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1 Palynological evidence for a warmer boreal climate in the Late Pliocene of the 2 Yukon Territory, Canada

3 Matthew J. Pound¹, Robert I. Lowther², Jeff Peakall², Robert J. Chapman² and Ulrich Salzmann¹

4 ¹Department of Geography, Northumbria University, Ellison Building, Newcastle upon Tyne, NE1 8ST, UK.

5 ²Placer Minerals Group, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK.

6

7 Abstract

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

16

17 1. Introduction

18 Global mean annual temperature of the Late Pliocene is estimated to have been 2 – 3°C higher than today
19 (e.g. Lunt et al. 2010). Late Pliocene atmospheric CO₂-concentrations close to or even higher than modern
20 values along with a near-modern palaeogeography, ocean bathymetry and palaeobiology, suggest that the
21 warm Pliocene climates may provide plausible comparative scenarios for interpreting the path of future

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22 climate warming during the 21st century (e.g. Meehl et al. 2007; Dowsett et al., 2010; Salzmann et al. 2011;
23 Haywood et al., 2013). The early Late Pliocene (3.3 – 3.0 Ma) represents one of the warmest climates of the
24 last four million years and has been intensively studied to understand the feedbacks, processes and impacts
25 of a climate significantly different from today (Dowsett et al. 2013; Haywood et al. 2013; Salzmann et al.
26 2013; Pound et al. 2014).

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

36 The Klondike Mining region is located on the Klondike Plateau within western central Yukon. Recent
37 fieldwork has revealed a Late Pliocene organic rich horizon, which provides an opportunity to better
38 constrain this region of the Late Pliocene global biome reconstruction (Salzmann et al., 2008). Today the
39 Klondike Plateau ecoregion experiences a subarctic continental climate with long cold winters and short mild
40 summers (Smith et al., 2004). This climate supports a boreal forest dominated by *Picea glauca* and *P.*
41 *mariana*, with rivers and fire disturbance creating areas of greater diversity and more variable habitats
42 (Smith et al., 2004). The Klondike plateau has also been a significant source of gold and the
43 palaeoenvironmental information from the organic rich horizon will contribute to the understanding of this
44 economic deposit (Lowther et al., 2014). The Klondike placer (mineral deposit concentrated through
45 mechanical action) gold district attained global prominence with the gold rush of 1896 and the rich and
46 geographically constrained placers (Burke, 2005, Chapman et al. 2010), which continue to support a

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47 regionally important mining industry. Placer gold was initially collected from the modern drainage of the
48 region, but economically valuable resources were subsequently discovered at the base of thick gravel
49 sequences which formed raised benches (McConnell 1905; 1907). The bench gravels became known as the
50 'White Channel Gravels' (the sediments currently do not have a formal name) as a consequence of the
51 appearance of freshly mined sections. The White Channel Gravels continue to be exploited, which involves
52 the removal of overburden to access the auriferous basal layer. Consequently, these mining activities have
53 generated excellent stratigraphic sections which permit sedimentological study at multiple points in the
54 Bonanza Creek drainage, (Lowther et al. 2014). The White Channel Gravels are an informal name for the
55 deposits and a future publication will formally define them as a stratigraphic unit. The White Channel
56 Gravels represent a braided river system and the gravels have traditionally been subdivided into a lower and
57 upper gravel, based on colour, lithology and clast preservation (McConnell 1905; 1907). However, the
58 gravels have also been considered to be a single unit, with the difference in colour being post-depositional
59 staining (Morison 1987). The recent discovery of a fine grained organic rich mud, dividing the upper and
60 lower gravels and representing a period of system shutdown, has confirmed that the traditional sub-division
61 is valid (Lowther et al. 2014).

62 McConnell (1907) considered the White Channel Gravels to be Pliocene and Morison (1987) used the
63 presence of *Corylus* pollen to support this hypothesis. Froese et al. (2000) provided two hypotheses for the
64 age of the upper and lower White Channel Gravels based on palaeomagnetic data. The first of these
65 proposed that the upper White Channel Gravels were Early Pleistocene (2.58 – 1.95 Ma) and the lower
66 White Channel Gravels were latest Pliocene (3.33 – 2.58 Ma) (Froese et al. 2000). The second postulated that
67 the whole sequence was older, placing the upper White Channel Gravels in the latest Pliocene and the lower
68 White Channel Gravels were as old as the early Piacenzian (3.58 Ma) (Froese et al. 2000). The presence of a
69 tephra layer inter-bedded with the upper White Channel Gravels has provided a radiometric age of 3.59 –
70 2.7 Ma (Westgate et al. 2002) and around 3 Ma using glass fission track dating (Lowey, 2004). Based on the
71 dating of this tephra layer the second palaeomagnetic age hypothesis is considered more likely (Westgate et

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72 al. 2002). Furthermore, the overlying Klondike Gravel has been dated to around 2.64 Ma, showing that the
73 upper White Channel Gravels have to be older than this further supporting the second palaeomagnetic age
74 hypothesis (Hidy et al. 2013).

