Article

Not peer-reviewed version

Revisiting the Permian Stratigraphy of the Kuznetsk Coal Basin Using Radioisotopic Data: Sedimentology, Biotic Events, and Palaeoclimate

Vladimir V. Silantiev *, Yaroslav M. Gutak , Marion Tichomirowa , Alexandra Käßner , Anna V. Kulikova , Sergey I. Arbuzov , Nouria G. Nurgalieva , Eugeny V. Karasev , Anastasia S. Felker , Maria A. Naumcheva , Aleksandr S. Bakaev , Lyubov G. Porokhovnichenko , Nikolai A. Eliseev , Veronika V. Zharinova , Dinara N. Miftakhutdinova , Milyausha N. Urazaeva

Posted Date: 7 May 2025

doi: 10.20944/preprints202505.0345.v1

Keywords: Permian; Kuznetsk Basin; regional stratigraphy; U–Pb geochronology; sedimentary hiatus; coal-bearing succession; biotic events; palaeoclimate reconstruction

Article

Revisiting the Permian Stratigraphy of the Kuznetsk Coal Basin Using Radioisotopic Data: Sedimentology, Biotic Events, and Palaeoclimate

Vladimir V. Silantiev [1,2,*], Yaroslav M. Gutak [3], Marion Tichomirowa [4], Alexandra Käßner [4], Anna V. Kulikova [1], Sergey I. Arbuzov [5,6], Nouria G. Nurgalieva [1], Eugeny V. Karasev [7], Anastasia S. Felker [7], Maria A. Naumcheva [7], Aleksandr S. Bakaev [7], Lyubov G. Porokhovnichenko [8], Nikolai A. Eliseev [2], Veronika V. Zharinova [1,2], Dinara N. Miftakhutdinova [1,2] and Milyausha N. Urazaeva [1]

[1] Institute of Geology and Petroleum Technology, Kazan (Volga Region) Federal University, 420008 Kazan, Russia
[2] Department of Earth Sciences, Branch of the Kazan (Volga Region) Federal University, 130100 Jizzakh, Uzbekistan
[3] Institute of Mining and Geosystems, Siberian State Industrial University, 654007 Novokuznetsk, Russia
[4] Institute of Mineralogy, Technical University Bergakademie Freiberg, 09599 Freiberg, Germany
[5] School of Earth Sciences & Engineering, National Research Tomsk Polytechnic University, 634050 Tomsk, Russia
[6] Far East Geological Institute, Far Eastern Branch of the Russian Academy of Sciences, 690022 Vladivostok, Russia
[7] Borrisiak Palaeontological Institute of the Russian Academy of Sciences, 117647 Moscow, Russia
[8] Faculty of Geology and Geography, National Research Tomsk State University, 634050 Tomsk, Russia
* Correspondence: vladimir.silantiev@kpfu.ru

Abstract: Radioisotopic dating of five stratigraphic levels within the Permian succession of the Kuznetsk Coal Basin refines the ages of the corresponding stratigraphic units and, for the first time, enables their direct correlation with the International Chronostratigraphic Chart (2024). The analysis reveals significant discrepancies between the updated ages and the previously accepted regional scheme (1982–1996). A comparison of the durations of regional stratigraphic units with estimated rates of coal and siliciclastic sediment accumulation indicates that the early Permian contains the most prolonged stratigraphic hiatuses. The updated stratigraphic framework enables a re-evaluation of the temporal sequence of regional sedimentological, volcano-tectonic and biotic events, allowing for more accurate comparison with the global record. Palaeoclimate reconstructions indicate that during the early Permian, the Kuznetsk Basin was characterised by a relatively warm, humid, and aseasonal climate, consistent with its mid-latitude position during the Late Palaeozoic Ice Age. In contrast, the middle to late Permian shows a transition to a temperate, moderately humid climate with pronounced seasonality, differing from the warmhouse conditions of low-latitude palaeoequatorial regions. The latest Lopingian reveals a distinct trend toward increasing dryness, consistent with global palaeoclimate signals associated with the end-Permian crisis.

