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The Early Miocene Paleoclimate of Erzhilansay: Interpretation of Climatic Parameters Using Modern Methods

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Abstract: Studying paleoclimatic conditions across geological epochs is essential for understanding climate evolution and its influence on Earth's biosphere. Leaf macrofossils serve as a crucial data source for reconstructing ancient climates due to their sensitivity to environmental changes. Advanced analytical methods, such as the Climate Leaf Analysis Multivariate Program (CLAMP) and the coexistence approach (CA), enable precise assessment of past climatic parameters using fossilized leaf remains. The Erzhilansay locality, dated to the early Miocene, represents a remarkable site with exceptionally preserved and diverse plant fossils, making it pivotal for paleoclimatic reconstructions. This study reveals that mean annual temperatures and summer temperatures in the early Miocene were relatively stable over millions of years. In contrast, winters were notably milder, exhibiting warmer and more consistent conditions. Precipitation levels were significantly higher, fostering the development of dense vegetation, unlike the arid environment seen today. These findings underscore the importance of employing integrated methodologies to reconstruct ancient climates and interpret geological-scale climate changes. The study also offers critical insights into climate dynamics, supporting the development of strategies to mitigate current environmental challenges.

Keywords: paleoclimate; leaf macrofossils; CLAMP; coexistence approach; early Miocene; Erzhilansay locality

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1. Introduction

The study of paleoclimatic conditions throughout geological epochs is crucial for understanding climate evolution and its broader effects on Earth's biosphere [1–4]. Leaf macrofossils provide invaluable insights into ancient climatic conditions due to their morphological sensitivity to environmental fluctuations. Modern analytical techniques, such as the Climate Leaf Analysis Multivariate Program (CLAMP) and the coexistence approach (CA), enable a detailed evaluation of climatic parameters based on fossilized leaf remains, as demonstrated in studies by Wolfe [5], Mosbrugger and Utescher [6], and Spicer et al. [7].

The Erzhilansay locality, situated in the Turgay Depression of Kazakhstan, is a key site for paleobotanical research due to its well-preserved plant fossils and diverse flora.

Located in Central Asia, this region's unique geological and climatic history makes it crucial for understanding paleoclimatic conditions during the early Miocene. The exceptional preservation and variety of plant remains provide valuable insights into the climate of that period, making Erzhilansay a prime location for paleoclimatic reconstructions [8–13].

This study aims to conduct a comprehensive analysis of the Erzhilansay flora using the CLAMP and CA methods to determine key paleoclimatic indicators. It focuses on reconstructing the climatic conditions of the early Miocene and exploring the relationships between leaf morphological characteristics and climatic parameters. The flora of Erzhilansay has been the subject of research by several scientists who have made significant contributions to its study and understanding. The Erzhilansay locality was discovered by the well-known Almaty geologist E.I. Soboleva in 1947. The first plant collections from Erzhilansay were made by V.S. Kornilova in 1947 and 1949. In 1956, Kornilova published the results of a study on the Oligocene flora of Turgay, where she first mentioned Erzhilansay [9,14,15].

S.G. Zhilin proposed a new approach to dating the floras of Western Kazakhstan and Turgay, including Erzhilansay. Initially, he attributed the paleoflora of Erzhilansay to the Middle Oligocene but later to the early Miocene (Aquitanian stage) [8,11,16–18]. Recent studies, including the dissertation work of S.A. Nigmatova, continue to deepen the knowledge of the Erzhilansay flora and its significance in the context of paleobotany and paleoclimatology [8].

Research has shown that the flora of Erzhilansay includes 53 species belonging to 23 systematic groups, with angiosperms (dicots and monocots) being the main ones. Erzhilansay is characterized as one of the richest localities of thermophilic deciduous floras of the Turgay ecological type, dating back to the early Miocene (Aquitanian stage) [8]. These studies have confirmed the significance of Erzhilansay as one of the largest and richest localities of Tertiary plants in Turgay, making it an important subject for further paleobotanical and paleoclimatic studies [8,14,19,20].

Reconstructing the paleoclimate based on leaf macrofossils is a widely used method in paleobotany. The Climate Leaf Analysis Multivariate Program (CLAMP) is a widely used tool for reconstructing paleoclimates based on the morphological characteristics of fossil plant leaves. Over recent decades, the CLAMP method has been successfully applied to analyze diverse floras from various geographic regions and geological epochs, providing valuable data on past paleoclimatic conditions.

One of the first and foundational studies on the CLAMP methodology is the work of Green (2006), in which the author proposes a graphical approach to analyzing data obtained using CLAMP [21]. This study provides a detailed examination of the principles and methodological aspects of applying CLAMP, allowing for a better understanding of the capabilities and limitations of this method [21].

Spicer and his co-authors (2008), in their encyclopedic article "Clamp", provide an extensive overview of the methodology and applicability of CLAMP. The authors describe the basic principles of the program and provide examples of its successful application for reconstructing paleoclimates based on leaf data [22].

An example of applying the CLAMP method for paleoclimate reconstruction is the study of the late Miocene (Tortonian) flora from the La Cerdanya Basin in Catalonia, Spain. In this study, the authors Tosal, Verduzco, and Martín-Closas (2021) use CLAMP data to determine paleoclimatic conditions and assess the paleoelevation of the Eastern Pyrenees [23].

Yang and co-authors (2007) applied the CLAMP method to reconstruct the climate during the Miocene epoch in Shanwang Basin, China. In this study, the authors compared the results obtained using CLAMP with data from leaf margin analysis and the CA, providing a comprehensive understanding of the Miocene climatic conditions in this region [24].

The study by Ivanov and co-authors (2019) aimed to compare different methods of climate reconstruction, including CLAMP, based on data from the Miocene flora of northwestern Bulgaria. The authors identified the strengths and weaknesses of each method including CLAMP and discussed their applicability for various paleoclimatic conditions [25].

Hayes and co-authors (2006) used the CLAMP method to analyze floras from the late Cretaceous on James Ross Island, Antarctica. This study allowed for the reconstruction of the climatic conditions of this era and provided insight into the climatic evolution of Antarctica [26].

In a recent study, He, Roth-Nebelsick, and Sun (2023) analyzed data on leaf traits from two Miocene floras in Eastern China and discussed their paleoclimatic implications. The authors used the CLAMP method to obtain quantitative data on climate changes in this region [27].

Uhl and co-authors (2007) provided a European perspective on the use of the CLAMP method for reconstructing paleotemperatures. This paper discusses data on Cenozoic temperatures and leaf morphology from various regions of Europe [28,29].

Finally, Nguyen and co-authors (2024) used the CLAMP method to analyze the late Miocene flora from northern Vietnam. The authors explored the impact of monsoons on the region's plant diversity and reconstructed the climatic conditions of that period [30].

Thus, the CLAMP method is an important and well-established tool for paleoclimatic research, allowing for the reconstruction of past climatic conditions based on the morphological characteristics of fossil plant leaves. Numerous studies demonstrate its successful application in various regions and geological epochs, underscoring the significance of this method for paleoclimatology [23,31–33].

The second method is the CA, based on analyzing modern analogs of fossil plants. This chapter presents the results of applying this method to reconstruct the climatic conditions of the Erzhilansay locality in the early Miocene.

