocene has implications for our understanding of future anthropogenic climate change. Although no geological time period should be referred to as an analogue; processes, features and patterns can provide valuable insight into the future of Earth under a warmer climate (Haywood et al. 2011). The Late Pliocene high latitude climate, reconstructed from the pollen preserved in the fine grained sediments, is considerably warmer and wetter than today (Fig. 3). Seasonally, our reconstruction appears to support a warmer (probably shorter) winter and a summer comparable, or slightly warmer than today (Fig. 3). This is consistent with previous findings for the Late Pliocene (Ager et al., 1994; Ballantyne et al., 2013) and other warm intervals during the Cenozoic (Ivany et al., 2000). The mosaic environment reconstructed from the pollen preserved between the upper and lower White channel Gravels would have a more variable surface albedo than a pure stand of dark coniferous forest (Davidson & Wang, 2004; McMillan et al. 2008). The surface albedo would also be modified by the presence of wetlands or lakes. Further to modifying surface albedo, recent work on the geographic distribution of Late Pliocene lakes has shown that the energy used to evaporate lake water has a summer cooling effect in the immediate vicinity of the lake (Pound et al. 2014). This might be a feedback that facilitated the warmer than modern winters, but comparable to modern summers at the high latitudes during the Late Pliocene. It is also well documented that wetlands are a major source of methane in the modern world (Yavitt et al. 1990; Ringeval et al. 2010), whereas forests are largely sinks (Yavitt et al. 1990). The presence of a wetland in the vicinity of the Cheechako Hills locality could therefore have been a small methane source during the Pliocene. The evidence from Bonanza Creek for a heterogeneous environment could be a local phenomenon or could have been more widespread. If more of the Late Pliocene high-latitude vegetation was heterogeneous, with a mosaic of forest, open environments and wetlands, then the cumulative impacts on the carbon cycle and surface albedo could have had a significant influence on the climate of the Late Pliocene.

4.2. Palynological contribution to the age of the White Channel Gravels

The age of the upper White Channel Gravels is constrained by a radiometric age of 3.59 – 2.7 Ma from the Dago Hill tephra (Westgate et al. 2002) and 3.21 – 2.73 Ma from the Quartz Creek tephra (Kunk 1995). As the inter-play of climate and evolution have modified vegetation through time it should be possible to use the flora preserved in the White Channel gravels to refine the age. From previous biostratigraphic work, Morison (1987) assigned a Pliocene age to the White Channel Gravels based on the occurrence of *Corylus*. The occurrence of *Polemonium* has long been considered an important stratigraphic marker in northwest North America (Ager et al. 1994; White et al. 1999; Duk-Rodkin et al. 2010). Although *Polemonium* has been reported from the Late Miocene from other localities outside of northwest North America (Müller 1981; Pound et al. 2012b), it appears in pollen assemblages of the Alaska-Yukon region during the Pliocene (Ager et al. 1994). The east Fifteenmile River and Rock Creek localities of the Tintina Trench, north of Dawson City have yielded a pollen flora dominated by Pinaceae and containing *Polemonium* pollen (Duk-Rodkin et al. 2010). Palaeomagnetic results place the pollen producing unit at 3.33 – 3.05 Ma and the ambient climate has been inferred as cool – cold alpine (Duk-Rodkin et al. 2010). The first appearance of *Polemonium* is one of the key biostratigraphical events of the regional Poaceae Zone (4.05 – 2.35 Ma) of White et al. (1999). It is known from numerous other localities in northwest North America and has been reported from the upper White Channel Gravels at Dago Hill (Schweger et al. 2011), but it was not found during this study of the fine grained sediments located between the upper and lower White Channel gravels (Fig. 2).

Preceding the Poaceae Zone is the Ericales Zone (6.15 – 4.05 Ma) in the regional biostratigraphy (White et al. 1999). This zone is based on two radiometrically dated localities in Alaska: Lava Camp (5.9 – 5.5 Ma) and McCallum Creek (5.37 – 5.05 Ma). The indicators of this zone are an abundance of Ericales, associated with lesser amounts of *Alnus* and *Betula* than the older zones and the first rare occurrences of Caryophyllaceae pollen (White et al. 1999). The pollen assemblages from between the upper and lower White Channel Gravels do contain rare amounts of Caryophyllaceae in the Cheechako Hill organic rich layer, but do not contain an abundance of Ericaceae pollen (Fig. 2). *Alnus* and *Betula* are relatively common in all samples except the French Hill locality (Fig. 2).

