Late Cretaceous climate of Eurasia and Alaska: a quantitative palaeobotanical approach

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Abstract: Physiognomic analysis of 19 late Albian and Late Cretaceous floras from Europe, Kazakhstan, North-eastern Asia and Alaska using the CLAMP technique yielded quantitative data on the mean annual, warm month mean, and cold month mean temperatures, the length of the growing season, mean annual, mean growing season, mean monthly growing season, and precipitation during the three driest consecutive months. In Eurasia the Cenomanian was probably the warmest stage of the Late Cretaceous. The cold month mean temperature of sites bordering the Arctic Ocean were at or above freezing. Given the lack of solar insolation for 3–4 months each year this suggests that there must have been significant poleward ocean heat transport. Precipitation in the Arctic was predicted to have been high reflecting a very weak polar high pressure cell. In moist regimes without a pronounced seasonal drought there appears to be little significant difference in the climate signal as captured by leaves preserved in different depositional environments. However, for warmer and seasonally drier regimes CLAMP is able to distinguish between microclimates experienced by different plant communities. The reasonably good agreement between CLAMP analysis of Cenomanian floras, palaeontologic signals, sedimentology and the predictions of Atmospheric General Circulation model (AGCM) in coastal areas of Europe, Asia and Alaska confirms the accuracy of the CLAMP. However, away from the coastal areas the AGCM predictions are incompatible with those from foliar physiognomy, vegetational diversity, and sedimentology. This may indicate that the Cretaceous atmospheric dynamics were different to those of the Present. Existing AGCMs fail to reproduce the CLAMP deduced continental interior conditions under greenhouse climates.

Keywords: Palaeoclimate, CLAMP, Late Cretaceous, Eurasia, Alaska, Palaeobotany

1. INTRODUCTION

Geologic evidence indicates that the Late Cretaceous represented an extremely warm phase of Earth history (BARRON et al., 1993; CHUMAKOV, 1995; CHUMAKOV et al., 1995; FRAKES, 1979; KRASSILOV, 1985; PARRISH, 1998; VAKHRAMEEV, 1991). The Cretaceous climate

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has often been described as warm and uniform and the polar regions in particular were much warmer than today (HERMAN, 1994; HERMAN & SPICER, 1996; 1997; HUBER, 1998; SPICER & PARRISH, 1990; SPICER at al., 1992). This was a time with little polar ice and when thermophilic floras and faunas spread into high latitudes of Northern and Southern Hemispheres and forests grew at latitudes as high as 85°N (BUDANTSEV, 1992; HERMAN, 1994; SPICER & PARRISH, 1990; VAKHRAMEEV, 1991). The equator-to-pole temperature gradient was therefore much less than it is today (SELLWOOD et al., 1994; HUBER et al., 1995).

During the last few decades a wealth of information on Cretaceous climate has come from diverse sources such as 1) data on the global distribution of sedimentologic indicators of past climates such as coals, bauxites, evaporites, glacial deposits, soils etc., 2) oxygen isotope data from Cretaceous ocean sediments, 3) data on the global distribution of fossil plant and animal assemblages, 4) computer modelling of the Cretaceous climates (Atmospheric General Circulation Models – AGCMs). The most comprehensive quantitative terrestrial climate proxy, and the one most recently developed, is however derived from the physiognomy of fossil woody dicot leaves (WOLFE, 1993; 1995; HERMAN & SPICER, 1996, 1997).

The most sensitive indicators of non-marine conditions are land plants. This is because they are spatially fixed and, therefore, have to be well adapted to local conditions in order to survive. Plants lack the homeostatic mechanisms of many animals that effectively isolate those organisms from the external conditions. Furthermore plants process the atmosphere for their existence because the exchange of oxygen and carbon dioxide is essential for photosynthesis. Plants are therefore intimately linked to the atmosphere and must be adapted to the climate in which they find themselves growing.

Plants have a strong relationship with climate. Similar climate regimes tend to be populated by plants with similar architecture irrespective of the taxonomy. Such plant architectural similarities also exist under similar environmental regimes separated in time, so we can use the plant fossil record to tell us a great deal about past climates. Leaf shape, size and texture, cuticular features and fossil woods provide both qualitative and quantitative data on the Cretaceous climate. This paper reviews the non-marine latest Albian and Late Cretaceous climate of Eurasia and Alaska using quantitative palaeo-botanical data. The data complement those from the marine realm.

2. METHOD

2.1. Nearest Living Relative

The nearest living relative (NLR) approach is one traditionally used by palaeobotanists for palaeoclimate analysis. The technique relies on the accurate identification of the nearest living relatives of the ancient plants composing a fossil flora, and the ancient climate is extrapolated from the climatic requirements of the living plants. The NLR approach usually works quite well for Quaternary and Neogene floras, and it is some-times applicable for Paleogene floras, but the antiquity of Cretaceous and older floras precludes its use. Apart from the difficulties of finding a relative at the species level for which climatic tolerances are the narrowest the technique implies that climatic require-ments of plant (or animal) taxa were not affected by evolution and are constant

throughout the geologic time. Clearly this cannot be true. Therefore, it is much safer to reconstruct past climates using taxonomically independent morphological or anatomical features characterising adaptations to particular environmental constraints.