The CA has been successfully used in various studies, confirming its reliability and effectiveness. For example, Mosbrugger and Utescher (1997,2014) applied this method to reconstruct the paleoclimate of Europe during the Tertiary period, revealing significant climate changes in the region [6,34,35]. Similarly, Grímsson et al. used the CA to analyze the climatic conditions in the North Atlantic during the Oligocene, providing accurate estimates of temperature and precipitation regimes [36].

The study by Bruch and Zhilin (2006) demonstrated the use of the CA to reconstruct the early Miocene climate in Central Eurasia based on the Aquitanian floras of Kazakhstan, with a paleoclimatic reconstruction for the Erzhilansay locality also presented in this work [37]. The results showed significant climate changes and the adaptation of plant communities to new conditions. In the study by Popova et al. (2021), this method was applied to analyze the Rupelian floras of Kazakhstan in the context of the climate and vegetation of the early Oligocene of Central Asia, confirming its effectiveness in reconstructing ancient climatic conditions [38].

Other studies provide theoretical justification and practical recommendations for using the CA for climatic quantification [39,40]. Bruch and Kovar-Eder (2003) used this method to assess the early Miocene climate from the flora of Oberdorf (Styria, Austria) [41]. Thiel et al. (2012) applied various paleobotanical techniques for climatic assessments of late Pliocene floras in Central Europe [42]. Ivanov et al. (2019) conducted a climate reconstruction based on Miocene leaf flora from northwestern Bulgaria, comparing the leaf physiognomy method and the nearest living relative method [25].

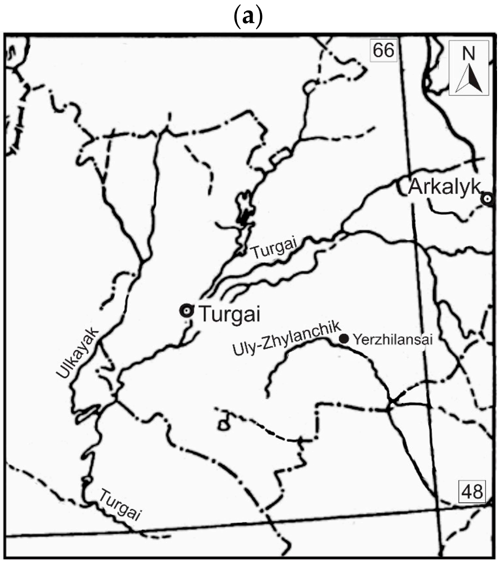
These studies conclude that the CA is a reliable and accurate tool for reconstructing past climatic conditions. Using this method provides detailed estimates of temperature and precipitation regimes in various geological epochs, which is important for understanding the evolution of climate and ecosystems.

1.1. Location and Geological Setting

The Erzhilansay locality is situated in the eastern part of the Southern Turgay Plain, 15–20 km north of the right bank of the Uly-Zhylanchik River, and 135 km upstream from the confluence of the Dulygaly-Zhylanchik and Ulken Zhylanchik Rivers, in the Amangeldy district of the Kostanay region [34] (Figure 1a,b).

The layers exposed by weathering, containing plant impressions, stand out with a light gray color with a slight lilac tint among other nearby, similar formations. Along the bedding planes of the layers, a vast number of impressions of leaves, fruits, vegetative shoots, and insect remains lie horizontally. The impressions are so densely packed that they resemble forest litter [8,12,14].

(**a**)



(**b**)

Figure 1. (**a**) Geographical location of the Erzhilansay locality within Kazakhstan. (**b**). A detailed map of the Turgay region indicating the Uly-Zhylanchik River and Erzhilansay.

This locality was discovered by geologist E.I. Sobolev in 1947, and plant fossils were collected from the kaolin clay deposits. Collections from this locality were gathered by V. Kornilova from 1947 to 1950.

1.2. Current Climatic Conditions

The current climatic data for the Erzhilansay region (coordinates 49°01′ N 65°30′ E) are characterized by the following indicators:

Mean annual temperature: Positive, ranging from 1 to 4 °C.

Average temperature of the coldest month (January): Ranges from −15 to −17 °C. In particularly harsh winters, temperatures can drop to −44 °C (down to −47 °C in the Kushmurun area).

Average temperature of the warmest month (July): Around 24 °C in the south. On hot days, temperatures can reach 40–45 °C.

Duration of the warm period (with temperatures above zero): On average, 210–218 days in the southern part of the region.

Average annual precipitation: Decreases to 220 mm or less towards the south.

Precipitation distribution: The warm period (April–October) receives more precipitation than the cold period. Summer sees significantly more precipitation than other seasons [43].

2. Methodology

2.1. Paleobotanical Materials and Processing

A total of 42 macrofossil samples (collection number 455) stored at the Astana Botanical Garden (Astana, Kazakhstan) were examined. The leaf blades are arranged in various planes, and most specimens are partially preserved, indicating a significant transport distance to the burial site (Figure 2).

To determine the systematic position of the specimens, morphological comparisons were conducted using light microscopes. Comparisons were made with fossils from the Turgay Depression, specifically from the Kushuk locality, collection nos. 3 and 16, as well as herbarium material from the Laboratory of Flora and Plant Resources, which includes flora from southeast Kazakhstan.

2.2. Research Methods

To reconstruct the climatic characteristics of the Erzhilansay flora, two well-established quantitative methods were employed: the CA and the CLAMP.

2.2.1. CA

The CA method involves comparing identified fossil taxa with their nearest living relatives (NLRs) to determine the climatic ranges in which all taxa could coexist. These ranges represent the environmental parameters suitable for the survival of modern plant species. For this analysis, the Paleoflora Database (PFDB; www.palaeoflora.de, accessed on 29 September 2024) was utilized, as it provides comprehensive climatic data for numerous vascular plant taxa. Climatic indicators considered include mean annual temperature (MAT), temperature of the coldest month (CMT), temperature of the warmest month (WMT), mean annual precipitation (MAP), and precipitation during the wettest (MPWET), driest (MPDRY), and warmest (MPWARM) months. Specimens with non-overlapping climatic ranges were treated as outliers and excluded from the final analysis [40].