The Betulaceae Zone, Cyperaceae subzone (8.85 – 6.15 Ma) is marked by a dominance of Betulaceae pollen and the first rare occurrences of Cyperaceae, *Nuphar* and *Sagittaria* pollen (White et al. 1999). *Pinus* pollen reaches its highest proportion of assemblages in this subzone and the percentage of Ericaceae pollen increases in pollen spectrums (White et al. 1999). Pollen of *Carya*, *Castanea*, *Ostrya/Carpinus* and *Sciadopitys* are found in trace amounts and this is the last zone in which many of these are present *in situ* (White et al. 1999). The flora of Adams Hill is dominated by genera of the Betulaceae and all samples yielded Cyperaceae pollen, though its high percentage means it cannot be considered rare (Fig. 2). Add to this the high proportion of *Pinus*, the rare occurrence of *Ostrya* and the flora from between the upper and lower White Channel Gravels could be considered as part of the Cyperaceae subzone (Fig. 2). This however would be contradictory to the other dating methods (Kunk 1995; Froese et al. 2000; Westgate et al. 2002).

It is difficult to place the Bonanza Creek flora into the White et al. (1999) biostratigraphic zonation. This is however likely an artefact of the construction of the regional biostratigraphy (White et al. 1999). The localities that define the Ericales and Poaceae Zones of the latest Miocene to latest Pliocene are chronologically clustered (White et al. 1999). The Lava Camp and McCallum Creek localities that define the Ericales zone are both older than 5 Ma, whilst the sites used to define the Poaceae Zone are younger than 3.1 – 2.7 Ma (White et al. 1999; Matthews et al. 2003). There is therefore a 2 - 3 Ma period without data to guide the regional biostratigraphy (White et al. 1999). This gap includes the mid-Pliocene Warm Period (Dowsett et al. 2010; Haywood et al. 2013). The flora preserved in Bonanza Creek indicates MATs as 6°C warmer than today. The diversity of the flora, including elements today found at least 10° latitude further south, testifies to an environment more favourable and productive. This flora certainly came from a warm interval in the Pliocene as it lacks the diversity of older Miocene floras (Leopold & Liu 1994; White et al. 1999; Pound et al. 2012a). Based on the ternary diagrams of White et al. (1999), the Bonanza Creek flora can be considered younger than 5.7 Ma due to the proportionally high occurrence of *Sphagnum* when compared to *Alnus* and *Betula* or *Betula* and Poaceae. Due to the data gap in the construction of the regional biostratigraphy it is not possible to confidently assign the Bonanza Creek flora to either the Ericales or Poaceae Zones and further work may redefine these zones. The absence of *Polemonium*, considering its appearance in the nearby Tintina Trench at around 3.33 – 3.05 Ma, suggests that the new flora from Bonanza Creek is at least older than 3 Ma (Duk-Rodkin et al. 2010). This would support the second hypothesis of Froese et al. (2000), placing the age of the lower White Channel Gravels to 3.58 – 3.11 Ma. Considering the climatic reconstruction from the pollen preserved in the fine grained layers, this significant change to the depositional environment most likely occurred during the mid-Pliocene Warm Period (3.3 – 3.0 Ma). This would make the lower White Channel Gravels older than at least 3.3 Ma (Westgate et al. 2002).

5. Summary

The pollen assemblage recovered from the fine grained sediments of the White Channel gravels shows the presence of a taxonomically diverse mosaic environment in Bonanza Creek during the mid – Pliocene Warm Period. A Cyperaceae dominated wetland/lake environment was centred on Cheechako Hill, a Betulaceae dominated forest inhabited a favourable site proximal to the wetland/lake, whilst a regional Pinaceae dominated taiga forest is preserved at French Hill. Combined the different environments reconstructed from the fine grained sediments of the White Channel Gravels would have been part of the Late Pliocene boreal forest biome. Providing additional evidence for the dominance of forest, rather than grassland at the high latitudes of the Late Pliocene.