2.2. Leaf Margin Analysis

An early attempt at quantifying physiognomic characters in terms of climatic data was that of BAILEY & SINNOT (1915).They examined the margin characteristics of woody dicot leaves and noted that there was a good direct relationship between the proportion of taxa with entire margins and mean annual temperature: entire margins are characteristic of warm climates and toothed margins of cool climates. By plotting the proportions of entire margined to toothed margined leaves in a flora, a clear relationship with mean annual temperature is apparent. Fig. 1 shows such a relationship for South-eastern Asian plants (WOLFE, 1979). In an ideal situation the ratio of leaf margins in a fossil flora with a high diversity of dicot leaf species in it could yield a reliable mean annual temperature experienced by the plants at the time they grew.

The leaf margin analysis has been used extensively for Tertiary and even Cretaceous material but the method has some serious limitations. Firstly, there is an underlying assumption that water is not limiting to growth in any of the taxa used in leaf margin analysis. If however drought is a factor, then leaf size tends to be diminished and teeth can be lost so giving an abnormally warm climatic signal. Secondly, because the mor-
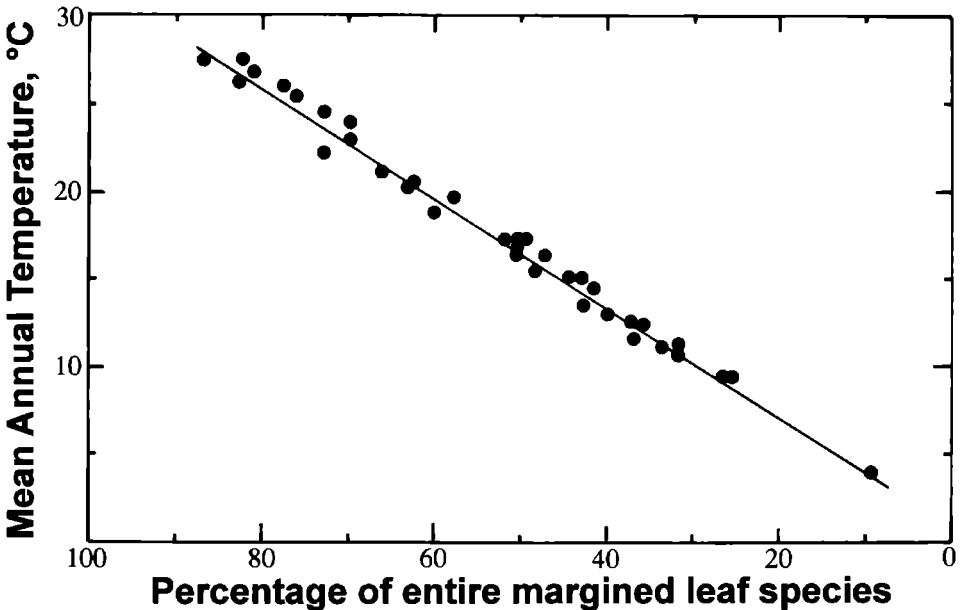

Fig. 1: Plot of mean annual temperature (MAT) against the percentage of leaf margin types (from WOLFE, 1979).

phology of a leaf is always a compromise between conflicting constraints (for example the advantage of having a large leaf surface area for light interception is moderated by evapotranspirational stresses and structural costs) a single character analysis provides only a partial, and possibly erroneous, climatic signal.

2.3. CLAMP

In an attempt to overcome these limitations and to obtain palaeoclimatic data from the leaf flora WOLFE (1993, 1995) developed a multi-character leaf physiognomic technique. Correspondence Analysis, a multivariate statistical ordination tool, was used to analyse 29 leaf characters found in modern taxa from present day vegetation at 106 sites for which climatic conditions were known from the meteorological observations. Wolfe was able to identify those characters that were most strongly correlated with climatic variables. These variables included mean annual, warm month mean, and cold month mean temperatures, mean annual, mean growing season, mean monthly growing season, and precipitation during the three consecutive driest months. Wolfe called this database and multivariate analysis Climate-Leaf Analysis Multivariate Program (CLAMP).