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

89

90 2. Methods

91 Samples for pollen analysis were collected in the summer of 2012 from four different gold mines (Adams Hill,
92 Cheechako Hill, French Hill and Gold Hill) in Bonanza Creek (63.924N, 139.324W), south of Dawson City (Fig.
93 1). Samples were collected from a fine grained horizon located between the lower and upper White Channel
94 Gravels. Samples were also taken from the gravel and sand layers, but these proved unproductive. The fine

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95 grained sediment is poorly consolidated and varies from a black organic rich mud to a brown coarser grained
96 mud (full details can be found in Lowther et al. (2014)).

97 One gram of the five samples was processed using the standard HCl – HF acid technique, before being
98 mounted in silicon oil for study (e.g. Faegri & Iversen 1989). A minimum of 300 grains were counted for each
99 site with the exception of the Gold Hill locality, which yielded a very low pollen concentration. To gain
100 information on the palaeoclimate during the deposition of the White channel Gravels we use the Co-
101 existence Approach (CA) of Mosbrugger and Utescher (1997) and the Mutual Climatic Range (MCR)
102 described by Thompson et al. (2012a, b). Pollen and spores have been identified using Bassett et al. (1978),
103 Beug (2004) and the pollen reference collection held at Northumbria University. Both of these techniques
104 use the nearest living relative of a fossil plant to reconstruct bioclimatic ranges within which all plants in a
105 fossil assemblage could have survived (Mosbrugger & Utescher, 1997; Thompson et al. 2012a, b). We use
106 the Palaeoflora Database (Utescher & Mosbrugger, 2010) to calculate Mean Annual Temperature (MAT) for
107 the flora recovered from the White Channel Gravels. However, as the Palaeoflora Database is primarily for
108 use on Eurasia we also use the datasets for North America published by Thompson et al. (1999a, b; 2000;
109 2006) to not only reconstruct MAT, but Mean Annual Precipitation (MAP), Mean Temperature of the Coldest
110 Month (MTCM), Mean Temperature of the Warmest Month (MTWM), Mean Precipitation of the Coldest
111 Month (MPCM) and the Mean Precipitation of the Warmest Month (MPWM). The MCR is used to produce
112 ranges of MAT, MAP, MTCM, MTWM, MPCM, MPWM, the Growing Degree Days on a 5°C base (Newman
113 1980) (GDD5) and the ratio between Actual Evapotranspiration and Potential Evapotranspiration (AE/PE),
114 which can be considered a moisture index (Thompson et al. 2012a, b).

115

116 3. Results

117 3.1. Palynology

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

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

130 The Cheechako Hill mud layer, which is stratigraphically below the Cheechako Hill organics layer, contains
131 44% wetland and aquatic taxa. This is mostly Cyperaceae pollen (26.8%), but also contains abundant
132 *Sphagnum* spores (15.4%) and lesser amounts of *Lemna* sp., *Saxifraga* cf. *hirsacula* and *Typha latifolia*-type
133 (Fig. 2). Tree and shrub taxa comprise another 43.2% of the assemblage and are predominantly *Pinus* sp.
134 (Fig. 2). Other tree and shrub pollen in the Cheechako Hill mud sample represent *Abies* sp., *Alnus* sp., *Betula*
135 sp., *Corylus* sp., Cupressaceae, Ericaceae, *Fraxinus* sp., *Juniperus* sp., *Larix* sp., *Myrica/Comptonia*, cf. *Ostrya*
136 sp., *Picea* sp. cf. *Quercus* sp. and *Salix* sp. (Fig. 2). Ferns form 7.6% of this assemblage and are mainly spores
137 of *Pteridium*-type (6.1%), there are also spores of *Huperzia selago*, *Lycopodium annotinum*, and
138 indeterminate monolete spores (Fig. 2). The herbaceous component of the Cheechako Hill mud layer
139 represents 5% of the total assemblage and shows the presence of *Campanula*-type, Gentianaceae, Iridaceae,
140 Poaceae and *Polygonum bistorta*-type (Fig. 2).

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

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

160

161 3.2. Palaeoclimate

162 We have reconstructed the climate within which the flora of the White Channel Gravels existed using the CA
163 and MCR (Fig. 3). As field relationships suggest that the sampled mud to organic-rich layers from each of the
164 gold mines were deposited at the same time, we utilize the whole flora of the region for our climate

165 reconstructions. However, we also present climate reconstructions where taxa with uncertain identification
166 in this study (e.g. their identification to an individual genus is not certain, such as: *Myrica/Comptonia* and
167 *Ostrya* sp.) and taxa only identified in the Cheechako Hills organic rich sample (due to it being a distinct layer
168 only found at Cheechako Hills) are excluded; we do this to show that the results of the analysis are
169 comparable even when issues of uncertainty are taken into account (Fig. 3). For all climatic parameters we
170 present the widest possible ranges from our reconstructions and then the ranges produced in individual
171 analysis.

