The Late Cretaceous continental interior of Siberia: a challenge for climate models

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Abstract

Geological evidence from the Late Cretaceous continental interior of the Vilui Basin, Siberia suggests a far wetter, warmer, and more equable annual climate than General Circulation Models (GCMs) can reproduce. The disparity cannot be bridged by the uncertainties inherent in either the models or the geological climate proxies. This implies the mismatch is genuine and that either 1) we have systematic errors in the interpretation/calibration of the climate proxies, and/or 2) lack of full knowledge of the boundary conditions needed for GCM models simulations of this period, and/or 3) an insufficient understanding of the nature of the coupled atmosphere-ocean-biosphere system and its representation within climate models during warm climate epochs. If it is

the third explanation, this would have important implications for the prediction of future climates and would suggest that we may currently be underestimating future climate change in such regions.

Keywords: climate modeling, palaeoclimate proxy data, Late Cretaceous, continental interior, palaeobotany.

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1. Introduction

Climate models are now widely used for macro-economic decision making (e.g.[1]), These models show considerable skill at simulating the last 150 years. However, climate models are undeniably imperfect because they represent necessary simplifications of the real world and we have limited knowledge of some processes. Imperfections can be measured in terms of uncertainty arising from factors intrinsic to the model (model inadequacy) and extrinsic uncertainties such as our ability to properly describe boundary conditions, forcing factors, and initial conditions.

The reasons for model intrinsic uncertainty are several and arise from the simplifications that are 1) associated with the model missing or imperfectly representing all of the processes inherent in the real world such as stratospheric processes, atmospheric chemistry, vegetation dynamics etc. and 2) those associated with fine spatial scales not resolved by the model. Whether predicting the future or retrodicting the past, numerous

Earth system processes such as ice dynamics, ocean dynamics or even growth of vegetation, operate over timescales measured in centuries to millennia. To integrate over such intervals simplifications (parameterizations) are necessary to facilitate computation. Coarse spatial scales are also inevitable for climate simulations because of the scale of the problem (global) and the complexity of the processes represented within a modern Earth Systems model.

Comparing model simulations against palaeoclimate reconstructions is one method for evaluating the ability of climate models to correctly represent climate change processes, and to better quantify the uncertainties associated with simulations of climate regimes that differ from those of the present. There is a broad literature for such model-data comparisons for the last millennium[2], Quaternary[3], and pre-Quaternary[4]. The first two time periods have extensive high-quality and relatively well-dated samples that are ideal for testing climate models. However, the climates during these periods were generally similar to or colder than present day. Within the Quaternary there are no time periods that are year round substantially warmer than the modern, yet there are many non-linear feedbacks in the climate system that are potentially temperature dependent. For instance, water vapour feedbacks are thought to be more important in a warmer climate than a colder climate and that the hydrological cycle in at least one widely used model might be inadequate at high pCO_2[5]. With the observed current warming being most strongly expressed at high latitudes and in continental interiors, it is essential that we test climate models against climate regimes that were markedly warmer than today. For this we need to look into the pre-Quaternary, and the extreme warmth of the Cretaceous and Eocene provides a demanding test of climate models.

Previous model-data studies for the so-called “equable” climates of the Cretaceous and Eocene have highlighted a qualitative problem associated with warmth of high latitudes[6-9]. Diverse data suggest that high latitudes were much warmer than present and more “equable” in that the summer-winter range of temperature was much reduced. Climate models have focused on experimentation with extrinsic uncertainties concerning boundary conditions such as palaeogeography, atmospheric composition and vegetation type, distribution and associated feedbacks [6-9]. Despite considerable effort using an array of models and boundary conditions, understanding the inability of models to correctly reproduce high latitude warmth and equability in continental interiors for past greenhouse climates, particularly the Late Cretaceous and Palaeogene, has so far proved intractable and has become a “classic” problem in palaeoclimatology [9]. Elevated CO_2 combined with dynamic vegetation feedbacks [9] have gone some way to reproducing high latitude warmth and high precipitation regimes evidenced by the geological record [10-14], but still the continental interiors present an enigma irrespective of which time period is under scrutiny. To better define the model - data mismatch quantitative estimates of a range of palaeoclimate variables are required from continental interior sites.

There is a common perception that there is a lack of geologic palaeoclimate data from the continental interiors of past greenhouse worlds that might be used to verify climate model simulations [6, 7]. However, in middle to Late Cretaceous times, when other continents were largely submerged, most of Siberia remained above sea level and constituted the only truly large continental region of the Northern Hemisphere [15, 16]. Middle and Late Cretaceous plant fossil museum material from Russian expeditions provided intriguing, but limited, palaeoclimate data from the interior of this region [17-19].

Collection size and lack of sedimentological context raised doubts as to how representative such material was of the Cretaceous vegetation and climate of the area. We therefore traversed the Vilui Basin of Central Siberia (Fig. 1) seeking potential middle to Late Cretaceous paleoclimate indicators such as plant fossils, palynomorphs and clay minerals. Paleomagnetic sampling was also undertaken to help constrain the paleolatitudinal position of the basin.