We have used the CLAMP methodology presented in WOLFE (1993) with some modifications. In CLAMP the architecture of woody dicot leaves from modern day vegetation growing under known climatic conditions is used as a reference data set against which to compare the architecture of leaves found in a fossil assemblage. There are now several of these datasets and they vary in size, geographical and climatic coverage. Here for comparability and appropriateness we use 103 modern Northern Hemisphere vegetation sites scored for 31 leaf characters (WOLFE, 1993, 1995; HERMAN & SPICER, 1996, 1997) and correlated with 8 climate variables. These variables are: mean annual temperature (MAT), warm month mean temperature (WMMT), cold month mean temperature (CMMT), mean annual precipitation (MAP), mean growing season precipitation (MGSP), mean monthly growing season precipitation (MMGSP), precipitation during the three consecutive driest months (3DRIMO), and length of the growing season (LGS). To be statistically reliable CLAMP requires the scoring of at least 20 leaf morphotypes at any given site. Whereas WOLFE (1993) originally used the indirect ordination engine of Correspondence Analysis, and consequently had to use subjective methods to position the climate vectors, we now use Canonical Correspondence Analysis (CANOCO) (TER BRAAK, 1986, 1987–92) which is a direct ordination technique that explicitly positions the climate vectors. CANOCO is used to identify and calibrate correlations between angiosperm leaf characters and climate variables.

CANOCO is a direct ordination method here used to order site, leaf character and environmental data in multidimensional space simultaneously; sites being ordered by their character scores, and characters by their distribution among the sites. The sites are, therefore, arranged relative to one another in multidimensional space using the physiognomic characters of the vegetation at that site; environmental data are not used to position the sites. Fig. 2, a shows 31–dimensional leaf character space collapsed to two dimensions. Axes 1 and 2 represent the two axes of greatest variation in the data so the plot is the least distorted projection from 31 dimensional space. The dots represent each of the 103 vegetation samples positioned relative to its neighbours based on the characters that are possessed by the leaves of at least 20 woody dicots in that vegetation.
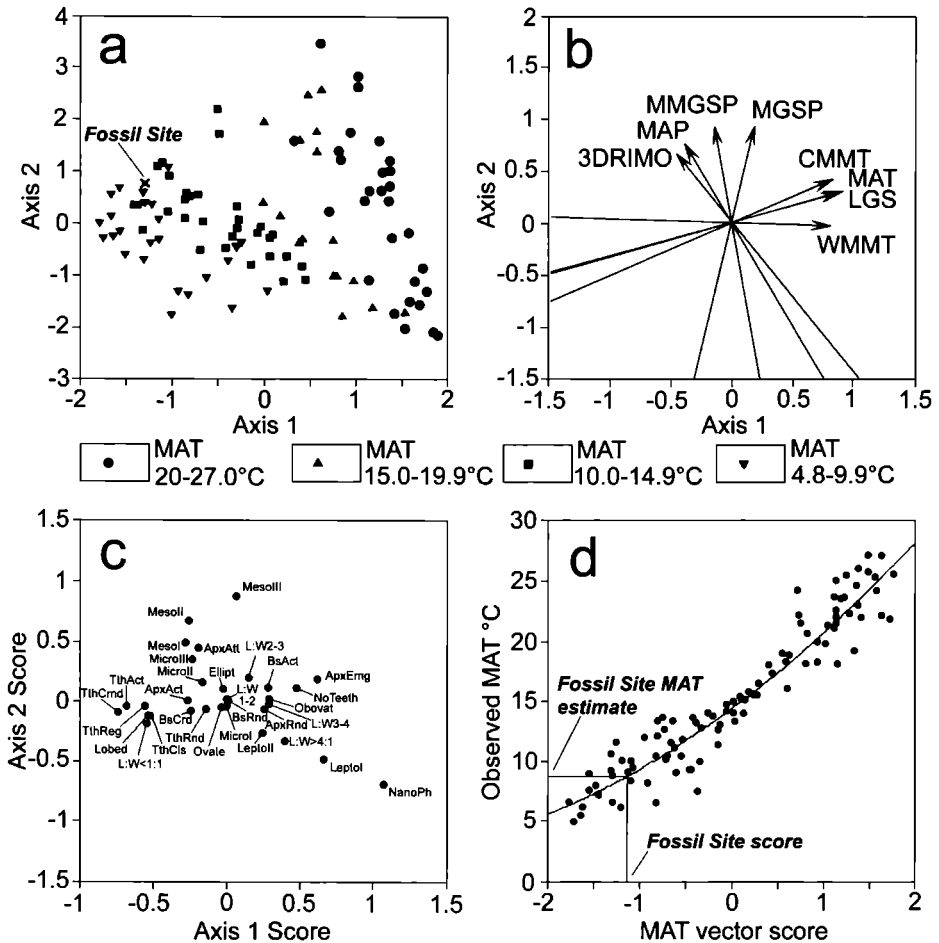
Fig. 2: Results of CLAMP analysis using CANOCO; a – distribution of modern and fossil sites in axis 1/axis 2 space as defined by leaf characteristics; b – the environmental vectors in axis 1/axis 2 space; vectors: 3DRIMO – precipitation during the three consecutive driest months, MAP – mean annual precipitation, MMGSP – mean monthly growing season precipitation, MGSP – mean growing season precipitation, CMMT – cold month mean temperature, MAT – mean annual temperature, LGS – length of the growing season, WMMT – warm month mean temperature; c – the distribution of leaf characters in axis 1/axis 2 space; leaf characters: ApxAct – apex acute, ApxAtt – apex attenuate, ApxEmg – apex emarginate, ApxRnd – apex round, BsAct – base acute, BsCord – base cordate, BsRond – base round, Ellipt – leaf elliptic, LeptoI – leptophyll I, LeptoII – leptophyll II, Lobed – lobed leaf, L:W<1:1 – length to width ratio less than 1:1, L:W1–2 – length to width ratio from 1:1 to 2:1, L:W2–3 – length to width ratio from 2:1 to 3:1, L:W3–4 – length to width ratio from 3:1 to 4:1, L:W>4:1 – length to width ratio more than 4:1, MesoI – mesophyll I, MesoII – mesophyll II, MesoIII – mesophyll III, MicroI – microphyll I, MicroII – microphyll II, MicroIII – microphyll III, NanoPh – nanophyll, Noteeth – no teeth, Obovat – leaf obovate, Ovate – leaf ovate, TthAct – teeth acute, TthCls – teeth close, TthCmd – teeth compound, TthReg – teeth regular, TthRnd – teeth round; d – MAT vector scores plotted against observed MAT values.