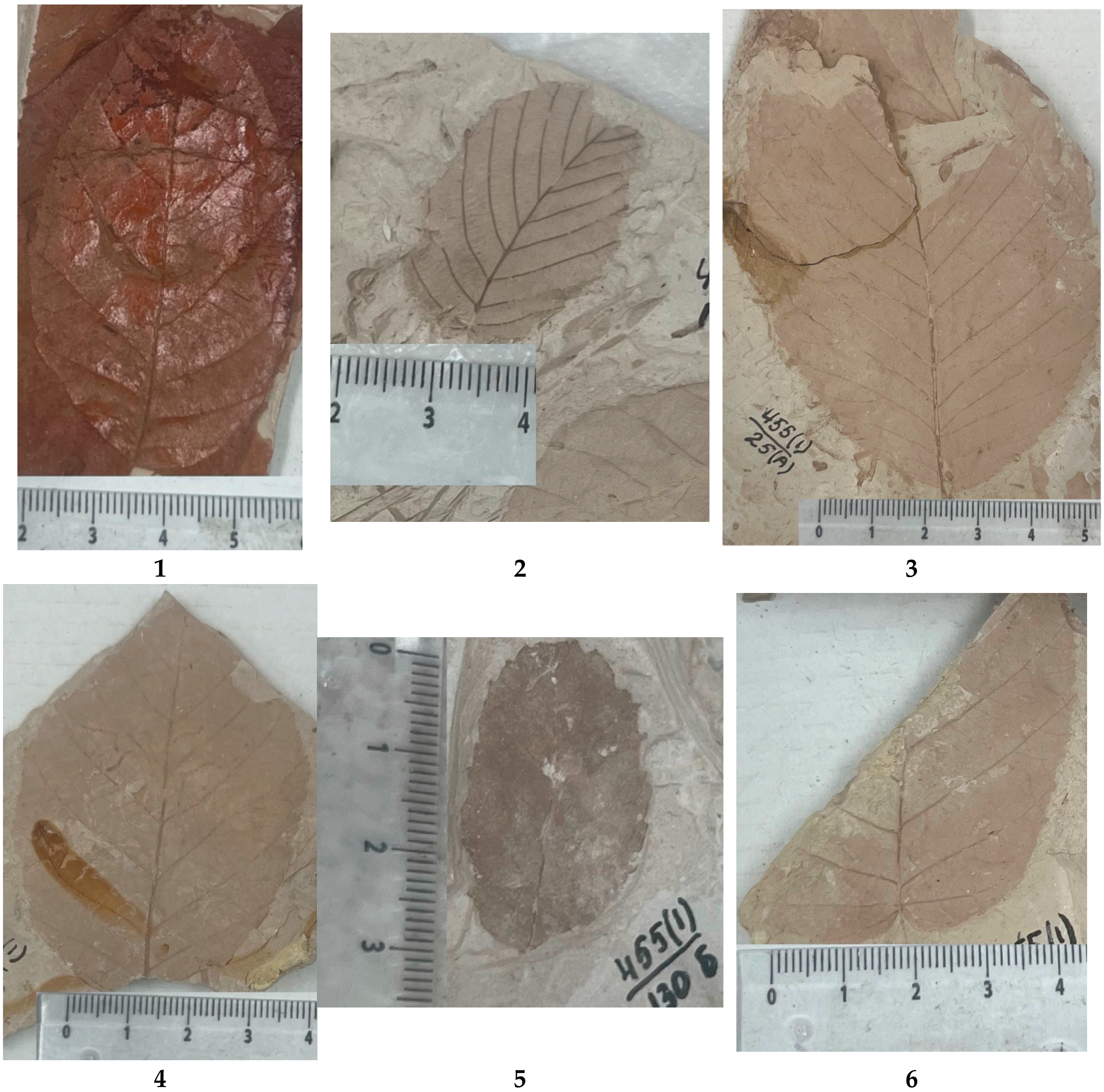


Figure 2. Selected fossil taxa from the early Miocene Erzhilansay. 1—*Carya Ungeri* (Juglandaceae); **2**—*Corylus Jarmolenkoi* (Betulaceae); **3**—*Ulmus dreponata* (Ulmaceae); **4**—*Alnus Shmalhauseni* (Betulaceae); **5**—*Pterocarya paradissica* (Juglandaceae); **6**—*Ostrya antiqua* (Betulaceae).

2.2.2. CLAMP

The CLAMP method leverages statistical correlations between leaf physiognomy and climatic parameters. Originally developed by J. Wolfe (1993, 1995) [5,44] and refined by subsequent researchers (e.g., Herman, 2004; Spicer et al., 2005, 2009), it uses morphological characteristics of leaves to infer climatic conditions [7,22,23,33]. For this study, the Physg3brcAZ_GRIDMet3brAZ dataset was employed as a calibration file, reflecting the relatively warm climatic conditions of Kazakhstan during the early Miocene. A total of 44 fossil impressions representing 22 distinct leaf taxa were analyzed to reconstruct key climatic parameters, such as MAT, seasonal variability, and precipitation patterns.

3. Results

The paleoclimatic conditions of the Erzhilansay locality, dated to the early Miocene, were reconstructed using the CLAMP method. This approach allowed the determination of key climatic parameters, including mean annual temperature (MAT), seasonal temperature variability, precipitation levels, and atmospheric humidity. A summary of the results is presented in Table 1 and detailed further in Supplementary File S1.

Table 1. Climatic indicators of the Erzhilansay locality according to the Climate Leaf Analysis Multivariate Program (CLAMP) method.

Parameter	Value
MAT (mean annual temperature, °C)	7.55
WMMT (mean temperature of the warmest month, °C)	20.42
CMMT (mean temperature of the coldest month, °C)	−4.39
GROWSEAS (length of the growing season, months)	5.13
GSP (annual precipitation, cm)	35.5
MMGSP (mean monthly precipitation during the growing season, cm)	9.66
Three_WET (three-month precipitation in the wettest period, cm)	43.97
Three_DRY (three-month precipitation in the driest period, cm)	15.59
RH (relative humidity, %)	78.83
SH (specific humidity, g/kg)	5.95
ENTHAL (enthalpy, kJ/kg)	30.41

The mean annual temperature (MAT) was estimated at 7.55 °C, suggesting a moderately cold climate with significant seasonal fluctuations typical of continental regions. During summer, temperatures reached 20.42 °C, creating favorable conditions for active vegetation growth. In contrast, winter temperatures dropped to −4.39 °C, restricting the growing season to approximately 5.13 months.

Overall, the paleoclimate of Erzhilansay during the early Miocene was characterized by moderately cold conditions with distinct seasonality, where warm and humid summers alternated with cold winters, fostering the development of unique ecosystems in this continental environment.

3.1. Climatic Indicators from CA

Based on modern analogs, the following average climatic indicators were determined for Erzhilansay in the early Miocene: number of fossil taxa—44; taxa with climate data—39.

Based on the CA method, temperature parameters are summarized in Table 2 and Supplementary File S2. The mean annual temperature ranged from 13.30 to 15.60 °C, with an average of 14.45 °C, indicating a mild climate with minor temperature fluctuations. Cold-month temperatures ranged from 0.70 to 5.20 °C, with an average of 2.95 °C, suggesting mild winters. During the warmest months, temperatures ranged from 23.10 to 24.10 °C, indicating warm, yet not extreme, summer conditions.

Table 2. Temperature parameters of the Erzhilansay locality using the CA method.

Parameter	Minimum (°C)	Average (°C)	Maximum (°C)
Mean annual temperature (MAT)	13.30	14.45	15.60
Cold-month temperature (CMT)	0.70	2.95	5.20
Warm-month temperature (WMT)	23.10	23.60	24.10

The CLAMP method, based on leaf morphological characteristics, yielded lower values for these parameters. According to CLAMP, the mean annual temperature was 7.55 °C, with warmest and coldest month temperatures of 20.42 and −4.39 °C, respectively. Figure 3 provides a comparative visualization of temperature ranges obtained using the CA and CLAMP methods.