[Fig. 1 near here]

2. The sedimentary successions

More than twenty exposures, 30 - 80 m high and up to several kilometers in lateral extent, were surveyed along the banks of the Lindya, Vilui and Tyung rivers (Fig. 2). Early Cretaceous sediments exposed in the peripheral parts of the basin encompass stream channel sandstones interbedded with floodplain fines, autochthonous coals and stacked paleosols. Middle to Late Cretaceous successions of the Timerdyakh Formation in the center of the Vilui Basin, show strong and upwardly increasing channel cannibalism and reworking of floodplain deposits. Bank failures at the time of deposition resulted in river channel deposits containing abundant mud and peat balls, slumped fossil tree bases, drift wood and log jams, and reworked siderite concretions. Rare immature paleosols with leaf mats, rooting, destratification and slickensides represent sites where ancient vegetation grew. In the central parts of the Vilui Basin, the Timerdyakh Formation is overlain by pebbly sandstones of the Linde Formation, which is dominated by minimally transported kaolinized basement material that reflects strong chemical weathering and tectonic rejuvenation. Due to the pronounced channel amalgamation muddy sediments are rare. However, 25 analyses with respect to clay mineralogy in Early Cretaceous mudstones and detrital mud balls show sub-equal kaolinite and smectite contents, while in the middle to Late Cretaceous (the Timerdyakh and Linde formations) kaolinite dominates, sometimes together with illite, but without any notable smectite content. This trend probably reflects increasingly humid weathering conditions from the middle Cretaceous onwards [20].

[Fig. 2 near here]

Although only weakly magnetized, the Timerdyakh sediments yielded a range of paleolatitudes between 71.5 and 73.2°N. This is slightly more northerly than the values derived from plate rotations on a regional scale and given the weak magnetization we have used plate rotations based on the Chicago PalaeoAtlas Project throughout our modeling and data analysis.

3. Floral remains

Palynological investigations of the Timerdyakh Formation reveal a high floral diversity, ferns and angiosperms being most strongly represented. Of over 170 taxa, 61 are spores (at least 33 represent ferns), 14 are gymnosperm pollen, 10 are pollen attributable to monocotyledonous taxa (including two probable palm species), and approximately 90 represent pollen of dicotyledonous plants. Not more than 10% of the assemblage shows evidence of reworking from pre middle Cretaceous rocks, and palynomorphs such as *Azonia calvata* (Samoilovitch) Wiggins suggest some of our samples are of latest Campanian /earliest Maastrichtian age [21]. Both *Aquilapollenites* forms and representatives of the *Normapolles* group are present. The remarkable diversity of palynomorphs, together with presence of taxa whose nearest living relatives are thermophyllic such as representatives of the Mastixiaceae, Araliaceae, Arecaceae and Cercidiphyllaceae, indicates warm and humid climatic conditions throughout the period of deposition of the Timerdyakh Formation (latest Albian to Maastrichtian). This warm temperate climate qualitatively indicated by both pollen and clay mineralogy (Section 2) is in marked disagreement with GCM retrodictions[6-9]. However, a fundamental understanding of the causes of disparity between climate models and geological observations in greenhouse world continental interiors requires quantification of the mismatch to determine if it is real, or can be explained by inherent uncertainties in the models and/or geological data. For non-marine environments measurement of the mismatch can be achieved using foliar physiognomy as a quantitative climate proxy, particularly as it can provide an array of different climate parameters. Vilui Basin leaf material from existing museum collections of known provenance was combined with newly collected material and analyzed using the Climate Leaf Analysis Multivariate Program (CLAMP) [22-27].

4. CLAMP analysis

Analysis of Timerdyakh Formation leaves (77 well preserved specimens representing 25 morphotypes and all assigned on comparative Russian morphological studies to a Cenomanian age) placed them within the physiognomic space occupied by modern temperate vegetation, unlike test samples from the modern Vilui Basin vegetation that plot in isolation (Fig. 3). These tests samples confirm that the modern foliar physiognomic adaptations to extreme annual temperature range [26] are not seen in the Cretaceous fossils and that the modern dataset used (PHYSG3AR) was appropriate for obtaining reliable paleoclimate data. The CLAMP analysis yielded a mean annual temperature (MAT) of 13.1±3.5°C (2σ), a warm month mean (WMMT) of 21.1±3.6°C, and a cold month mean temperature (CMMT) of 5.8±5.1°C. The length of the growing season (7.4±1.7 months) is more a function of the high paleolatitude light regime than temperature. The growing season total precipitation (827±632 mm), the mean monthly growing season precipitation (133±73 mm), the three consecutive wettest months precipitation (495±274 mm) and the three consecutive driest months precipitation (293±176 mm), all suggest a moderately wet regime year round, but the uncertainty in reconstructed precipitation is high. This wetness is also reflected in the mean annual relative humidity (77.5±16.3%).