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The dots (Fig. 2, a) are coded to demonstrate that they are arranged according to the MAT experienced at each sample site; a mean annual temperature vector appears to run from left (low MATs) to right (high MATs). CANOCO explicitly positions the environmental vectors within this physiognomically defined vegetation space (Fig. 2, b). Fig. 2, c shows the positions of leaf characters as defined by their distribution between the different vegetation sites. An imaginary line connecting "NoTeeth" and "Teeth Compound" dots (Fig. 2, c) lies close to the MAT vector (Fig. 2, b) confirming that leaf margin characteristics do indeed correlate with MAT and that leaf margin analysis is actually a more primitive version of CLAMP. The "leaf size" line going from Nanophyl (small leaf) to MesoIII (large leaf) (Fig. 2, c) lies close to MAP vector (Fig. 2, b) as we would expect.

Fig. 2, a shows a fossil site (in this instance it is a Turonian flora from the Novaya Sibir Island, Arctic Russia) positioned in the leaf character space side by side with modern vegetation sites.The characteristics of the fossil leaves were scored in the same way as the modern leaves and added to the statistical analysis as "passive" samples. This means that their inclusion in the analysis did not disturb the structure of the "physiognomic space" as defined by the modern leaves. The position of the fossil site relative to those of the modern sites with known climates allows us to estimate, with a measurable degree of precision, the ancient climatic conditions under which the fossil flora grew. To do this, the environmental vectors (Fig. 2, b) are calibrated using modern sites with known climates. Fig. 2, d shows the relationship between distance along the MAT vector, in arbitrary units, and the observed MAT, for modern sites. The position of the fossil site along the MAT vector can be used to determine the ancient MAT by seeing where the vector position intercepts the regression line. Alternatively, an equation describing the regression curve can be used to calculate the unknown MAT.

The scatter of dots about the regression line indicates a statistical uncertainty of being able to estimate the correct MAT. In this instance one standard deviation of the residuals about the regression line is 1.8°C.

3. DATA AND DISCUSSION

The positions of 19 fossil floras of latest Albian to Senonian age are shown in Fig. 3. The review of these floras are in Budantsev (1992), Herman (1994, 1999), Spicer & Herman (1998), Spicer & Parrish (1990), Spicer et al. (1992) and Vakhrameev (1991). For each flora, except Vilui-1, there were 20 or more (up to 84 for the Grebenka Flora) leaf morphotypes analysed. Woody dicot leaf morphotypes were scored for as many of the 31 characters as were preserved. In a discussion below our results of CLAMP analysis of these floras are grouped according to their geologic age: latest Albian – Cenomanian floras, Turonian – Coniacian floras and Santonian – Campanian floras.

3.1. Latest Albian – Cenomanian Floras

Twelve fossil floras of latest Albian to Cenomanian were analysed using CLAMP (Fig. 3 and Tab. 1). These floras belong, according to Vakhrameev (1991), to two main phyto-

Fig. 3: Map showing the modern day positions of plant fossil sites of Europe, Asia and Alaska which were used in the CLAMP floral analysis.

choria: a Euro-Sinian Region, characterised by a subtropical climate, and a Siberian-Canadian Region, characterised by a temperate climate. Our CLAMP results are compatible with both Vakhrameev's qualitative characteristics of these climates and palaeolatitudinal position of the floral sites.