172 During the Late Pliocene we reconstruct a MAT in the range of 1 to 12°C for the White Channel Gravel flora
173 (Fig. 3A). Using the CA we produce a range of 2.5 to 10.8°C using the dataset of Utescher and Mosbrugger
174 (2010) and 1.4 to 11.2°C with the Thompson et al., (1999a,b; 2000; 2006) data (Fig. 3A). Using the MCR we
175 reconstruct a warmer MAT range of 8.3 to 11.6°C (Fig. 3A). Taking into account the uncertainties mentioned
176 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).
177 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 -
178 0.2°C and the CA a range of -12.8 to -1°C (Fig. 3B). Taking into account our identified uncertainties the MCR
179 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
180 produces a MTWM range of 14.1 to 24.4°C; once again the MCR reconstructs a warmer range of 16.3 to
181 23.5°C, whereas the CA range is 15.1 to 17.9°C (Fig. 3C). Excluding our uncertain taxa the MCR produces a
182 MWTM range of 15.8 to 23.5°C and the CA reconstructs a range of 14.1 to 17.9°C (Fig. 3C).

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

190 157 mm, the CA reconstructs a range of 63 – 150 mm and the CA excluding uncertain taxa presents a range
191 of 9 – 150 mm (Fig. 3E). The White Channel Gravel Formation had a MPWM in the range of 24 – 157 mm,
192 this again reflects the lowest estimate of the CA excluding uncertain taxa and the upper estimate from the
193 MCR analysis using the whole flora (Fig. 3F). Using the whole pollen assemblage the MCR produces a range
194 of 48 – 146 mm, the MCR minus uncertain taxa a range of 24 – 143 mm, the CA a range of 71 – 157 mm and
195 the CA without uncertain taxa a range of 35 – 157 mm (Fig. 3F). Using the MCR the GDD5 of the White
196 Channel Gravels flora is reconstructed as 1.27 – 2.74 (x1000), when uncertain taxa are excluded the range
197 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
198 is widened to 0.42 – 0.94 when the identified uncertainty is taken into account.

199

200 4. Discussion

201 4.1. Palaeoenvironment of the fine grained sediments of the White Channel Gravels

202 The pollen and spores extracted from the fine grained layer of the White Channel Gravel show the presence
203 of a diverse flora during the Late Pliocene (Fig. 2). The four samples that produced countable pollen show a
204 comparable regional flora, but with some local variations (Fig. 4). The microflora extracted from the two
205 Cheechako Hill samples were dominated by aquatics and wetland taxa, whereas the flora from Adams Hill
206 and French Hill show proportionally more tree taxa. The organic rich layer from Adams Hill, Cheechako Hill
207 and French Hill are all coeval, with the Cheechako mud layer being below the organic rich layer. We interpret
208 the organic rich layer to indicate the presence of a wetland/lake in the vicinity of Cheechako Hill; the lower
209 mud layer possibly represents an earlier stage of environmental development, although the pollen
210 assemblage differences between the two layers at Cheechako Hill are minor (Fig. 2). Adams Hill is
211 geographically very close to Cheechako Hill; it contains some of the wetland/aquatic taxa, but has a much
212 greater proportion of tree and shrub taxa (Fig. 4). The Adams Hill locality was located in an area of marsh on
213 the edge of the Cheechako Hill lake and may have had favorable growing conditions for broadleaf trees and

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214 shrubs (Fig. 2). French Hill, which is a greater distance from Cheechako Hill than Adams Hill is, lacks the
215 majority of wetland/aquatic taxa, has a lower taxonomic diversity than the other samples and is dominated
216 by Pinaceae pollen (Fig. 2). French Hill was deposited in a drier setting, towards the outer edge of the
217 wetlands and reflects the regional Pinaceae dominated boreal forest. At the north of Bonanza Creek, at the
218 modern junction with the Klondike River, Schweger et al. (2011) found a pollen flora in the White Channel
219 Gravels at Jackson Hill that is comparable to that of French Hill. In neither the Jackson Hill nor the Dago Hill
220 (situated to the east in Hunker Creek) localities did Schweger et al. (2011) find significant amounts of
221 *Corylus*, *Cyperaceae*, *Salix* or *Sphagnum*, as well as many of the other taxa reported in this study, in the
222 White Channel Gravels. This suggests that the flora from Adams Hill and Cheechako Hill is a unique local
223 depositional environment, which has captured a diverse flora that was previously unknown from the region.
224 The localized wetland/lake situated within a diverse boreal forest is also comparable to the reconstructed
225 palaeoenvironment of the Late Pliocene sediments of the Lost Chicken gold mine, Alaska (Matthews 1970;
226 Matthews et al. 2003).