[Fig. 3 near here]

5. Climate Modeling

For any rigorous test of climate modeling using paleo data, it is essential to quantify the uncertainty in the simulations caused by uncertain boundary conditions. Therefore, we have performed an extensive suite of simulations for the Cretaceous, using various versions of the Hadley Centre climate model. This is a state-of-the-art model widely used for future climate change prediction. More specifically, we have used 3 sets of paleogeographies corresponding to the Cenomanian, Turonian, and Maastrichtian (Markwick unpublished). We have also investigated the sensitivity of the model to different orbital conditions (using orbits equivalent to 9000 year BP, and 115000 years BP as examples), different CO_2 (ranging from 2x pre-industrial to 6 x pre-industrial) and CH_4 (pre-industrial to 6x pre-industrial), different ocean surface conditions (using prescribed sea surface temperatures corresponding to warm tropics and poles, or with a slab ocean model with prescribed ocean heat transports, or using fully coupled atmosphere-ocean simulations using the HadCM3L model with an ocean model resolution of 3.75^o x 2.5^o x 20 levels), and different vegetation conditions (ranging from shrubs everywhere, to predictive modeling using a dynamic vegetation model TRIFFID [28]). A total of 42 simulations were considered. For each simulation, we calculated the WMMT, CMMT and MAT at the appropriate paleolongitude/paleolatitude corresponding to the Vilui Basin (Fig. 4). We then computed the mean, standard deviation, and absolute maximum and minimum for each variable and these are shown on figure 5, separated into different time periods. A greater range of sensitivity experiments have been performed for the Maastrichtian and Turonian and this is the principal reason that the standard deviation of model results for the Cenomanian is smaller.

[Figs. 4 & 5 near here]

In addition to these boundary condition uncertainties, there are also uncertainties due to model physics. We can make a conservative measure of these by comparing a modern day simulation to observations. For continental interiors, the typical model bias is in the range of 2-4 C^o [29]. There the model uncertainties are at least of the same order as those presented here for CLAMP (which are similarly a conservative measure of uncertainty, since they currently do not include estimates of calibration errors associated with evolutionary processes or alternative environmental influences on leaf morphology, such as CO_2).

6. Discussion

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. This is in marked contrast with the wide annual temperature ranges seen in continental interiors today [26]), and with the results from variously configured climate models [9, 30].

Although the uncertainty in both CLAMP and GCM model results are large, the extent of the mismatch greatly exceeds the quantifiable errors in the methods. Hence, this comparison is an important test of the climate models in a previous warm period, and is clearly showing that there is a major model-data mismatch that cannot be simply explained by the inevitable uncertainties associated with both models and proxy climate data interpretation. Furthermore, this mismatch is not confined to the Hadley Centre model. Previous climate model simulations using a variety of different climate models and boundary conditions for the Late Cretaceous and Early Eocene [6, 9, 30] all show similar results. Hence this is a robust mismatch that cannot be simply explained by uncertainties in GCM boundary conditions, or by the modest differences in parameterization schemes and resolution between different GCMs.

One of the model simulations which is nearest to the winter CMM temperatures is for a Maastrichtian fully coupled atmosphere-ocean-vegetation simulation with 4 x CO_2 and an Arctic ocean fully linked to the other ocean basins (via the western interior seaway) [31]. This resulted in a significant warming of the Arctic and corresponding warmth in Eurasia. However, this is not a simple result of a warm Arctic because other atmosphere simulations with prescribed warm Arctic oceans did not result in such warmth. A fuller discussion of this simulation is in preparation. Nonetheless, even for this simulation there is still more than a 10^{o}C discrepancy with the CLAMP data.

The causes of this mismatch are difficult to identify, but can be simply categorized into three groups of errors. Firstly, it is possible that we continue to incorrectly interpret the data. Leaf morphological analysis is one of the very few techniques to produce quantitative estimates of terrestrial temperatures, and it is possible that we do not fully understand all of the environmental and other controls on this proxy. The biophysical processes that result in plant traits having a relationship with their environment are numerous (e.g. [32]) and, for instance, it is possible that changes in atmospheric CO_2 could influence the calibration by changing the slope or intercept, although this seems unlikely [33]. However, in coastal regions, CLAMP based reconstructions compare favorably with those from the marine realm (particularly oxygen isotope data) and the results are also consistent with crocodilian data, although these are not available in the key continental interior regions. Also CLAMP has been demonstrated to give similar results to other palaeobotanical methods for reconstructing temperature [34, 35] but where differences exist CLAMP tends to yield cooler estimates. Palaeoelevation estimates derived from CLAMP enthalpy estimates also compare well to those derived from oxygen isotopes [36, 37]. An additional complication is that the greatest model-data mismatch occurs with the cold month mean temperature. CLAMP is one of the few techniques that attempts to estimate this quantity even though it could be argued that dormancy may render many woody plants insensitive to winter temperatures. The fact that the CMMT is reflected, albeit with increased error, in regimes where the winter temperatures fall below –40°C suggests that rates of spring warming might indirectly code for the CMMT in foliar physiognomy [26]. In the modern calibration dataset, CMMT is closely correlated to MAT, since for our present climate the warmest mean annual temperatures occur in the tropics that have a low range of temperatures. However, the Vilui fossil leaves do not display those architectural features found in modern Siberian vegetation but are most similar to leaves in warm temperate regimes. Whether or not the CLAMP results contain systematic error the congruity between the CLAMP results, the interpretation of the clay mineralogy and the qualitative climatic interpretation of the palynoflora is striking.

A second group of problems are related to uncertainties in the boundary conditions used for these simulations. For instance, we have relatively good reconstructions of paleogeographies for these periods but very poor knowledge of atmospheric composition. Higher levels of greenhouse gases would warm the continental interiors but traditionally it has been difficult to achieve sufficient warming of the mid-latitude continents without overheating the tropics. In addition, the data cannot be dated to a specific part of an orbital cycle and hence it is possible that there have been a preservational bias towards time periods when the orbit corresponded to warm N. Hemisphere winters. However, it is difficult to believe that this is true for all of the collected samples. More likely is that fossil assemblages could accumulate over thousands of years and thus represent in some way “average” climatic conditions over large parts of orbital cycles.