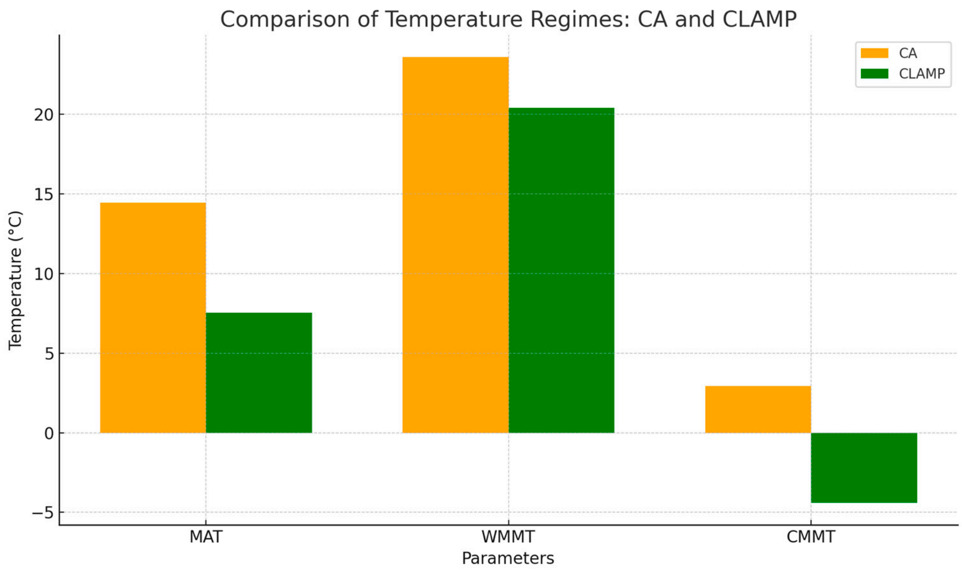


Figure 3. Comparison of temperature regimes in the early Miocene using the coexistence approach (CA) and Climate Leaf Analysis Multivariate Program (CLAMP).

3.2. Precipitation Parameters

The CA method's precipitation data are presented in Table 3. The analysis showed high annual precipitation levels, ranging from 879 to 1179 mm, with an average of 1029 mm, indicating a humid climate with evenly distributed rainfall. During the wettest months, precipitation ranged from 118 to 157 mm, with an average of 137.5 mm, confirming high humidity during this period. In the driest months, precipitation remained moderate, ranging from 35 to 47 mm, with an average of 41 mm. During the warmest months, it ranged from 107 to 141 mm, with an average of 124 mm, further indicating high summer humidity.

Table 3. Precipitation parameters of the Erzhilansay locality using the coexistence approach (CA) method.

Parameter	Minimum (mm)	Average (mm)	Maximum (mm)
Mean annual precipitation (MAP)	879	1029	1179
Precipitation in the wettest month (MPWET)	118	137.5	157
Precipitation in the driest month (MPDRY)	35	41	47
Precipitation in the warmest month (MPWARM)	107	124	141

The CA method demonstrates significantly higher precipitation values across all parameters compared to the CLAMP method, which may suggest that CA tends to provide wetter estimates of climatic conditions (Figure 4). The differences in annual precipitation and precipitation during the wettest period are particularly notable, and this should be taken into account when interpreting the climate reconstruction. This chart highlights the importance of using a combined approach to achieve the most accurate climate assessments, as the results of precipitation reconstruction by the two different methods vary substantially.

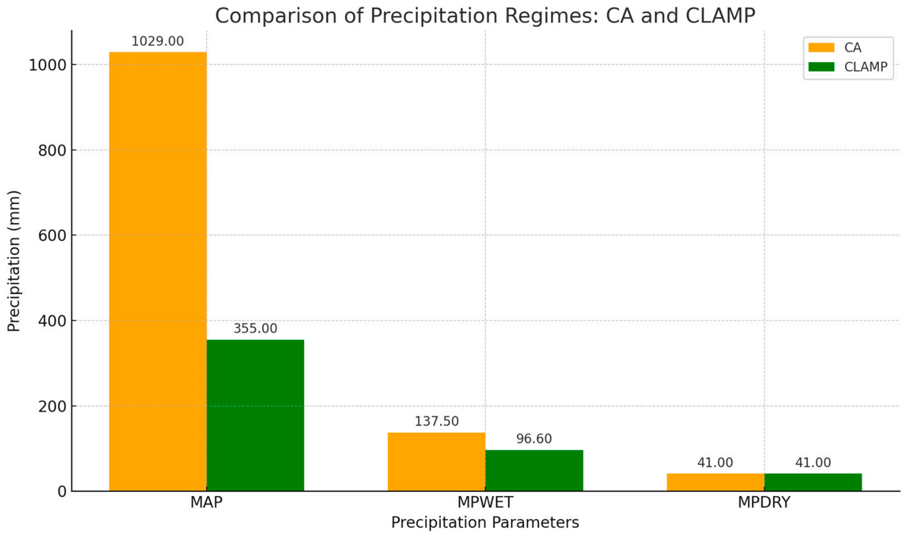


Figure 4. Comparison of precipitation in the early Miocene using the CA and CLAMP.

3.3. Climatic Characteristics of the Region

Data on temperature and precipitation indicate a temperate climate with pronounced seasonality and significant precipitation throughout the year. Such conditions likely supported the development of forest and forest–steppe ecosystems, as evidenced by the diversity of macrofossils found in the region. The temperature characteristics confirm the presence of cold winters and warm summers, typical of a modern temperate climate zone.

The findings provide a detailed understanding of the paleoclimatic conditions in the Erzhilansay region and establish a basis for future studies aimed at reconstructing ancient ecosystems and their climatic dynamics.

4. Discussion

This study examined the climate of the Erzhilansay region during the early Miocene using the CLAMP and CA methods. A comparison with modern climatic data revealed significant shifts over time, particularly in temperature and precipitation patterns. These findings are consistent with similar studies conducted in Central Asia and Eurasia for this geological period.

4.1. Geological Context and Significance

The early Miocene, approximately 23 to 16 million years ago, was a period of substantial climatic and geological transformations, marking the onset of modern climate systems and continental configurations. Notably, the climate of Eurasia during this era was significantly warmer and more humid than it is today [45]. During this period, average temperatures were significantly higher, and the climate was subtropical, allowing extensive forests and diverse ecosystems to thrive. High precipitation levels supported dense vegetation, contributing to the formation of vast swamps and forests, especially in the central and eastern parts of the continent [12].

4.2. Description of the Locality and Stratigraphy and the Flora Position in the Stratigraphy

The flora of Erzhilansay is located within kaolin clays that are part of the third river terrace of the *Uly-Zhylanchik* River. The strata are horizontally layered, forming deposits rich in plant remains, including impressions of leaves, fruits, vegetative shoots, and insect remnants. These remains are often so densely packed that they resemble forest litter [8,46]. The Kaidagul Suite, established as an independent formation at the 1960 All-Union Stratigraphic Conference, is observed along the *Dulygaly-Zhylanchik* River and across the entire shoreline of the *Uly-Zhylanchik* River. The layers of the Kaidagul Suite were first described by V.A. Bronev. The full stratigraphic sequence is shown in Figure 5.