Leaves from two localities within the Peruc Flora (Tab. 1), Vysehorovice and Praha Mala Chuchle, represent florules of the same age, but different environments. Plant fossils from the locality Praha Mala Chuchle come from the fluvial sediments of a river bordered by slopes of Palaeozoic limestone bedrock, whereas those from the Vysehorovice locality come from fluvial sediments of a larger river meandering across an extensive lowland floodplain.

CLAMP analysis of these florules demonstrates the precision of the technique. Both localities yield very similar predicted temperatures (19 and 20°C), but show differences in precipitation. There are two reasons for this difference. The first is caused by the presence of a comparatively high number of broad-leaved riparian species in the Vysehorovice florule, while the Mala Chuchle locality possesses a more mixed population of riparian and "upland" species from better drained substrates. Taphocoenoses from swamps and river flood plains tend to have a minimal influx of upland taxa. The second reason relates to the microclimates experienced by the two vegational communities. In well drained sites water can occasionally be limiting to the plants if periodic dry seasons

FOSSIL FLORA	Palaeo-latitude	Mean Annual Temperature (°C)	Warm Month Mean Temperature (°C)	Cold Month Mean Temperature (°C)	Mean Annual Precip. (mm)	Mean Growing Season Precip. (mm)	Mean Monthly Growing Season Precip. (mm)	Precip. during 3 Consecutive Driest Months (mm)	Length of Growing Season (months)
KULDENEN-TEMIR Latest Albian	45°N	9.6	18.9	0.8	1400	562	83.1	187.6	6.0
PERUC Cenomanian	40°N	17.3	22.7	11.6	1468	1033	108.1	180.2	9.5
VYSEHOROVITSE Cenomanian	40°N	19.4	21.9	15.7	2248	1966	186.6	367.6	10.4
CHUCHLE Cenomanian	40°N	20.2	24.4	15.2	1432	1163	111.5	165.4	10.7
TEREKTY-SAI Cenomanian	45°N	14.7	21.3	8.2	1475	894	102.4	188.8	8.4
VILUI RIVER-A Cenomanian	62°N	12.7	19.4	6.4	1951	1173	137.9	313.6	7.5
VILUI RIVER-B Cenomanian	62°N	12.8	19.6	6.2	1803	1048	125.0	275.0	7.5
ARMAN RIVER Latest Albian - Cenomanian	72°N	8.0	18.2	-1.9	1339	652	72.0	173.0	5.3
YUKON-KOYUKUK Cenomanian - ? Turonian	72°N	13.5	19.4	7.9	2188	1443	161.7	374.0	7.8
GREBENKA RIVER Latest Albian - Early Cenomanian	76°N	13.0	20.8	5.5	1298	663	83.8	153.7	7.6
GREBENKA-22 Latest Albian - Early Cenomanian	76°N	12.3	20.2	4.7	1377	686	88.4	173.4	7.3
GREBENKA-MIX Latest Albian - Early Cenomanian	76°N	11.2	19.7	3.1	1381	632	86.0	177.7	6.8
Standard Deviation		1.8	3.1	3.3	430	280	23	70	1.1

Tab. 1: Climate data for the latest Albian – Cenomanian floras of Eurasia and Alaska.

are a feature of the climate. However, in lowland areas the water table is extensive and close to the surface so the plants rarely experience water stress. Moreover, evaporation from the wet ground, together with evapotransiration from water replete vegetation produces a humid local microclimate and this is reflected in the leaf physiognomy. These differences are detected, in this instance, in the CLAMP analyses.

Similar analysis of two florules within the Grebenka Flora, Grebenka-22 and Grebenka MIX, and within the Vilui Flora, Vilui -A and Vilui -B (Fig. 3 and Tab. 1), which yield temperate moist climate signals with no suggestion of pronounced seasonal droughts, show no significant differences either in temperatures or precipitation. Therefore, when analysing mesothermal subtropical Cretaceous floras, such as the Peruc Flora, it is particularly important to consider sedimentological conditions of each locality. A combi-

nation of different florules in the analysis averages results for palaeotemperatures and mean annual precipitation, but cannot reflect detailed climatic signals such as seasonal droughts. When analysing humid mesothermal maritime margin Cretaceous floras without a pronounced seasonal drought, such as the Grebenka or Vilui floras, there appears to be little significant difference in the climate signal as captured by leaves preserved in different depositional environments.

At this point it is worth also considering the issue of sample sizes. Ideally, as many samples should be analysed as possible because local taphonomic variables that would preferentially sample specific communities, such as streamside or mire vegetation, are averaged out. A larger sample size also reduces statistical uncertainties associated with the method. However this raises the problem of isochronicity (particularly marked in non-marine environments) and if vegetation samples of significantly different ages are inadvertently analysed this introduces a genuine error into palaeoclimatic determinations.

Two Kazakhstan floral sites – Kuldenen-Temir and Terekty-Sai (Fig. 3) – are situated close to each other, but the Cenomanian Terekty-Sai Flora reflects a significantly warmer climate than that of the late Albian Kuldenen-Temir Flora (Tab. 1). This is probably due to a global cooling at the end of Albian, reported from different regions of the Northern Hemisphere (VAKHRAMEEV, 1991).