A final group of problems are associated with the intrinsic properties of climate models. The most comprehensive versions now include detailed representations of the atmosphere, ocean, and vegetation. However, it is possible that the representations are oversimplified and there has been excessive tuning towards the modern climate regime. This introduces the need for parameterizations that go beyond those used for the present. Exploring parameter space in models configured to simulate present or near future conditions is an important and ongoing process involving small numbers of model versions [29] to grand ensembles e.g. climate*prediction*.net [38] but to date comprehensive explorations of parameter space for models attempting to reproduce past greenhouse conditions have not been undertaken. A further possibility is that the models are missing an "Earth Systems" process that is of minor importance today, but was important during past greenhouse epochs. An example of such a process could be hurricanes (e.g. [39]). These play a relatively small role in the overall energetics of the present day climate, but it has been proposed to be important mechanism during warm climate epochs, through their impacts on oceanic mixing [40, 41]. Hurricanes are too small to be resolved in the present generation of climate models, and their effect on the ocean mixed layer is also not parameterized.

The strength of the mismatch between model and data during these previous warm epochs of Earth history highlights an area of major concern. These time periods are unique in showing how the Earth system operated during intervals that were substantially warmer than the present, and where greenhouse gases are thought to have been a major contributor to the warming. The warmth of Quaternary interglacial periods are predominantly caused by changes in orbit which have a very different characteristic (seasonal) forcing to that implied for higher greenhouse gases [42]. Thus these pre-Quaternary periods are unique in testing the models in higher and warmer CO_2 environments.

The lack of agreement between models and data must be reconciled, and there is an urgent need to explore both the modeling and data questions associated with this controversy. Our quantification of the discrepancy highlights its magnitude and is indicative of the potential errors inherent in current models and parameterization of past and possible future greenhouse climates. The conservative systematic mismatch between the models and the data in which the models appear to impose a modern thermal regime (i.e., a large mean annual range and a low mean annual temperature) on the Siberian Cretaceous continental interior suggests that the models may well underestimate the magnitude of future climate change in such regions.

6. Methods and materials

Sedimentological, clay mineralogical, and palynological studies were performed according to standard procedures [43-47]. Paleomagnetic samples were obtained from 110 oriented samples from 10 outcrops of the Timerdyakh Formation along the Tyung and Vilui rivers and analyzed using standard techniques [14]. The Timerdyakh Formation deposits have very low magnetic properties. The most reliable data from these weakly magnetized sediments were obtained from 16 samples collected in outcrops along the Tyung River. Palynological samples were crushed with a mortar and pestle, and the resultant rock powder treated with standard wet chemical processes using HCl and HF. The organic extract was acetolyzed but was not sieved in order to retain palynomorphs smaller than10μm. Quantitative palynological data were obtained by point counting [45]. The CLAMP technique decodes the climatic signal inherent in the physiognomy of leaves of woody dicotyledonous plants by calibrating the numerical relations between leaf physiognomy and meteorological parameters in modern terrestrial environments. Using this calibration, past climatic data are determinable from leaf fossil assemblages. The statistical engine used is Canonical Correspondence Analysis (CANOCO v. 4.0), which is a direct ordination method that orders samples, in this case vegetation sites, based on a set of attributes. In CLAMP the attributes are the scores of the 31 leaf character states taken from more than 20 species of woody dicots in each vegetation site. The largest available calibration dataset was used here (PHYSG3AR obtainable from http://tabitha.open.ac.uk/spicer/CLAMP/Clampset1.html) that consisted of foliar physiognomic measurements and climate observations from 173 modern vegetation sites, predominantly Northern Hemisphere, and included low temperature sites comprising the “alpine nest”. The raw Vilui CLAMP scores and information on model configurations, including orbital parameters are available as supplementary data. The simulations with the Hadley centre model (HadAM3, HadSM3 or HadCM3L) used paleogeographies as in [7]. Vegetation was either prescribed as shrub over all land surfaces or was predicted using BIOME 4 [48] or TRIFFID ([28]). Sea surface temperatures were either a simple function of latitude constrained by oxygen isotope data, or predicted using a simple slab ocean model with ocean heat transport prescribed as modern, or were based on a fully coupled atmosphere/ocean simulation.

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Figure captions

Fig. 1. Geological map of the Vilui Basin. The Sangar Group (dotted) includes Lower Cretaceous strata. The Vilui Group includes the uppermost Albian to Maastrichtian Timerdyakh Formation and the Maastrichtian and possibly lower Tertiary Linde Formation. The ages of the formations are constrained by palynological and paleobotanical data. Numbered fossil localities are those of Vachrameev [17, 18].

Fig. 2. An approximately 30m high river bank outcrop showing amalgamating middle Cretaceous river channel fills (1-5) in cross-section at the Tyung River locality 421 (Fig.1) . Well-preserved fossil leaf assemblages were found in abandoned channel deposits (channel fill No. 3), and in rhythmical low-discharge (autumn) interbeds of seasonally active channels (channel fill No. 2). Preservation of delicate leaves suggests limited downstream transport prior to deposition.