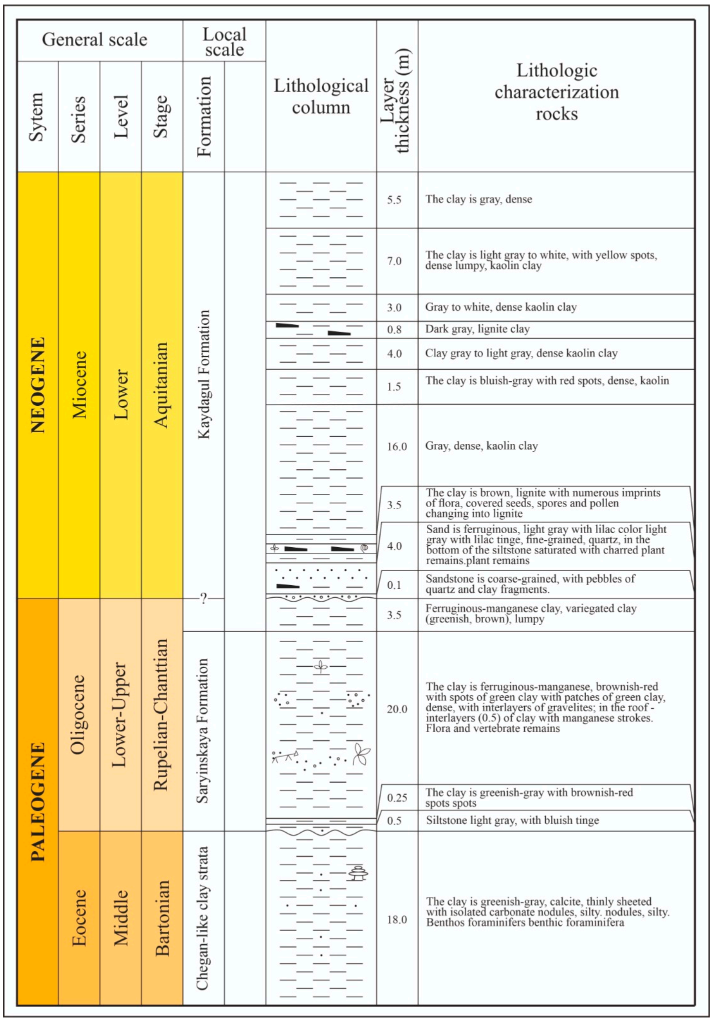


Figure 5. Stratigraphic sequence of sedimentary layers in the Erzhilansay locality.

Within the stratigraphic section of Erzhilansay, several characteristic layers can be distinguished. At the Lower Miocene level (Aquitanian stage), a series of clays of various compositions and densities is present. At the base lies dense gray clay lacking organic residues, indicating calm depositional conditions. Above it, there is dense, light gray kaolin clay with yellow spots, suggesting weathering processes. This is followed by grayish-white dense kaolin clay, also reflecting stable depositional conditions. In the upper layers, dark gray lignitic clay rich in organic material likely represents coastal or swampy conditions. The next layer consists of dense, light to gray kaolin clay with low organic content. Above it lies bluish-gray clay with red spots, indicating oxidative processes in the depositional environment. The top of this section contains dense gray kaolin clay, suggesting a prolonged period of stable sedimentation.

In the Oligocene (Rupelian–Chattian stages), there are brown clays with numerous plant impressions, transitioning into lignite, indicating swampy conditions with subsequent peat formation. These layers contain plant impressions, seeds, and spores. Above the brown clay is coarse-grained sandstone with quartz and clay fragments, suggesting high-energy depositional conditions.

Further up is ferruginous greenish-brown clay enriched with iron and manganese, indicating specific chemical conditions. Above it lies brownish-red clay with green patches, containing gravel layers and plant remains, likely formed in coastal or deltaic settings.

At the Middle Eocene level (Bartonian stage), there is light gray, weakly cemented argillite with a bluish tint, suggesting shallow, low-energy depositional conditions. At the base of the section lies greenish-gray clay with carbonate nodules and benthic foraminifera, reflecting marine depositional conditions.

These layers allow for the reconstruction of the ancient ecological conditions and climate that existed in the region during the formation of the Erzhilansay deposits.

4.3. Comparison of Temperature Regimes

The temperature analysis indicates that the early Miocene climate in the Erzhilansay region was significantly warmer than today. According to the CA method, the mean annual temperature (MAT) was approximately 14.45 °C, whereas the CLAMP method produced a slightly lower estimate of about 7.55 °C. Both values considerably exceed modern temperatures, which range between 1 and 4 °C. These results are consistent with previous studies, such as those by Bruch and Zhilin (2006), who also observed elevated MATs for the early Miocene, ranging from 13.30 to 16.90 °C, indicating a similar warming trend across the region [37]. Furthermore, Spicer et al. (2004) identified similarly high temperatures in Eurasia during the early Miocene using comparable paleoclimatic methodologies [32].

Winter temperatures were also notably milder during the early Miocene. CLAMP results suggest cold-month temperatures (CMTs) around −4.39 °C, while the CA estimates a higher CMT of 2.95 °C. This contrasts with current winter temperatures in the Erzhilansay region, which can drop to −15 or even −17 °C. These findings align with earlier studies by Uhl et al. (2006), who also reported milder winter temperatures across Eurasia during the early Miocene [28]. Summer temperatures appear relatively stable, with the CLAMP and CA methods estimating approximately 20.42 and 23.60 °C, respectively, which is comparable to present-day summer values ranging from 19 to 24 °C. Stable summer temperatures were also noted by Yang et al. (2007) in studies of Miocene climates in China [25].

Figure 6 illustrates temperature regimes during the early Miocene as reconstructed using the CA and CLAMP methods, including modern data for comparison. This figure clearly shows that early Miocene temperatures significantly exceeded current values, particularly in winter, highlighting milder winters and moderate summer temperatures.

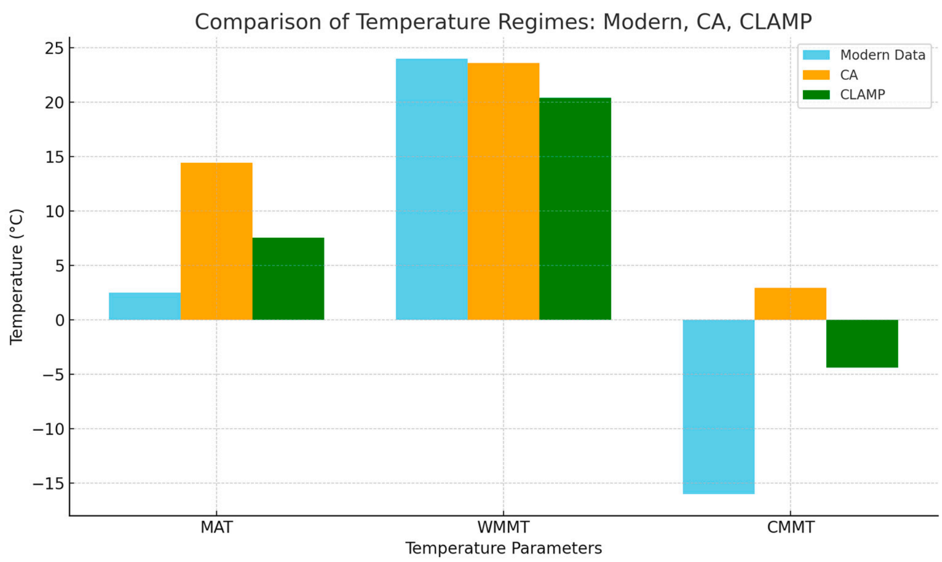


Figure 6. Comparison of temperature regimes in the early Miocene using the CA and CLAMP with modern data.

4.4. Comparison of Precipitation

The early Miocene climate in the Erzhilansay region was substantially wetter than today. The CA method estimated annual precipitation levels exceeding 1029 mm, while CLAMP provided a lower estimate of 355 mm, with both values being higher than the present-day range of 220–330 mm. This discrepancy likely reflects differences in methodology: the CA method relies on modern analogs, which may represent environments with significant annual precipitation outside the wettest months, while CLAMP captures leaf physiognomy, which might be influenced by growing-season conditions. This suggests a highly seasonal precipitation pattern in early Miocene climate of Erzhilansay.