The Grebenka and Arman floral sites are also situated close to each other, and are probably of the same, or very similar, age. However, the Grebenka Flora grew on the coastal plain close to the Proto-Pacific, whereas the Arman Flora comes from the Okhotsk-Chukotka volcanogenic belt and reflects climate conditions of an inter-montaine basin or plateau.

The Grebenka and Yukon floras both grew on coastal plains adjacent to the northern Proto-Pacific, but the Yukon Flora reflects a slightly warmer and significantly wetter climate than that of the Grebenka Flora (Tab. 1). This difference may have been due to a warmer eastern northern Pacific with a northern counterclockwise gyre, just as exists in the northern Pacific today and/or higher palaeolatitude of the Grebenka Flora.

There is more or less good agreement between geologic data, such as CLAMP analysis of fossil floras (SPICER & HERMAN, 1998), other palaeontologic signals, sedimentology, etc. (CHUMAKOV et al., 1995), and the predictions of AGCMs configured for the Cenomanian in coastal areas of Alaska, North-eastern Asia, Kazakhstan and Central Europe (VALDES et al., 1999). However, based on CLAMP, the Cretaceous continental interior of Asia (Vilui Basin) appears remarkably equable, with winter temperatures well above freezing for all but the coldest days, and a warm summer (Tab. 1). This is in marked contrast with the wide annual temperature ranges seen in continental interiors today, and with the results from variously configured climate models. According to the models, in the Cenomanian-Turonian the Vilui Basin was characterised by hot summers (WMMT between 26 and 36°C) and cold winters (CMMT between -16 and -21°C) (VALDES, SPICER et al., 1999; SPICER et al., submitted). Another difference between the data and the models is that CLAMP (in agreement with our palynological and clay mineralogical data) predicts a moderately wet regime year round, whereas the climate models frequently suggest drier conditions.

That there is reasonably good agreement between the data and the model in coastal areas indirectly confirms the accuracy of the CLAMP analysis and the ability of plants to provide quantitative climate signals. This is because the model was constrained by sea

FOSSIL FLORA	Palaeo-latitude	Mean Annual Temperature (°C)	Warm Month Mean Temperature (°C)	Cold Month Mean Temperature (°C)	Mean Annual Precip. (mm)	Mean Growing Season Precip. (mm)	Mean Monthly Growing Season Precip. (mm)	Precip. during 3 Consecutive Driest Months (mm)	Length of Growing Season (months)
NORTH-WESTERN KAMCHATKA Late Turonian	73°N	7.1	17.8	-3.6	1320	578	66.0	163.0	4.8
NORTH-WESTERN KAMCHATKA Coniacian	73°N	9.2	18.7	0.1	1383	766	82.0	189.0	5.8
TYLPERGYRGYNAI Early Coniacian	74-76°N	8.2	18.6	-1.8	1187	383	64.3	143.7	5.4
NORTH SLOPE, ALASKA Coniacian	78°N	13.1	20.2	6.2	1582	887	107.1	219.0	7.6
NOVAYA SIBIR' ISLAND Turonian	82°N	8.8	18.6	-0.6	1344	488	76.7	177.4	5.6
Standard Deviation		1.8	3.1	3.3	430	280	23	70	1.1

Tab. 2: Climate data for the Turonian and Coniacian floras of Eurasia and Alaska.

surface temperatures determined from oxygen isotope studies. However, away from the coastal areas the model predictions do not match those from foliar physiognomy, palynology, clay mineralogy and sedimentology (SPICER et al., submitted) and may indicate that the Cretaceous atmospheric dynamics were significantly different to those of the Present and those simulated by AGCMs.

3.2. Turonian – Coniacian Floras

The results of CLAMP analysis of two fossil floras of Turonian age and three Coniacian (Fig. 3) are shown in Tab. 2. It is interesting that the most northerly samples for each time horizon, Turonian and Coniacian, exhibited the highest values for mean annual temperature, cold month mean temperature and all precipitation data. Warm month mean temperature (WMMTs) estimates are uniformly between 17.8 and 20.2°C, but CMMTs range from -3.6 to 6.2°C. A warm MAT in conjunction with a long dark polar winter appears anomalous. A possible explanation for this unusual combination of darkness and warmth lies in the WMMT and CMMT statistics. The WMMT values are remarkably similar but the CMMT temperatures are significantly different; winter temperatures remain above freezing in northern Alaska while those in Kamchatka drop to freezing in the Coniacian and to -3.6°C in the Turonian. This strongly implies a mechanism for maintaining winter warmth at sites close to the Arctic Ocean.