227 The flora preserved in the fine grained layer of the White Channel Gravels represents a diverse boreal forest
228 type vegetation and show differences with the plant communities found in this region today. The present
229 day lowland vegetation of the region is boreal forest where fire disturbances create a mosaic of communities
230 (Smith et al. 2004). *Picea glauca* and *P. mariana* dominate the forests, occasionally in mixed stands with
231 *Betula papyrifera*, *Populus balsamifera* and *P. tremuloides* (Smith et al., 2004). On warmer slopes mid-
232 successional communities of *Betula occidentalis*, *B. papyrifera*, *Picea glauca*, *Populus balsamifera*, *P.*
233 *tremuloides* and *Salix* are found. Along rivers these mid-successional communities can be joined by *Alnus*,
234 whereas poorly drained sites are characterized by *Picea mariana* – *Sphagnum* spp. communities (Smith et al.
235 2004). Understory shrub vegetation is comprised of *Cyperaceae* and *Ericaceae*, with *Hypnaceae* and lichens
236 found beneath the shrubs (Smith et al. 2004).

237 The Late Pliocene boreal forests of Bonanza Creek would have been dominated by members of the Pinaceae
238 associated with smaller trees or shrubs of *Alnus*, *Betula*, *Corylus*, *Ostrya* and *Salix* (the inference of small

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239 angiosperm trees and shrubs is based on reports of Pliocene fossil wood of large trees in Wheeler and
240 Arnette (1994) only representing members of the Pinaceae). This forest community is more diverse than
241 those of the modern Klondike Plateau region, including those found on warmer slopes (Smith et al. 2004).
242 The presence of large amounts of *Pinus* pollen in this region during the Pliocene has been highlighted as one
243 of the significant differences with floras post 1.4 Ma (Schweger et al. 2011). Although *Pinus* pollen is
244 probably over-represented in this assemblage (Webb & McAndrews 1976; Bradshaw & Webb 1985), it is a
245 common fossil occurring in Neogene floras throughout northwest North America indicating it was an
246 important component of the boreal forests during this time (Matthews & Ovenden 1990; Ager et al. 1994;
247 Wheeler & Arnette 1994; Matthews et al. 2003; Schweger et al. 2011; Pound et al. 2012a). Conversely, *Abies*
248 and *Larix* are likely under-represented in the pollen assemblages from Bonanza Creek (Webb & McAndrews
249 1976; Ager et al. 1994; Schweger et al. 2011), but macrofossils again show they were significant components
250 in the regional flora (Wheeler & Arnette 1994; Matthews et al. 2003). The taxa list reported for Bonanza
251 Creek is comparable to other Pliocene macro- and micro-floras reported from across north - west North
252 America, with the exception of the tentative identification of *Ostrya* (Matthews & Ovenden 1990; Ager et al.
253 1994; White et al. 1999; Matthews et al. 2003; Duk-Rodkin et al. 2010). Today *Ostrya virginiana* reaches its
254 northern limit in Canada at about 50°N, where it inhabits a climate with MTWM of around 16°C and MTCM
255 of -17°C (Metzger 1990).

256 The climate of the Klondike Mining region today is subarctic continental with a MAT of -5°C, cold long
257 winters of -23 to -32°C and short mild summers with temperatures between 10°C and 15°C (Smith et al.
258 2004). Annual rainfall is typically 300 – 500 mm/yr with low January precipitation (10 – 20 mm) and wetter
259 summers with up to 90 mm a month (Smith et al. 2004). The reconstructed climate parameters from the
260 Bonanza Creek flora are higher than modern. The Late Pliocene MAT was 6 - 17°C warmer than today,
261 Pliocene summers were at or above the highest mean temperatures experienced today and MTCM was 3 -
262 31°C warmer than present day winters (Smith et al., 2004). Similar temperature reconstructions have been
263 presented for the Pliocene localities near Circle Alaska (Ager et al., 1994) and further north on Ellesmere

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264 Island (Csank et al. 2011). The Pliocene flora of the Circle region would have grown under a MAT of at least
265 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
266 reconstructions do not all overlap (Fig. 3B). The MCR based reconstruction has a narrow range and is 0.5°C
267 warmer than either of the CA reconstructions (Fig. 3B). This is likely a nuance of the techniques: the MCR
268 approach ignores the extreme ends of the range; on the grounds that few species actually inhabit the edge
269 of their climatic ecospace (Thompson et al., 2012a). Our reconstructed MAP range is large and covers the
270 modern MAP to nearly four times present day MAP (Fig. 3 D). Comparing the reconstructed GDD5 with
271 present day measurements shows that the Late Pliocene Yukon had a GDD5 more familiar to latitudes 5 - 10°
272 further south (Thompson et al. 2012b). Comparing the bioclimatic parameters reconstructed for the White
273 Channel Gravels to those of North American ecoregions presented in Thompson et al. (2007), shows that
274 they are most similar to modern forest ecoregions found 5 - 10° latitude further south of Dawson City. In
275 particular the MCR reconstructions for the Late Pliocene of the White Channel gravels are bioclimatically
276 comparable to the modern forests of eastern Canada.