Such seasonal variability is consistent with other Miocene climates in Central Asia, where monsoon-like systems or westerly-driven precipitation contributed to uneven rainfall distribution throughout the year. These findings align with the research by Popova et al. (2021), who also identified increased precipitation levels in Central Asia during the early Oligocene and Miocene [38]. Precipitation during the wettest months was also much higher—the CA and CLAMP methods estimate around 137.5 and 96.6 mm, respectively, compared to today's range of 43–97 mm in the wettest months. These values are comparable to findings by Tosal et al. (2021), who observed high rainfall levels during the wettest periods of the Miocene in Spain [23]. Both methods indicate stable precipitation levels of around 41 mm during the driest months, which is significantly higher than current values in the driest months, ranging from 15 to 50 mm. This stability suggests a consistent hydrological regime in the early Miocene, similar to patterns of hydrological stability described by Ehlers et al. (2022) [3].

Figure 7 presents a comparative analysis of precipitation as estimated by the CA and CLAMP methods alongside modern data for Erzhilansay, illustrating a substantial decrease in precipitation under current climatic conditions and an increase in seasonal variation, compared to the more stable early Miocene conditions.

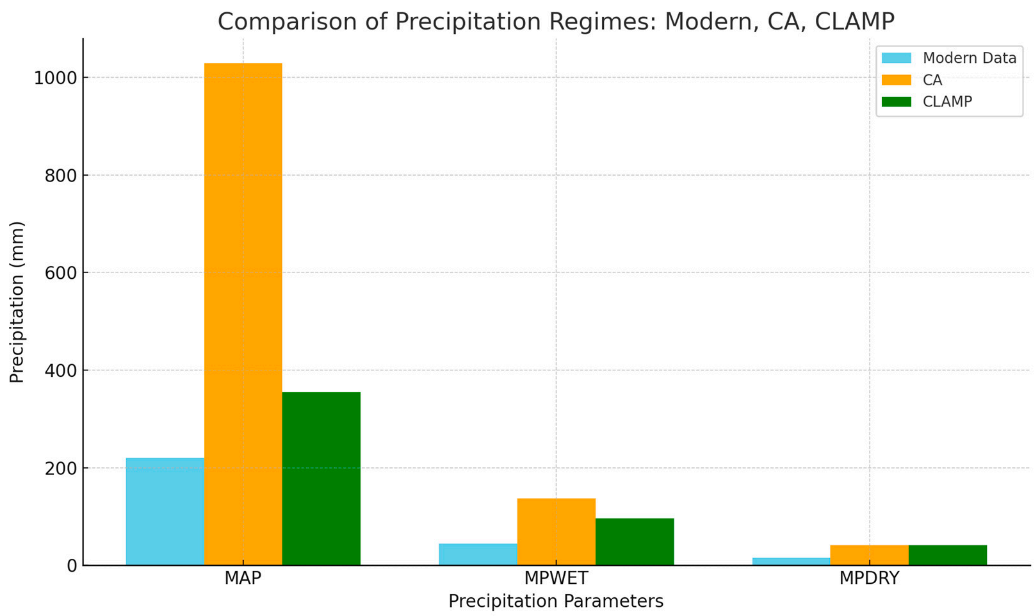


Figure 7. Comparison of precipitation in the early Miocene using CA and CLAMP with modern data.

Thus, the early Miocene climate in the Erzhilansay region can be characterized as warmer and more humid, with mild winters and abundant precipitation, especially during the wet season. In contrast, modern data indicate a reduction in annual precipitation and a shift towards a drier climate.

4.5. Factors Contributing to Climate Change

The transition from a warmer and wetter early Miocene climate to today's colder and drier conditions can be attributed to various geological and global climatic processes. Over millions of years, the global climate underwent significant transformations, including glacial cycles, atmospheric circulation shifts, and tectonic activity. These changes likely contributed to the cooling and drying observed in the Erzhilansay region. Mosbrugger and Utescher (1997) emphasize the role of glaciations and tectonic changes in driving major climate transitions, providing a possible explanation for these long-term trends [6].

The early Miocene warm and humid conditions in Erzhilansay were likely influenced by global climatic trends, including the gradual warming following the cooler Oligocene epoch and tectonic changes that reshaped atmospheric circulation patterns. Such trends contributed to elevated temperatures and increased precipitation, as noted in global reconstructions by Zachos et al. (2001) [47].

At the regional level, tectonic changes, such as the uplift of the Tibetan Plateau and the retreat of the Paratethys Sea, significantly influenced atmospheric circulation and increased precipitation in East Asia and Central Asia. Zhang et al. (2006) demonstrated that these large-scale topographic changes intensified westerly winds, which transported moisture from nearby water bodies to Central Asia, creating favorable conditions for the development of thermophilic flora [48]. Similarly, Herold et al. (2008) suggest that tectonic boundary conditions during the Miocene influenced atmospheric circulation, supporting this mechanism [45].

In addition, continental drift and sea level fluctuations significantly affected climatic regimes and air circulation patterns in Central Asia. Gladenkov (2005) notes that these processes likely contributed to changes in regional climate dynamics, reinforcing the understanding of climatic shifts during the early Miocene [1].

Differences in the results obtained from the CLAMP and CA methods may arise from variations in the methodologies, which can yield slight discrepancies in climate reconstructions. The CLAMP method focuses on leaf morphology, reflecting growing-season conditions, whereas CA relies on modern analogs of plant communities, which may not always capture extreme ancient conditions. These methodological differences, discussed by Spicer et al. (2005, 2008) and Mosbrugger et al. (2005), highlight the importance of using multiple methods to achieve a more comprehensive climate reconstruction [6,7,49].

Overall, comparing paleoclimatic and modern data underscores that the Erzhilansay region was significantly warmer and wetter during the early Miocene than today. This long-term shift toward colder and drier conditions reflects broader global trends. Research by Ehlers et al. (2022) emphasizes the influence of long-term geological processes on climate, helping explain the cooling and aridification observed in Central Asia over millions of years [3]. Regional factors, such as topographic changes and continental drift, could also have influenced the climate in the Erzhilansay area. Zhilin (2002) associated topographic changes and the formation of the Turgay Depression with shifts in regional climate regimes, potentially playing a role in the environmental changes observed [50]. Additionally, changes in vegetation density and composition could have impacted the regional climate by altering evapotranspiration rates, which in turn influenced precipitation levels and the region's overall climate, as discussed by Nigmatova et al. (2023) [51]. In this study, we examined the climate of the Erzhilansay region during the early Miocene using the CLAMP and CA methods and compared these data with modern climatic conditions to identify the changes that have occurred since then. These findings align with other studies on early Miocene climates in Central Asia. For example, Bruch and Zhilin (2006) identified similar patterns of warmer and wetter conditions in Central Eurasia during the early Miocene, corroborating our results regarding higher mean annual temperatures and increased precipitation [37].