The data suggest that an Arctic Ocean maintained Northern Alaska coastal temperatures above freezing, locally reversing the equator to pole temperature gradient; a phenomenon not seen in the northern proto-Pacific. The reverse equator to pole
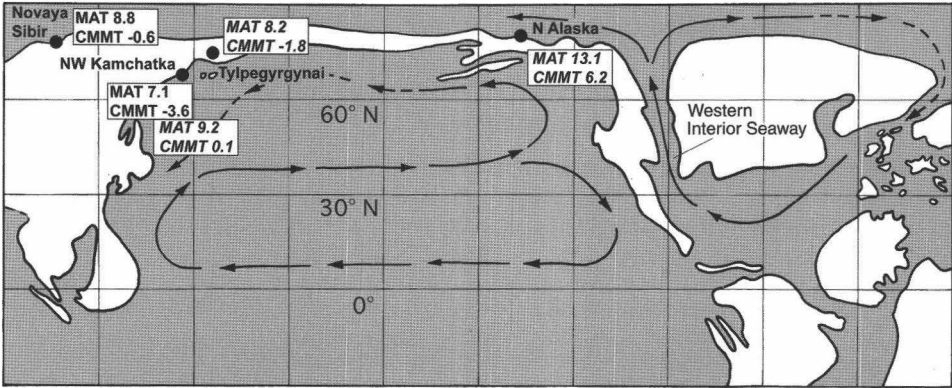
Fig. 4: Locations of the Turonian and Coniacian floras of North-eastern Asia and Northern Alaska plotted on a Coniacian coastlines map derived from FUNNEL (1990). Mean annual (MAT) and cold month mean (CMMT) temperatures are shown in italics for the Coniacian floras and in plain text for the Turonian ones. Proposed ocean circulation is shown by arrows: solid arrows represent warm currents; dashed arrows cool currents.

temperature gradient in Northern Alaska and North-eastern Asia is also predicted by an atmospheric-ocean GCM configured for Turonian time (SPICER et el., 2001). Given the lack of solar insolation for three to four months each year (ANONYMOUS, 1978) this strongly suggests there must have been significant poleward ocean heat transport despite shallow and narrow connections with the rest of the world's ocean system (Fig. 4). A warm Arctic Ocean would have damped seasonal temperature oscillations; while it would have contributed little to summer warmth, but maintained winter temperatures above freezing. High evaporation would also have formed extensive cloud cover which could have contributed to maintaining warm polar temperatures. Precipitation in Alaska, Northern and North-eastern Asia was predicted by CLAMP to have been high, and this is compatible with the extensive coal formation (CHUMAKOV et al., 1995; KRASSILOV, 1992; ZHARKOV et al., 1995) and AGCM results (VALDES, SPICER et al., 1999). This wet pole is a manifestation of substantially different precipitation patterns to Present and reflects a very weak polar high pressure cell.

The Turonian has been reconstructed as being a cool interval in the early Late Cretaceous and the Coniacian warmer (HERMAN, 1994; SPICER & PARRISH, 1990; SPICER et al., 1992). Both were times of high relative sea levels and transgression in the Western Interior Seaway (HANCOCK & KAUFFMAN, 1979). The Alaskan Coniacian CMMT of 6.2°C may have been due the site's proximity to warm water entering the Arctic Ocean from the equatorial Tethys Ocean via the Western Interior Seaway, with a return path southward through the proto North Atlantic (Fig. 4). To maintain this air temperature throughout the winter darkness the adjacent sea surface temperature must have been at least 7–8°C. The Novaya Sibir' CMMT may have been cooler because of its greater distance along the current path from the Western Interior Seaway (Fig. 4), the cooler Turonian, and the high palaeolatitude of the site. The nearby Arctic Ocean sea surface

temperature cannot have been below 0°C. The relative winter coolness of the Kamchatkan sites argues against atmospheric poleward heat transport and may have been due to a cooler northern Pacific with a northern counterclockwise gyre (Fig. 4), just as exists in the northern Pacific today. A second possible explanation for the Kamchatka temperatures is that the region experienced the marginal effects of colder air masses developed in the winter over the Asian continental interior. Northern Alaska was isolated from the influence of both the proto-Pacific Ocean and the Asian interior air masses by the newly uplifted Brooks Range.

3.3. Senonian (Santonian – Campanian) Floras

We have analysed two Central European fossil floras of Senonian age (Fig. 3 and Tab. 3).

The Grünbach Flora comes from the Grünbach Formation of the Gosau Group in the Grünbach-Neue Welt Basin in the Eastern Alps, Austria. The probable early Campanian age of this flora is based on the correlation of plant-bearing deposits with marine biostratigraphy and on palynological data (EGGER et al., 2000; SUMMESBERGER, 1997). The rich shallow-marine fauna of the Gosau Group belongs to the Tethyan bioprovince. The palaeogeographic situation is that of a large island with unknown relief. Terrestrial freshwater swamps and shallow water sediments indicate a relatively large deltaic plain. According to the CLAMP results, the Grünbach Flora experienced a humid sub-tropical to maritime mesothermal climate with warm/hot summers and short relatively dry, but not arid, seasons. This is corroborated by lithological climate indicators as well as by the presence of large foraminifers, rudists, corals and a reptile fauna (carnosaurs, iguanodons, pterosaurs, scelidosaurs and crocodiles) in the Santonian-Maastrichtian of the Grünbach Basin.