277 The warmer world of the Pliocene has implications for our understanding of future anthropogenic climate
278 change. Although no geological time period should be referred to as an analogue; processes, features and
279 patterns can provide valuable insight into the future of Earth under a warmer climate (Haywood et al. 2011).

280 The Late Pliocene high latitude climate, reconstructed from the pollen preserved in the fine grained
281 sediments, is considerably warmer and wetter than today (Fig. 3). Seasonally, our reconstruction appears to
282 support a warmer (probably shorter) winter and a summer comparable, or slightly warmer than today (Fig.
283 3). This is consistent with previous findings for the Late Pliocene (Ager et al., 1994; Ballantyne et al., 2013)
284 and other warm intervals during the Cenozoic (Ivany et al., 2000). The mosaic environment reconstructed
285 from the pollen preserved between the upper and lower White channel Gravels would have a more variable
286 surface albedo than a pure stand of dark coniferous forest (Davidson & Wang, 2004; McMillan et al. 2008).
287 The surface albedo would also be modified by the presence of wetlands or lakes. Further to modifying
288 surface albedo, recent work on the geographic distribution of Late Pliocene lakes has shown that the energy

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289 used to evaporate lake water has a summer cooling effect in the immediate vicinity of the lake (Pound et al.
290 2014). This might be a feedback that facilitated the warmer than modern winters, but comparable to
291 modern summers at the high latitudes during the Late Pliocene. It is also well documented that wetlands are
292 a major source of methane in the modern world (Yavitt et al. 1990; Ringeval et al. 2010), whereas forests are
293 largely sinks (Yavitt et al. 1990). The presence of a wetland in the vicinity of the Cheechako Hills locality
294 could therefore have been a small methane source during the Pliocene. The evidence from Bonanza Creek
295 for a heterogeneous environment could be a local phenomenon or could have been more widespread. If
296 more of the Late Pliocene high-latitude vegetation was heterogeneous, with a mosaic of forest, open
297 environments and wetlands, then the cumulative impacts on the carbon cycle and surface albedo could have
298 had a significant influence on the climate of the Late Pliocene.

299 300 4.2. Palynological contribution to the age of the White Channel Gravels

301 The age of the upper White Channel Gravels is constrained by a radiometric age of 3.59 – 2.7 Ma from the
302 Dago Hill tephra (Westgate et al. 2002) and 3.21 – 2.73 Ma from the Quartz Creek tephra (Kunk 1995). As the
303 inter-play of climate and evolution have modified vegetation through time it should be possible to use the
304 flora preserved in the White Channel gravels to refine the age. From previous biostratigraphic work, Morison
305 (1987) assigned a Pliocene age to the White Channel Gravels based on the occurrence of *Corylus*. The
306 occurrence of *Polemonium* has long been considered an important stratigraphic marker in northwest North
307 America (Ager et al. 1994; White et al. 1999; Duk-Rodkin et al. 2010). Although *Polemonium* has been
308 reported from the Late Miocene from other localities outside of northwest North America (Müller 1981;
309 Pound et al. 2012b), it appears in pollen assemblages of the Alaska-Yukon region during the Pliocene (Ager
310 et al. 1994). The east Fifteenmile River and Rock Creek localities of the Tintina Trench, north of Dawson City
311 have yielded a pollen flora dominated by Pinaceae and containing *Polemonium* pollen (Duk-Rodkin et al.
312 2010). Palaeomagnetic results place the pollen producing unit at 3.33 – 3.05 Ma and the ambient climate has

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313 been inferred as cool – cold alpine (Duk-Rodkin et al. 2010). The first appearance of *Polemonium* is one of
314 the key biostratigraphical events of the regional Poaceae Zone (4.05 – 2.35 Ma) of White et al. (1999). It is
315 known from numerous other localities in northwest North America and has been reported from the upper
316 White Channel Gravels at Dago Hill (Schweger et al. 2011), but it was not found during this study of the fine
317 grained sediments located between the upper and lower White Channel gravels (Fig. 2).

318 Preceding the Poaceae Zone is the Ericales Zone (6.15 – 4.05 Ma) in the regional biostratigraphy (White et al.
319 1999). This zone is based on two radiometrically dated localities in Alaska: Lava Camp (5.9 – 5.5 Ma) and
320 McCallum Creek (5.37 – 5.05 Ma). The indicators of this zone are an abundance of Ericales, associated with
321 lesser amounts of *Alnus* and *Betula* than the older zones and the first rare occurrences of Caryophyllaceae
322 pollen (White et al. 1999). The pollen assemblages from between the upper and lower White Channel
323 Gravels do contain rare amounts of Caryophyllaceae in the Cheechako Hill organic rich layer, but do not
324 contain an abundance of Ericaceae pollen (Fig. 2). *Alnus* and *Betula* are relatively common in all samples
325 except the French Hill locality (Fig. 2).