5. Conclusions

This study explored the climate of the Erzhilansay region during the early Miocene and its comparison with contemporary climatic conditions. Climate reconstructions using the CA and CLAMP methods indicate that mean annual and summer temperatures have experienced minimal variations over millions of years. In contrast, winter conditions have become significantly harsher in the modern era. During the early Miocene, winters were markedly milder, characterized by warmer and more stable conditions, as confirmed by both approaches. Precipitation analysis reveals that the early Miocene climate was substantially wetter. Present-day precipitation levels in the Erzhilansay region are markedly lower compared to the early Miocene, both annually and during the wettest and driest months. These results suggest a progressive shift toward a more arid climate, likely driven by global climatic changes. In the early Miocene, the relatively stable precipitation levels likely supported the development of dense plant communities. In contrast, modern conditions show a decrease in moisture availability, placing stress on the region's ecosystems.

Recent climate data for the Kostanay region, particularly the Amangeldi district, further highlight rising mean annual temperatures and decreasing precipitation over the past few decades. These shifts, influenced by global warming and anthropogenic activities, are already impacting agriculture, water resources, and local ecosystems. Consequently, modern conditions necessitate adaptation efforts and the implementation of strategies to mitigate the adverse effects of climate change.

This study highlights the importance of integrating multiple methods for precise paleoclimate reconstruction and meaningful comparisons with modern climatic conditions. Such an approach enriches our understanding of climate dynamics over geological timescales and provides critical insights for developing effective adaptation strategies to address contemporary environmental challenges. Addressing the impacts of climate change will require carefully designed strategies focused on both mitigation and adaptation to ensure resilience in the face of ongoing environmental shifts.

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References

1. Gladenkov, Y.B. Stratigraphy and Current Directions of Paleobiogeographic Research. *Geol. Rev.* **2005**, *43*, 123–145.

2. Tierney, J.E.; Poulsen, C.J.; Montañez, I.P.; Bhattacharya, T.; Feng, R.; Ford, H.L.; Zhang, Y.G. Past climates inform our future. *Science* **2020**, *370*, eaay3701. [CrossRef] [PubMed]
3. Ehlers, T.A.; Li, G.; Farley, K.A.; Stock, G.M.; Kong, P.; Mackey, B.H. Past, present, and future geo-biosphere interactions on the Tibetan Plateau and implications for permafrost. *Earth-Sci. Rev.* **2022**, *234*, 104197. [CrossRef]
4. Sinitsyn, V.M. *Introduction to Paleoclimatology*; Nedra: Leningrad, Russia, 1980; pp. 187–188. (In Russian)
5. Wolfe, J.A. *A Method of Obtaining Climatic Parameters from Leaf Assemblages*; U.S. Geological Survey Bulletin 2040; US Government Printing Office: Washington, DC, USA, 1993; pp. 1–71.
6. Mosbrugger, V.; Utescher, T. The Coexistence Approach—A Method for Quantitative Reconstructions of Tertiary Terrestrial Paleoclimate Data Using Plant Fossils. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **1997**, *134*, 61–86. [CrossRef]
7. Spicer, R.A.; Herman, A.B.; Kennedy, E.M. The Sensitivity of CLAMP to Taphonomic Loss of Foliar Physiognomic Characters. *Palaios* **2005**, *20*, 429–438. [CrossRef]
8. Nigmatova, S.A. *Fossil Flora of Erzhilansay (Turgay Depression): Ph.D. Dissertation Abstract in Biological Sciences: 03.00.05*; Institute of Botany of the Academy of Sciences of the Republic of Kazakhstan: Almaty, Kazakhstan, 1998; 18p. (In Russian)
9. Kornilova, V.S.; Lavrov, V.V. On the Findings of the Tertiary Xerophytic Flora in Turgay and Its Stratigraphic Position. *Bull. Acad. Sci. Kazakh SSR* **1949**, *5*, 50. (In Russian)
10. Kornilova, V.S. Results of the Study of the Oligocene Flora of Turgay. *Proc. Inst. Bot. Acad. Sci. Kazakh SSR* **1956**, *3*, 59–101. (In Russian)
11. Zhilin, S.G. History of the Development of the Temperate forest Flora in Kazakhstan, U.S.S.R. from the Oligocene to the Early Miocene. *Bot. Rev.* **1989**, *55*, 205–330. [CrossRef]
12. Volkova, V.S. Stratigraphy and paleotemperature trend in the Paleogene and Neogene of Western Siberia (based on palynological data). *Geol. Geophys.* **2011**, *52*, 906–915. (In Russian)
13. Akhmetiev, M.A.; Zaporozhets, N.I. Paleogene events in Central Eurasia: Their role in the flora and vegetation cover evolution, migration of phytochore boundaries, and climate changes. *Stratigr. Geol. Correl.* **2014**, *22*, 312–335. (In Russian) [CrossRef]
14. Kornilova, V.S. Main Stages of Development of Cenozoic Floras in Kazakhstan. Ph.D. Thesis, Academy of Sciences of the Republic of Kazakhstan, Almaty, Kazakhstan, 1963. (In Russian)
15. Kornilova, V.S. *New Species of Tertiary Flora from Turgay and Their Stratigraphic Significance*; Scientific Notes of Kazakh State University Named after S.M. Kirov, XXI, Biology and Soil Science; Kazakh State University: Almaty, Kazakhstan, 1956. (In Russian)
16. Zhilin, S.G. Main Stages of the Formation of Temperate Forest Flora in the Oligocene–Early Miocene of Kazakhstan. Komarov Lecture Series No. 33; 2024, pp. 1–112. Available online: https://www.jstor.org/stable/4354136 (accessed on 29 September 2024). (In Russian)
17. Zhilin, S.G. The standard floras and their importance in the correlation of the continental deposition. In *Abstracts of the 31th Session of the All-Union Palaeontological Society "Rise and Evolution of the Continental Biotas"*; Nauka: Leningrad, Russia, 1985; pp. 23–24. (In Russian)
18. Zhilin, S.G. Structure of the Turgayan flora in the Oligocene and Miocene and its palaeoclimatic features. *Acta Palaeobot.* **2002**, *41*, 141–146.
19. Tokar, L.B.; Shilin, P.V. Miocene floras of the Turgay depression and their significance for palaeofloristic studies. *Proc. Inst. Geol. Mineral.* **2008**, *51*, 123–132. (In Russian)
20. Golubeva, L.A. Turgay flora and its significance for palaeofloristic and palaeoclimatic reconstructions. *Bull. Mosc. Soc. Nat. Dep. Geol.* **2006**, *81*, 54–62. (In Russian)
21. Green, W.A. Loosening the CLAMP: An exploratory graphical approach to the Climate Leaf Analysis Multivariate Program. *Palaeontol. Electron.* **2006**, *9*, 1–17.
22. Spicer, R.A. *CLAMP, Climate Leaf Analysis Multivariate Program*; The Open University: Milton Keynes, 2016.
23. Tosal, A.; Verduzco, O.; Martín-Closas, C. CLAMP-based palaeoclimatic analysis of the late Miocene (Tortonian) flora from La Cerdanya Basin of Catalonia, Spain, and an estimation of the palaeoaltitude of the eastern Pyrenees. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2021**, *564*, 110186. [CrossRef]
24. Yang, J.; Wang, Y.F.; Spicer, R.A.; Mosbrugger, V.; Li, C.S.; Sun, Q.G. Climatic reconstruction at the Miocene Shanwang basin, China, using leaf margin analysis, CLAMP, coexistence approach, and overlapping distribution analysis. *Am. J. Bot.* **2007**, *94*, 599–608. [CrossRef]
25. Ivanov, D.; Tsenov, B.; Utescher, T.; Kováčová, M.; Mosbrugger, V.; Ashraf, A.R. Climate reconstructions based on Miocene leaf flora from NW Bulgaria: Comparing leaf physiognomy and nearest living relative approach. *Phytol. Balc.* **2019**, *25*, 137–144.
26. Hayes, P.A.; Francis, J.E.; Cantrill, D.J.; Crame, J.A. Palaeoclimate analysis of Late Cretaceous angiosperm leaf floras, James Ross Island, Antarctica. *Geol. Soc. Lond. Spec. Publ.* **2006**, *258*, 49–62. [CrossRef]
27. He, W.; Roth-Nebelsick, A.; Sun, B. Leaf trait data of two Miocene floras from eastern China and its palaeoclimate implications. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2023**, *634*, 26.2.a23. [CrossRef]