Palaeomagnetic directions from the Gosau K/T boundary beds in the Elendgraben near Salzburg, Austria indicate a palaeolatitude of the Gosau Basin of 32°N (PREISINGER et al., 1986). A recent palaeomagnetic investigation yielded a palaeolatitude of the Grünbach Basin about 1000 km south of the present day position of the plant-bearing deposits (SUMMESBERGER, 1997). To check this hypothesis, we decided to compare the

FOSSIL FLORA	Palaeo-latitude	Mean Annual Temperature (°C)	Warm Month Mean Temperature (°C)	Cold Month Mean Temperature (°C)	Mean Annual Precip. (mm)	Mean Growing Season Precip. (mm)	Mean Monthly Growing Season Precip. (mm)	Precip. during 3 Consecutive Driest Months (mm)	Length of Growing Season (months)
ZLIV, KLIKOV, HLUBOKA Senonian	40°N	15.6	22.2	9.0	1284	780	88.6	144.1	8.7
GRÜNBACH Early Campanian	?	15.3	21.8	8.8	1373	840	95.2	164.1	8.6
Standard Deviation		1.8	3.1	3.3	430	280	23	70	1.1

Tab. 3: Climate data for the Senonian (Santonian – Campanian) floras of Eurasia.

Grünbach palaeoclimate with those obtained from CLAMP analysis of Senonian flora of Zliv, Klikov and Hluboka, Czech Republic (NEMEJC, 1962; NEMEJC & KVACEK, 1975). Despite the different taxonomic composition and angiosperm leaf forms in these two floras, we obtained identical palaeoclimatic results, both for palaeotemperatures and precipitation (Tab. 3). Therefore, our CLAMP results do not support the idea that the Grünbach Flora existed 1000 km south of the present day position of the Grünbach Basin. However, our data do not argue against this idea, because both Czech Senonian and Grünbach floras reflect climates of two relatively small islands the climates of which were considerably influenced by the warm Tethys Ocean. Moreover, we cannot be sure that these floras are of the same age; the Grünbach Flora may reflect a relatively cooler time interval within the Senonian and therefore could have had a more southerly position despite the similarity of temperature.

4. CONCLUSIONS

Within the last decade a potentially powerful technique has been developed that provides both thermal and hydrological quantitative palaeoclimate data. Known as Climate Leaf Analysis Multivariate Programe (CLAMP), this technique decodes the climatic signal inherent in the physiognomy of leaves of woody dicotyledonous plants. It was developed as an evolutionarily robust, accurate, and precise tool for direct atmospheric palaeoclimate determinations over land, and as such complements marine-based climate proxies. The CLAMP methodology provides a framework for interpreting ancient vegetation in quantitative climatic terms. It is a technique that is both explicit and repeatable. It can provide estimates of climatic parameters with quantified uncertainties. In its present form CLAMP is a tool that allows us to predict what climatic conditions would be required to support a fossil flora if it grew today. Multivariate statistical analysis of fossil leaves complements isotopic analysis because it is not prone to diagenetic alteration, requires only the leaf impression (not original organic material), provides information on atmospheric rather than marine conditions, can yield a range of temperature and precipitation data, and relates to conditions over land.

Our data shows distinct variations and trends of warming and cooling. Late Cretaceous European floras demonstrate that the Cenomanian was warmer than the Santonian-Campanian, while Asiatic floras show that in general the latest Albian and Turonian-Coniacian were cooler than the Cenomanian. Late Turonian climate cooling appears to be a global phenomenon (VOIGT, 2000). Therefore in Europe and Asia the Cenomanian was probably the warmest stage of the Late Cretaceous over land. This is corroborated by palaeoceanological data (BARRERA, 2000; HUBER et al., 2000; KRASHENINNIKOV & BASOV, 1985).

In moist regimes without a pronounced seasonal drought, and provided the species diversity is high, there appears to be little significant difference in the climate signal as captured by leaves preserved in different depositional environments. However, for warmer and seasonally drier regimes CLAMP is able to distinguish between microclimates experienced by different florules or plant communities.

Existing numerical climate models fail to reproduce the qualitative and CLAMP deduced quantitative continental interior conditions under greenhouse climates. This

raises serious issues concerning the reliability of using such models to predict Eurasian conditions during, and following, future possible global warming. The uncertainties associated with such model results need to be quantified as does the reliability of CLAMP when winter temperatures are very low (i.e. less than -10°C).

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