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

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336 It is difficult to place the Bonanza Creek flora into the White et al. (1999) biostratigraphic zonation. This is
337 however likely an artefact of the construction of the regional biostratigraphy (White et al. 1999). The
338 localities that define the Ericales and Poaceae Zones of the latest Miocene to latest Pliocene are
339 chronologically clustered (White et al. 1999). The Lava Camp and McCallum Creek localities that define the
340 Ericales zone are both older than 5 Ma, whilst the sites used to define the Poaceae Zone are younger than
341 3.1 – 2.7 Ma (White et al. 1999; Matthews et al. 2003). There is therefore a 2 - 3 Ma period without data to
342 guide the regional biostratigraphy (White et al. 1999). This gap includes the mid-Pliocene Warm Period
343 (Dowsett et al. 2010; Haywood et al. 2013). The flora preserved in Bonanza Creek indicates MATs as 6°C
344 warmer than today. The diversity of the flora, including elements today found at least 10° latitude further
345 south, testifies to an environment more favourable and productive. This flora certainly came from a warm
346 interval in the Pliocene as it lacks the diversity of older Miocene floras (Leopold & Liu 1994; White et al.
347 1999; Pound et al. 2012a). Based on the ternary diagrams of White et al. (1999), the Bonanza Creek flora can
348 be considered younger than 5.7 Ma due to the proportionally high occurrence of *Sphagnum* when compared
349 to *Alnus* and *Betula* or *Betula* and Poaceae. Due to the data gap in the construction of the regional
350 biostratigraphy it is not possible to confidently assign the Bonanza Creek flora to either the Ericales or
351 Poaceae Zones and further work may redefine these zones. The absence of *Polemonium*, considering its
352 appearance in the nearby Tintina Trench at around 3.33 – 3.05 Ma, suggests that the new flora from
353 Bonanza Creek is at least older than 3 Ma (Duk-Rodkin et al. 2010). This would support the second
354 hypothesis of Froese et al. (2000), placing the age of the lower White Channel Gravels to 3.58 – 3.11 Ma.
355 Considering the climatic reconstruction from the pollen preserved in the fine grained layers, this significant
356 change to the depositional environment most likely occurred during the mid-Pliocene Warm Period (3.3 –
357 3.0 Ma). This would make the lower White Channel Gravels older than at least 3.3 Ma (Westgate et al. 2002).

358

359 5. Summary

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

368 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
369 could have been just below zero. Summer temperatures were greater than 15°C and the area would have
370 been more productive with a higher GDD5. The fine grained sediments, which represent a significant change
371 in palaeoenvironment from the gravels were deposited in the Late Pliocene, though further work on the
372 regional biostratigraphy could greatly improve the dating of Pliocene floras.

373

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534

535 8. Author Biographies

536 MATTHEW J. POUND is a research fellow at Northumbria University in Newcastle, United Kingdom. He is
537 involved in several projects including the incorporation of geological data into palaeoclimate models,
538 Cenozoic palynology and onshore Miocene successions of the United Kingdom.

539 ROBERT I. LOWTHER is a PhD researcher at the University of Leeds, United Kingdom. His research focuses on
540 placer deposits, combining both field studies and physical modelling to investigate the processes involved in
541 their formation and evolution.

542 JEFF PEAKALL is Professor of Process Sedimentology at the University of Leeds, United Kingdom. His work
543 focuses on sedimentation processes and deposits across a wide range of terrestrial and deep marine
544 environments.

545 ROBERT J. CHAPMAN is a Senior Lecturer in the School of Earth and Environment at the university of Leeds
546 and PI of the Placer Minerals Group. His research interests centre on the relationships between placer and
547 lode gold and their application to mineral exploration.