The MAT was 6°C to 17°C warmer than modern and the area would have had MCMT of at most -20.3°C, but could have been just below zero. Summer temperatures were greater than 15°C and the area would have been more productive with a higher GDD5. The fine grained sediments, which represent a significant change in palaeoenvironment from the gravels were deposited in the Late Pliocene, though further work on the regional biostratigraphy could greatly improve the dating of Pliocene floras.

6. Acknowledgements

A special thanks is given to the placer miners of Dawson area namely, John Alton, the Christie family, Ivan Daunt, Daryl Fry, Doug Jackson, Mike McDougall, Eric Rauguth, Don Ruman and Chuck Sigurdson, without whom this research would not have been possible. Thanks are also given to the Natural Environment Research Council, Yukon Geological Survey, Canadian Northern Development Agency, Society of Economic Geologists, and the International Association of Sedimentologists, for providing support for the field component of this project. We gratefully thank A. Dolan and H. Dowsett for their reviews that have greatly improved the manuscript.

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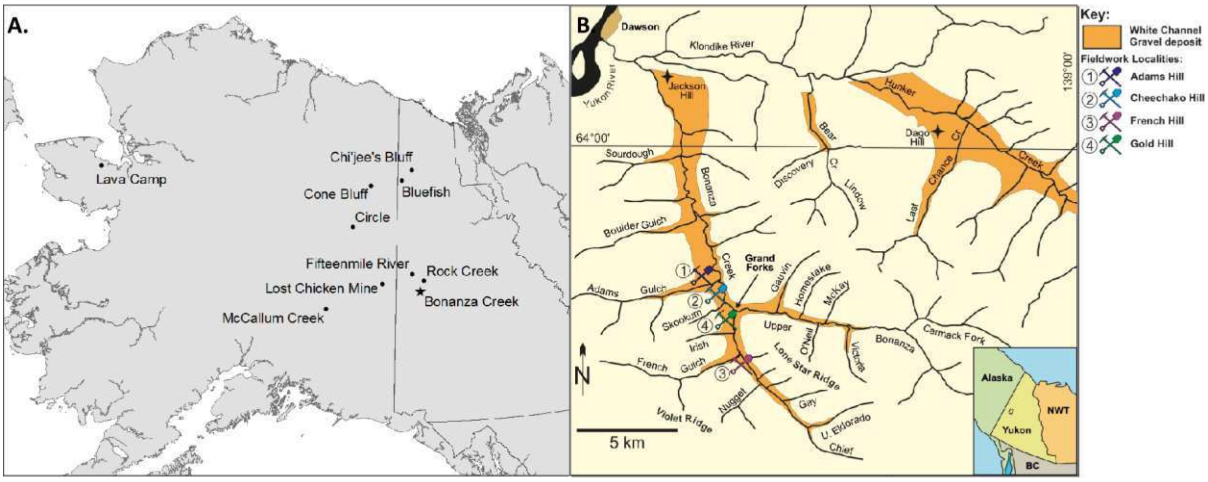

Figure 1. The location of the study area. A. shows the location of the Bonanza Creek region relative to other important Pliocene palaeobotanical sites in north-west North America. B. Location of sample sites within Bonanza Creek and position of them south of Dawson City.

Reference: *Pound, M.J., Lowther, R.I., Peakall, J., Chapman, R.J., Salzmann, U., 2015. Palynological evidence for a warmer boreal climate in the Late Pliocene of the Yukon Territory, Canada. Palynology 39, 91-102.*
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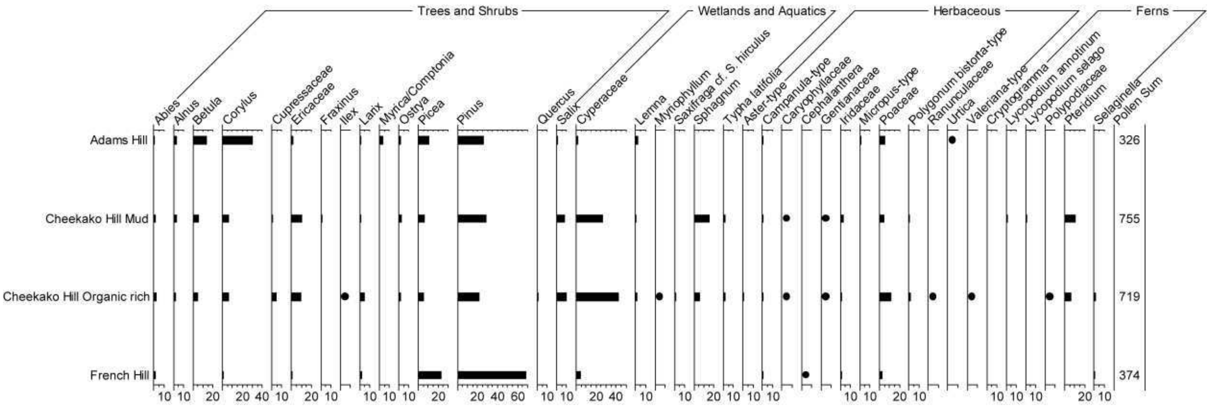