Fig. 3. CLAMP Canonical Correspondence Analysis plot in axis 1/axis 3 space showing the separation of the samples representing modern Vilui Basin leaf physiognomy from that of the Cretaceous leaves. Open circles represent the positions of samples included in the Physg3ar modern calibration data set, primarily from northern hemisphere sites. The closed square represents the Vilui Cenomanian (Timerdyakh Formation) fossils. Closed circles represent the positions of samples of modern vegetation from the Vilui Basin [26]. The Vilui fossil sample is associated with Physg3ar samples derived from modern temperate environments. See supplementary data. Vector labels: MAT – Mean Annual temperature, WMMT – Warm Month Mean Temperature, CMMT – Cold Month Mean Temperature, LGS – Length of the Growing Season, GSP – Growing Season

Precipitation, MMGSP – Mean Monthly Growing Season Precipitation, 3DRY – precipitation during the three driest months, 3WET – precipitation during the three wettest months.

Fig. 4. Cenomanian January mean surface (2m) air temperature (°C) map derived from one of the suite of simulations, in this case using HadAM3 with a slab ocean heat transport similar to the modern. The position of the Vilui Basin is marked by a black diamond.

Fig. 5. Graph illustrating MAT, WMMT and CMMT temperatures predicted by CLAMP for the Late Cretaceous compared with MAT (closed squares), CMMT (open circles) and WMMT (closed circles) based on model predictions. Uncertainties (± 2σ) for CLAMP are illustrated by bands surrounding the lines denoting the means. Model uncertainties (± 2σ indicated by bars) were derived from the standard deviations about the mean of several model runs (4 in the case of the Cenomanian, 16 for the Turonian, and 20 for the Maastrichtian) with different boundary conditions.

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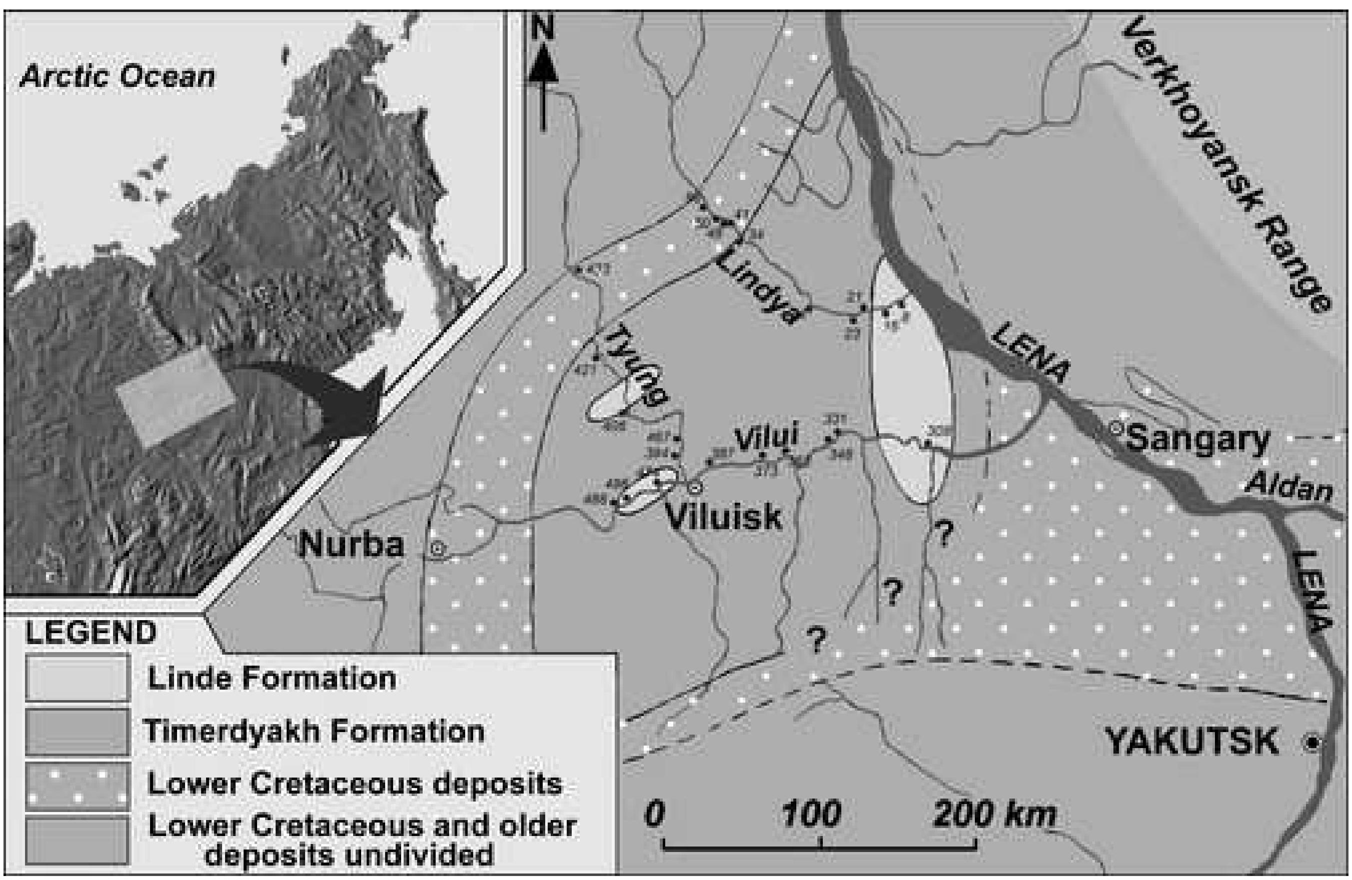