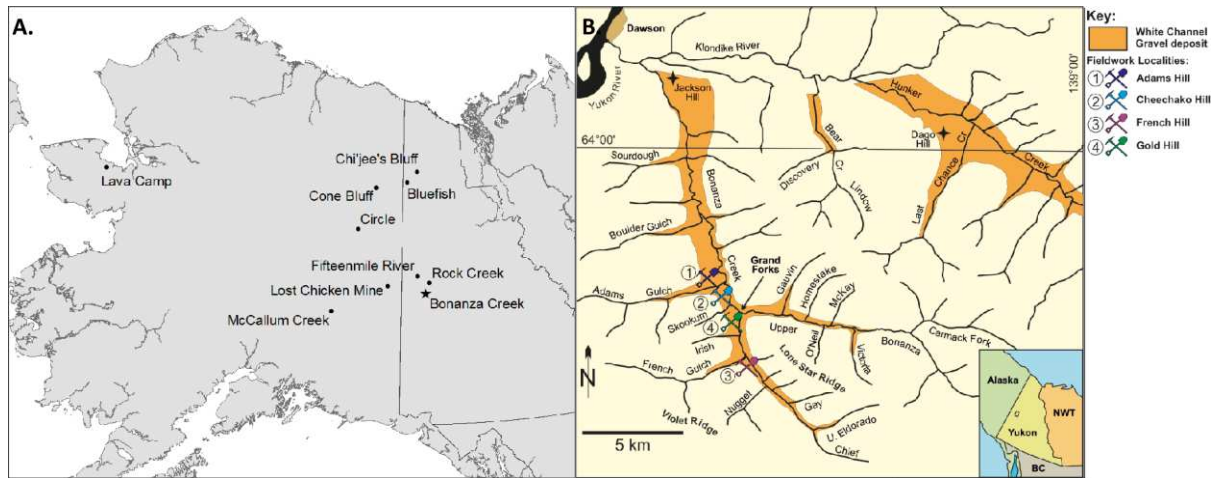
548 ULRICH SALZMANN is a Palynologist and Professor of Palaeoecology at Northumbria University in Newcastle,
549 United Kingdom. His research focuses on global palaeoecology and climatology and the reconstruction of
550 past environments using a combined proxy data and modelling approach.

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

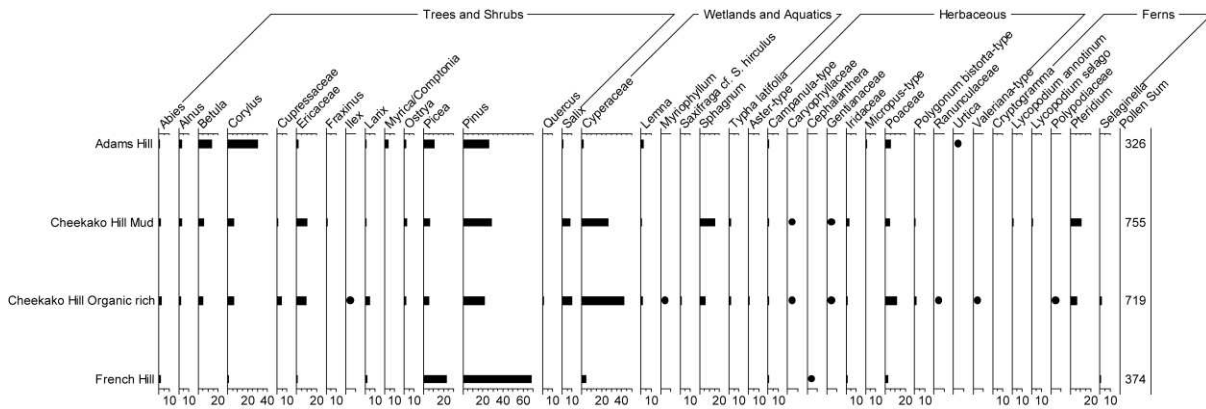
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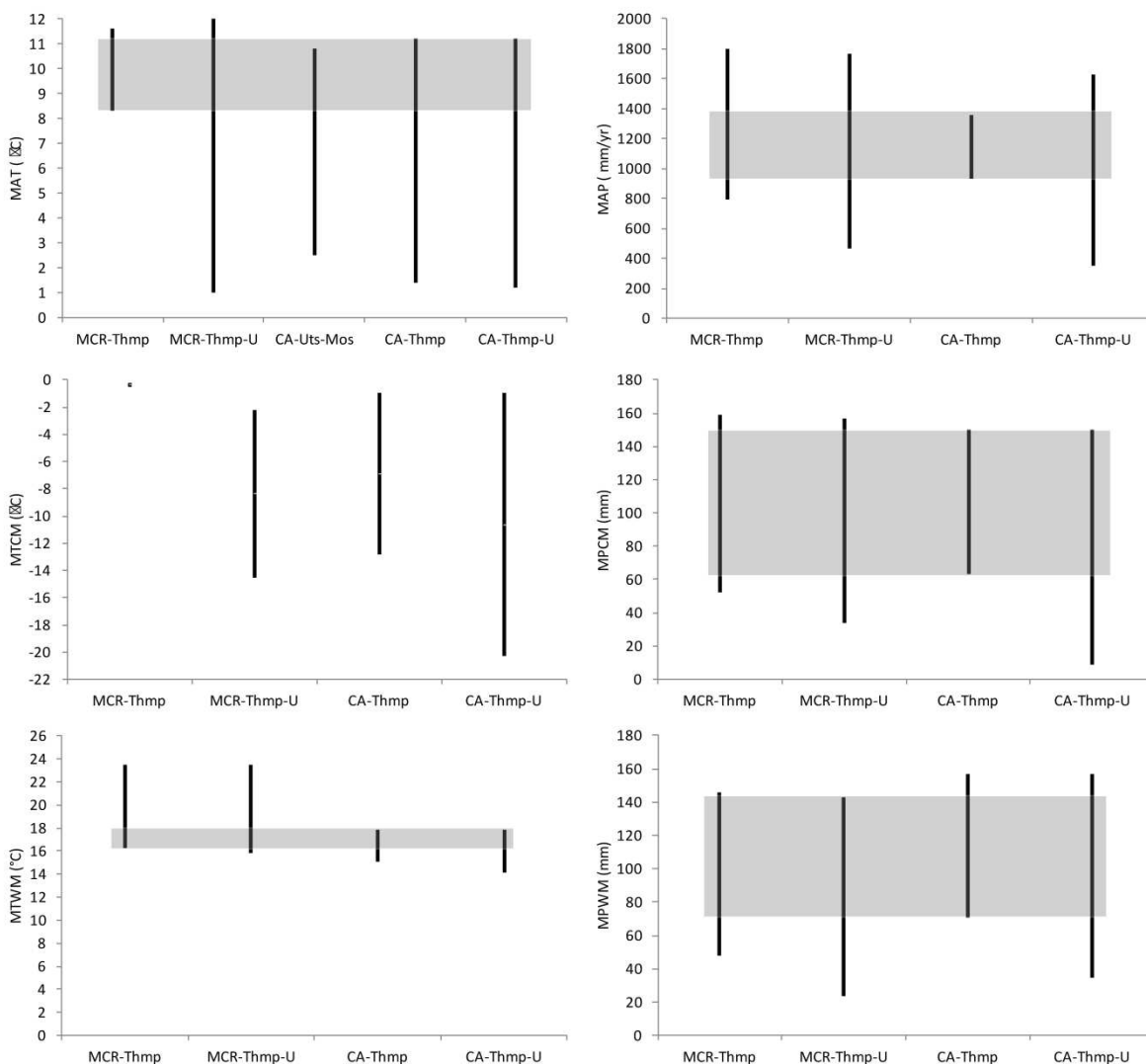