Figure 2. Pollen diagram showing the percentage of pollen (x-axis) in each sample. Circles indicate the presence of a pollen type where it only occurs once or twice in the assemblage.

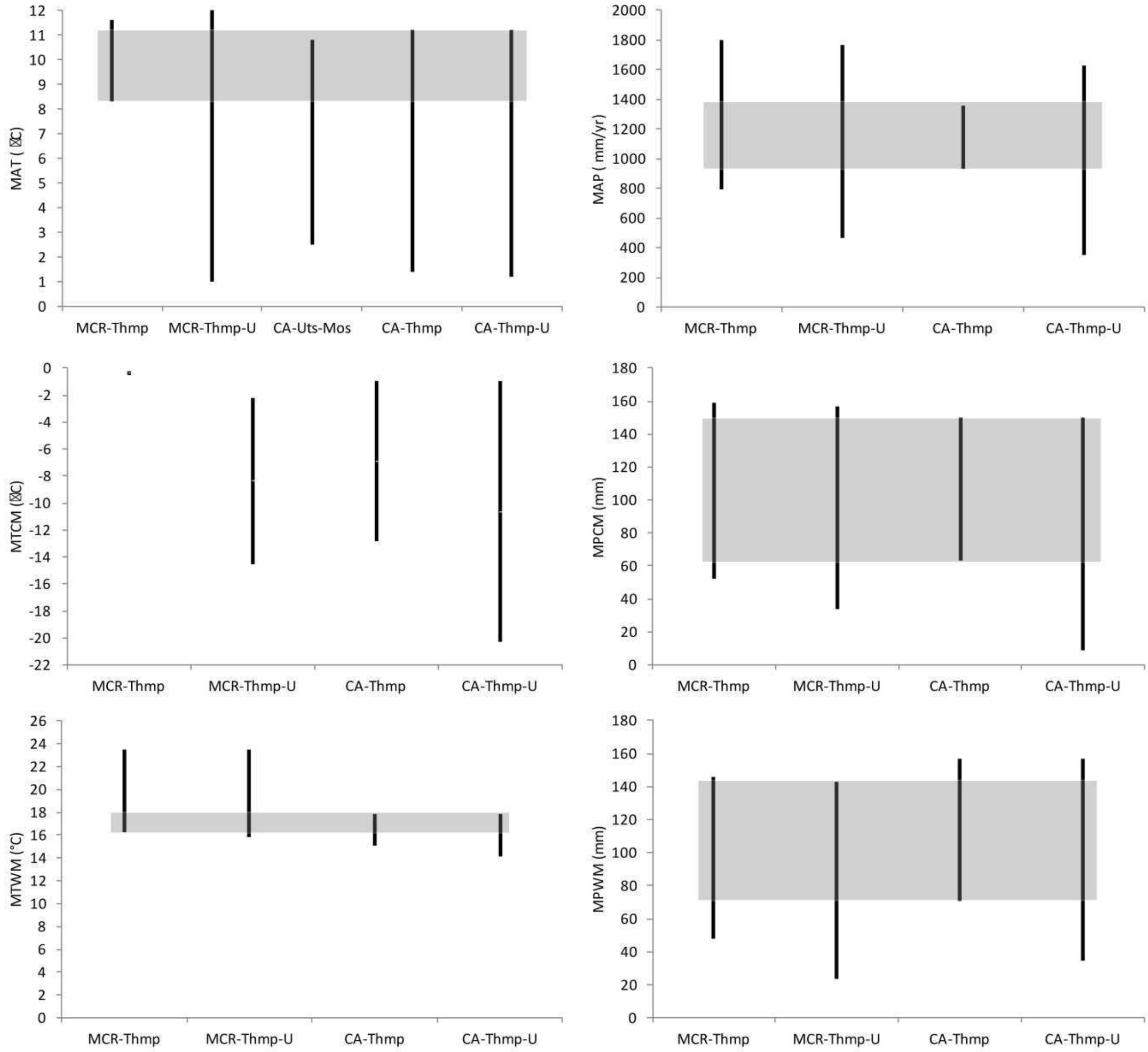

Figure 3. Reconstructed climate information for the Bonanza Creek flora. A. Mean Annual Temperature (MAT), B. Mean Temperature of the Coldest Month (MTCM), C. Mean Temperature of the Warmest Month (MTWM), D. Mean Annual Precipitation (MAP), E. Mean Precipitation of the Coldest Month (MPCM) and F. Mean Precipitation of the Warmest Month (MPWM). Abbreviations on the x-axis refer to the technique and climatic dataset used: MCR-Thmp; Mutual Climatic Range (MCR) using the dataset of Thompson et al. (2012a, b), MCR-Thmp-U; MCR excluding taxa with uncertain identification of using the dataset of Thompson et al. (2012a, b), CA-Uts-Mos; Co-existence Approach (CA) using the dataset of Utescher and Mosbrugger (2010), CA-Thmp; CA using the dataset of Thompson et al. (2012a, b), CA-Thmp-U; CA excluding taxa with uncertain identification of using the dataset of Thompson et al. (2012a, b). Shaded area indicates range of agreement between the different techniques.

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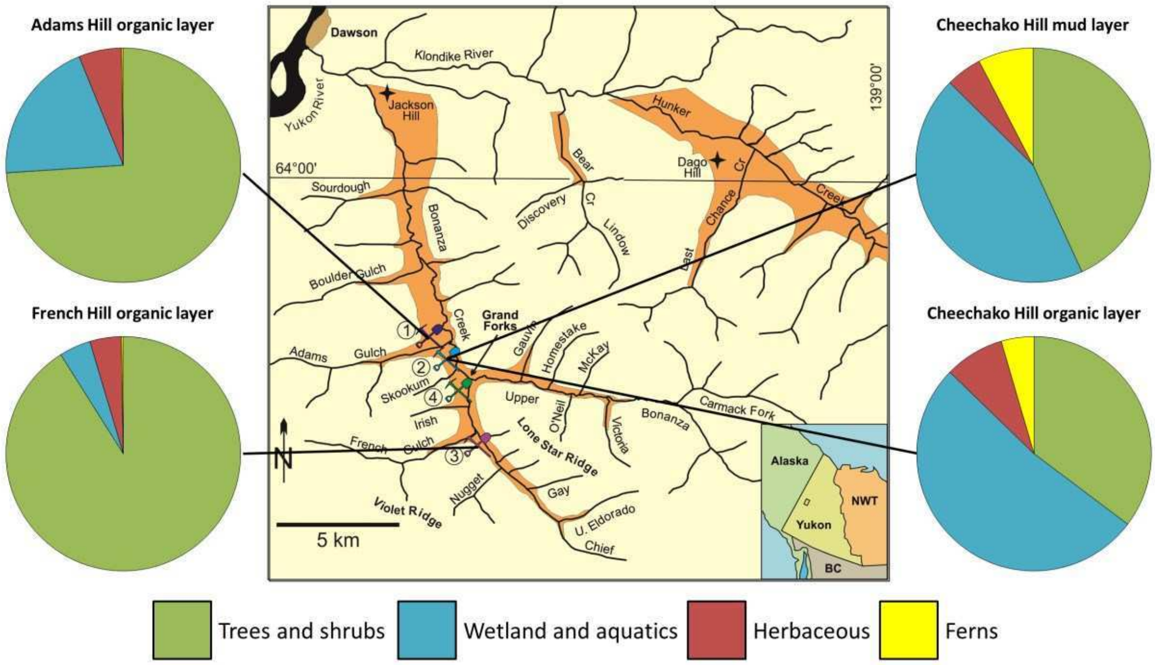

Figure 4. The percentages of pollen groups (Fig. 2) in the four different sample locations.