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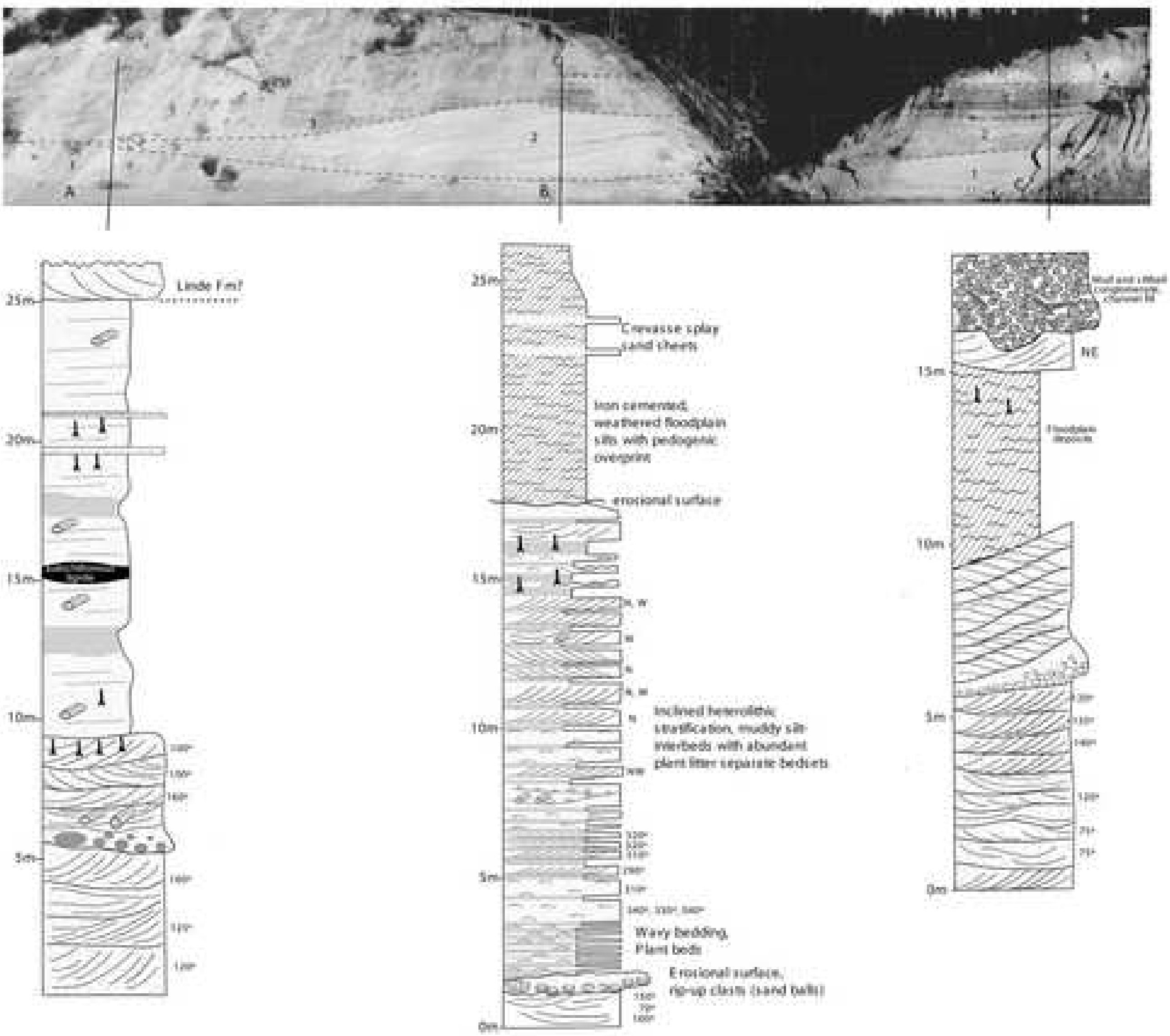