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559 Figure 2. Pollen diagram showing the percentage of pollen (x-axis) in each sample. Circles indicate the presence of a

560 pollen type where it only occurs once or twice in the assemblage.

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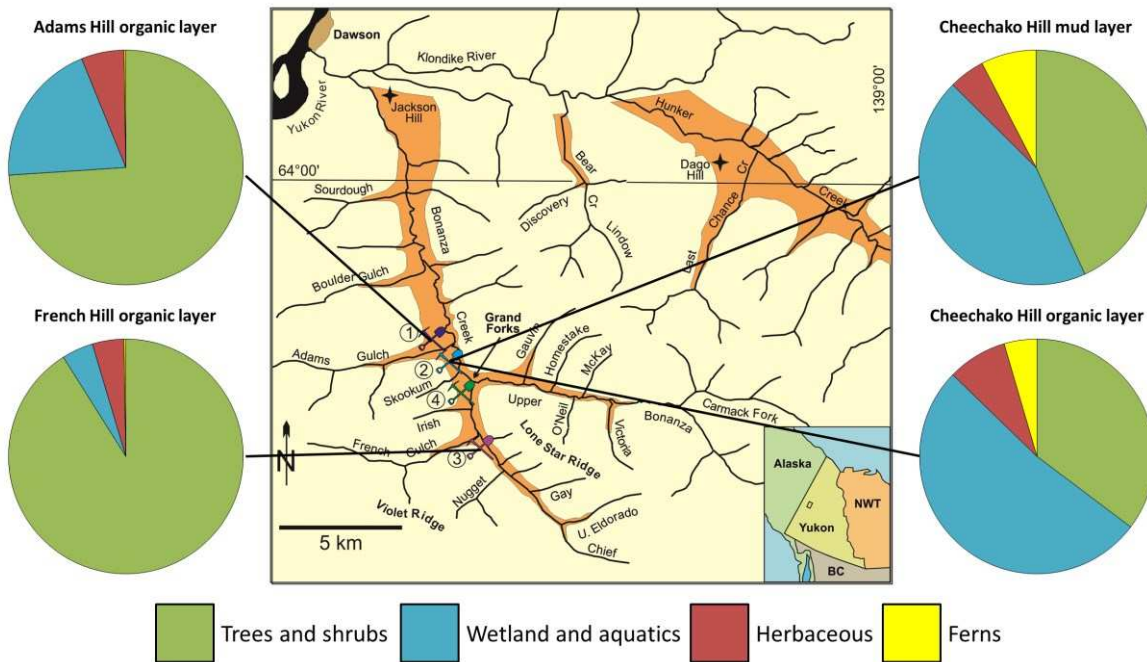


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563 Figure 3. Reconstructed climate information for the Bonanza Creek flora. A. Mean Annual Temperature (MAT), B. Mean
 564 Temperature of the Coldest Month (MTCM), C. Mean Temperature of the Warmest Month (MTWM), D. Mean Annual
 565 Precipitation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

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