28. Uhl, D.; Bruch, A.A.; Traiser, C.; Klotz, S. Palaeoclimate estimates for the Middle Miocene Schrotzburg flora (S Germany): A multi-method approach. *Int. J. Earth Sci.* **2006**, *95*, 1071–1085. [CrossRef]
29. Uhl, D.; Klotz, S.; Traiser, C.; Thiel, C.; Utescher, T.; Kowalski, E.; Dilcher, D.L. Cenozoic paleotemperatures and leaf physiognomy—A European perspective. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2007**, *248*, 24–31. [CrossRef]
30. Nguyen, H.B.; Huang, J.; Van Do, T.; Nguyen, H.M.T.; Li, S.F.; Nguyen, M.T.; Doan, H.D.; Zhou, Z.-K.; Spicer, R.A.; Su, T. Monsoon influence on plant diversity in northern Indochina: Evidence from the late Miocene Yen Bai flora, northern Vietnam. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2024**, *634*, 111925. [CrossRef]
31. Spicer, R.A.; Herman, A.B.; Kennedy, E.M. Foliar physiognomic record of climatic conditions during dormancy: Climate leaf analysis multivariate program (CLAMP) and the cold month mean temperature. *J. Geol.* **2004**, *112*, 685–702. [CrossRef]
32. Spicer, R.A.; Valdes, P.J.; Spicer, T.E.V.; Craggs, H.J.; Srivastava, G.; Mehrotra, R.C.; Yang, J. New developments in CLAMP: Calibration using global gridded meteorological data. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2009**, *283*, 91–98. [CrossRef]
33. Spicer, R.A.; Yang, J. Quantification of uncertainties in fossil leaf paleoaltimetry: Does leaf size matter? *Tectonics* **2010**, *29*, TC6001. [CrossRef]
34. Mosbrugger, V.; Utescher, T.; Dilcher, D.L. Cenozoic Continental Climatic Evolution of Central Europe. *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 14964–14969. [CrossRef]
35. Utescher, T.; Bruch, A.A.; Erdei, B.; François, L.; Ivanov, D.; Jacques, F.M.B.; Kern, A.K.; Liu, Y.-S.; Mosbrugger, V.; Spicer, R.A. The coexistence approach—Theoretical background and practical considerations of using plant fossils for climate quantification. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2014**, *410*, 58–73. [CrossRef]
36. Grímsson, F.; Denk, T.; Zetter, R. Fagaceae pollen from the early Oligocene of Central Europe and the Late Oligocene of Iceland: A morphometric approach. *Grana* **2015**, *54*, 1–28.
37. Bruch, A.A.; Zhilin, S.G. Early miocene climate of Central Eurasia—Evidence from Aquitanian floras of Kazakhstan. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2007**, *248*, 32–48. [CrossRef]
38. Popova, S.; Tarasevich, V.; Utescher, T.; Li, S.; Mosbrugger, V. Rupelian Kazakhstan Floras in the Context of Early Oligocene Climate and Vegetation in Central Asia. *Terra Nova* **2021**, *33*, 383–399. [CrossRef]
39. Utescher, T.; Mosbrugger, V.; Ashraf, A.R. Terrestrial climate evolution in northwest Germany over the last 25 million years. *Palaios* **2000**, *15*, 430–449. [CrossRef]
40. Utescher, T.; Bruch, A.; Mosbrugger, V. The Palaeoflora Database—Documentation and Data. *Zenodo* **2024**. [CrossRef]
41. Bruch, A.A.; Kovar-Eder, J. Climatic evaluation of the flora from Oberdorf (Styria, Austria, Early Miocene) based on the Coexistence Approach. *Phytol. Balc.* **2003**, *9*, 175–185.
42. Thiel, C.; Klotz, S.; Uhl, D. Palaeoclimate Estimates for Selected Leaf Floras from the Late Pliocene (Reuverian) of Central Europe Based on Different Palaeobotanical Techniques. *Turk. J. Earth Sci.* **2012**, *21*, 263–287. [CrossRef]
43. Kazhydromet. Climate Characteristics of the Regions of Kazakhstan. Kazhydromet 2024. Available online: https://www.kazhydromet.kz/uploads/files/72/file/5ec145504ea54-oblast.pdf (accessed on 1 November 2024). (In Russian)
44. Wolfe, J.A. Paleoclimatic estimates from Tertiary leaf assemblages. *Annu. Rev. Earth Planet. Sci.* **1995**, *23*, 119–142. [CrossRef]
45. Herold, N.; Seton, M.; Muller, R.D.; You, Y.; Huber, M. Middle Miocene Tectonic Boundary Conditions for Use in Climate Models. *Geochem. Geophys. Geosyst.* **2008**, *9*, Q10009. [CrossRef]
46. Zhilin, S.G. *Tertiary Floras of Ustyurt*; Komarov Botanical Institute of the Academy of Sciences of the USSR: Leningrad, Russia, 1974. (In Russian)
47. Zachos, J.C.; Pagani, M.; Sloan, L.; Thomas, E.; Billups, K. Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present. *Science* **2001**, *292*, 686–693. [CrossRef]
48. Zhang, Z.; Wang, H.; Guo, Z.; Jiang, D. Impact of Topography and Land-Sea Distribution on East Asian Paleoenvironmental Patterns. *Adv. Atmos. Sci.* **2006**, *23*, 258–266. [CrossRef]
49. Spicer, R.A.; Herman, A.B.; Wolfe, J.A. CLAMP. In *Encyclopedia of Paleoclimatology and Ancient Environments*; Springer: Berlin/Heidelberg, Germany, 2008; pp. 156–158.
50. Zhilin, S.G. Methods and problems of palaeofloristics (on the material of the Paleogene and the Neogene floras of Kazakhstan). In *Development of the Flora in Kazakhstan and Russian Plain from the Eocene to the Miocene*; Zhilin, S.G., Ed.; Nauka: Leningrad, Russia, 1991; Volume 2, pp. 98–127, (In Russian with English Summary).
51. Nigmatova, S.; Zhamangara, A.; Akmagambet, S.; Madyarova, I.; Abubakirova, N.; Kashaganov, K.; Seidali, A.; Zadagali, A. *Possibilities for Reconstructing the Paleoclimate of the Paleogene and Neogene based on the Study of Fossil Flora (Using the Example of the Paleoflora of the Uly-Zhilanshik River)*; Bulletin of the LN Gumilyov Eurasian National University—Chemistry, Geography, Ecology Series; Astana: Almaty, Kazakhstan, 2023; Volume 145, pp. 71–82. (In Russian)