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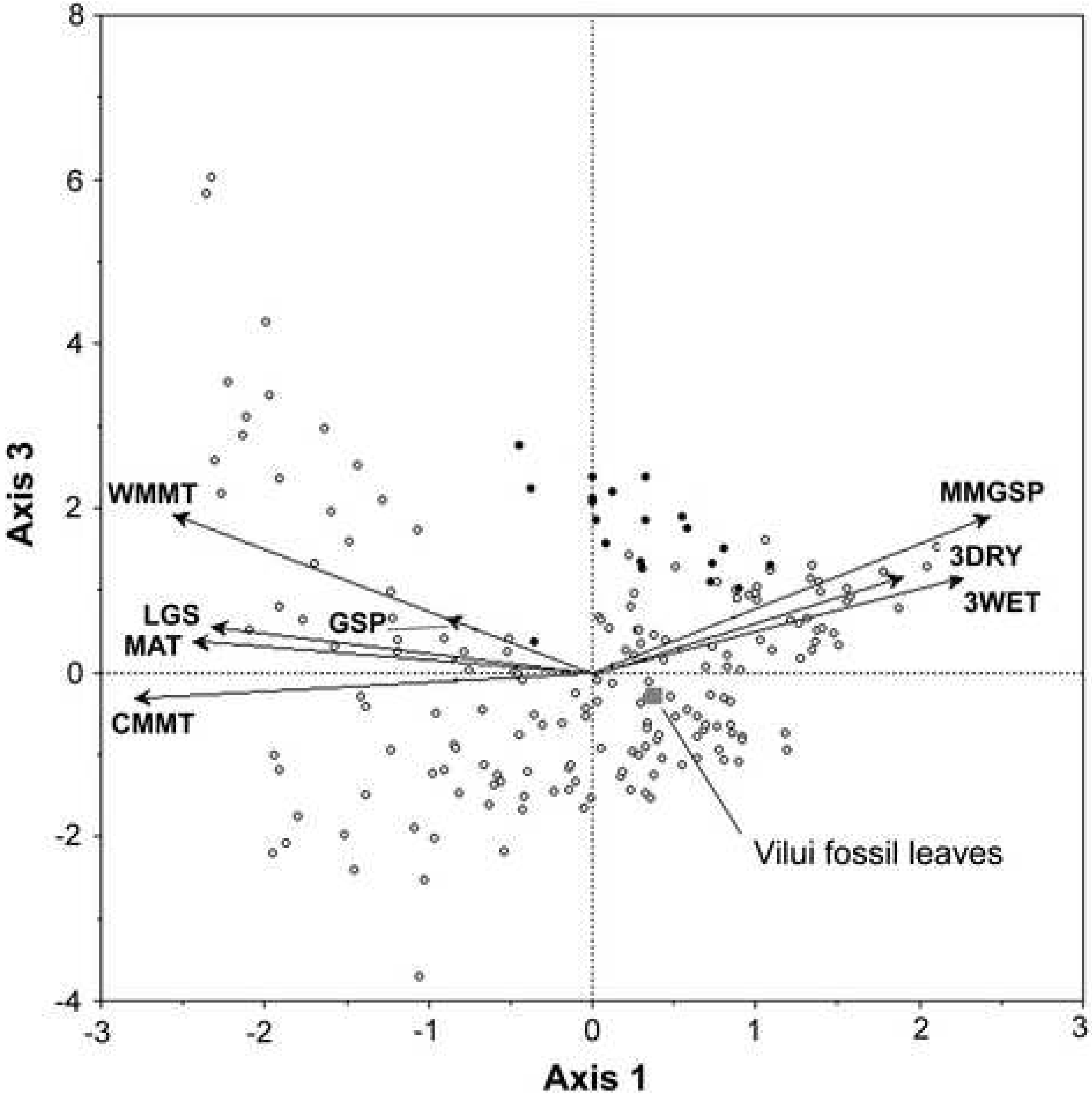

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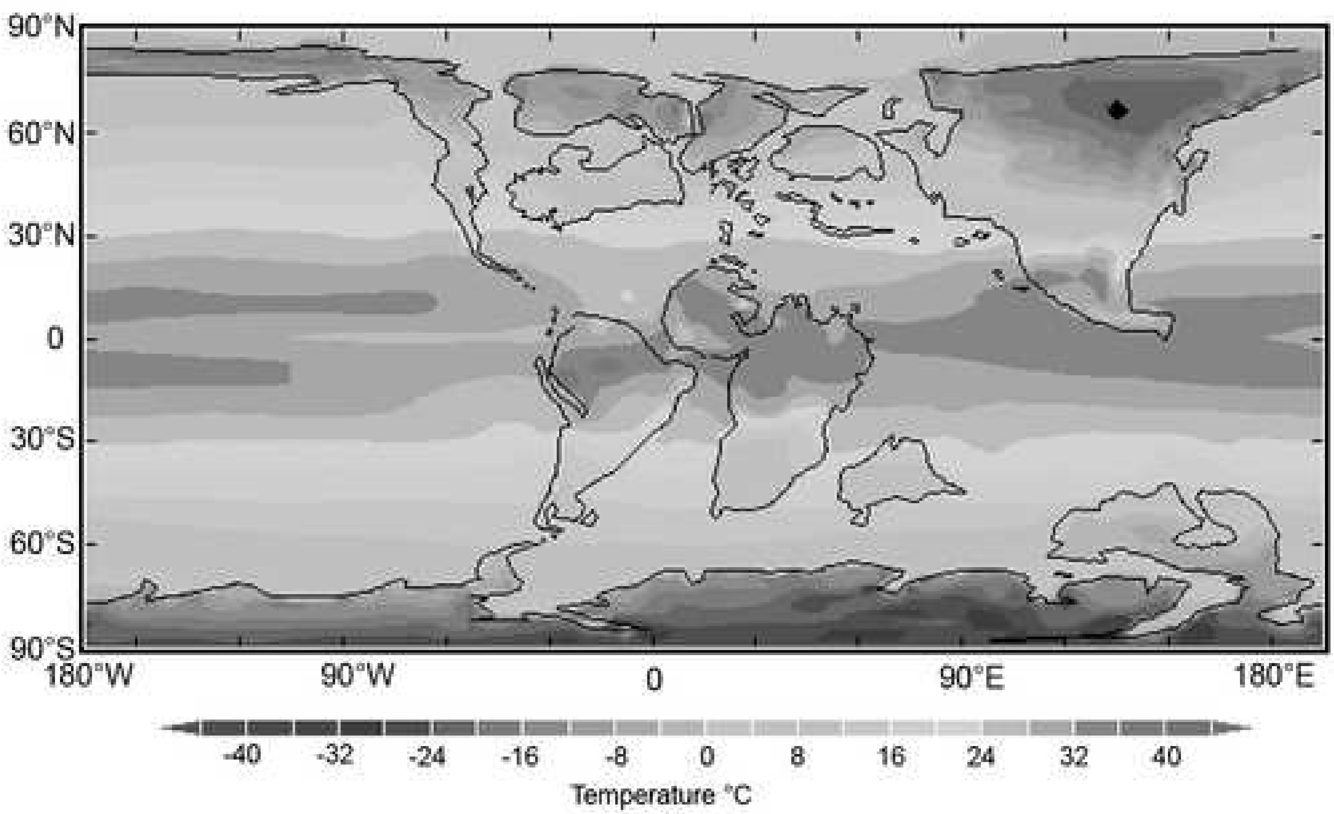

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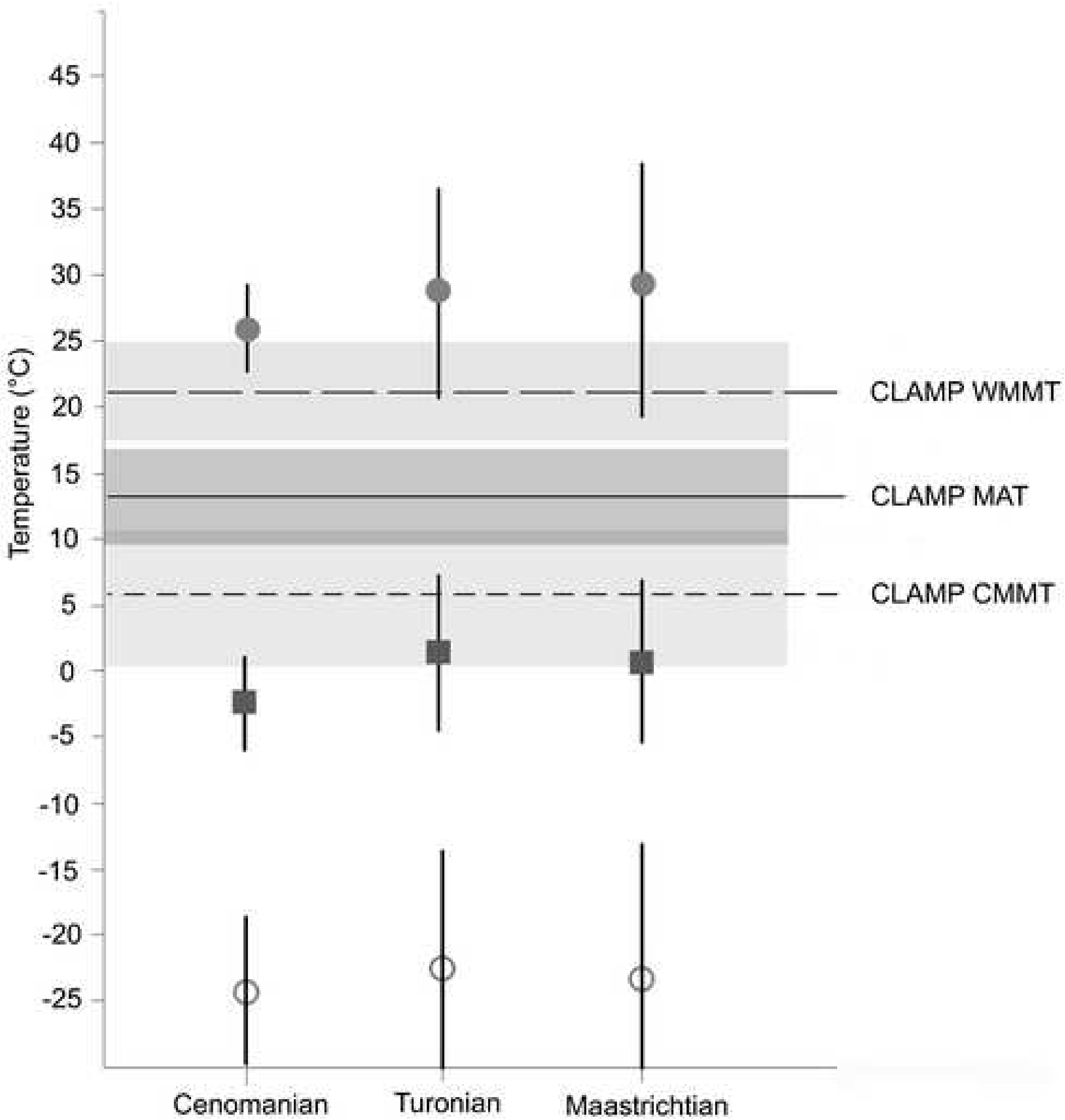

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