Keywords: Permian; Kuznetsk Basin; regional stratigraphy; U–Pb geochronology; sedimentary hiatus; coal-bearing succession; biotic events; palaeoclimate reconstruction

1. Introduction

The Permian Period was a time of profound geological, climatic, and biotic transformations, which are recorded in sedimentary basins worldwide [1–3]. Understanding the timing and nature of these processes requires accurate and regionally constrained stratigraphic frameworks [4–6]. In the

 doi:10.20944/preprints202505.0345.v1

Kuznetsk Coal Basin (Western Siberia), regarded as a reference region for the stratigraphy of the Siberian palaeocontinent, the regional stratigraphic scheme currently in use – developed over 40 years ago [7] – remains largely unchanged [8], despite major advances in geochronology [9]. In particular, the lack of reliable radioisotopic age constraints has limited the direct correlations with the International Chronostratigraphic Chart and restricted the integration of regional sedimentological data and biotic events into the global record [10]. This study presents both previously published [11–13] and new U–Pb zircon ages from five stratigraphic levels within the Permian succession of the basin, enabling refinement of the regional stratigraphic framework. The results provide new insights into stratigraphic discontinuities, event correlation, and palaeoclimatic conditions in the mid-latitudes of the Siberian palaeocontinent during the Permian.

The problem of correlating the regional Permian scheme of the Kuznetsk Basin with the Standard Global Chronostratigraphic Scale (SGCS) has been debated for decades [14–18]. Despite the high degree of investigation of the Permian coal-bearing succession in the Kuznetsk Basin [19,20], its direct correlation with the marine-based SGCS (International Chronostratigraphic Chart, 2024) [21] as well as with the General Stratigraphic Scale of Russia (GSSR) [22] remains largely tentative.

Direct biostratigraphic correlation with the SGCS is hindered by the absence of marine fossil groups – such as conodonts, fusulinids, and ammonoids – that serve as key global chronostratigraphic markers. At the same time, correlation with the Russian GSSR, whose middle and late Permian subdivisions are also primarily based on continental deposits [23], is complicated by the palaeogeographic and biogeographic isolation of the Kuznetsk Basin during the Late Palaeozoic. This isolation resulted in a high degree of endemism in its floral and faunal assemblages [24–26].

The aim of this study is to refine the geochronological boundaries of the Permian deposits of the Kuznetsk Coal Basin and to revise the regional stratigraphic framework based on new radioisotopic ages. This involved U-Pb zircon dating from two newly sampled stratigraphic levels using CA-ID-TIMS and LA-ICP-MS methods, together with the integration of previously published dates from three additional levels. The ages obtained were compared with the International Chronostratigraphic Chart (ICC) enabling direct correlation. A comparative analysis was made between the updated stratigraphic framework and the officially adopted 1982-1996 regional stratigraphic scheme. Particular attention was paid to evaluating the duration of stratigraphic hiatuses and the completeness of the sedimentary record within regional units. Finally, the refined chronology was used to interpret the sequence of regional sedimentological, biotic and palaeoclimatic events within the broader context of global environmental changes during the Permian.

2. Geological Setting

The Kuznetsk Coal Basin is one of the largest in Siberia. It is located in the northern part of the Altai-Sayan Folded Area, between the Caledonian and Hercynian orogenic belts (Figure 1A, B). According to current geological models, the Kuznetsk Basin represents a Late Palaeozoic foreland depression formed during the accretion and collision of the Siberian palaeocontinent with the terranes of the Palaeo-Asian Ocean [27,28]. Its eastern and southern boundaries are marked by the Caledonian structures of the Kuznetsky Alatau and Gornaya Shoria, while its western and northern margins are adjacent to the Hercynian mobile belts of the Salair and Kolyvan-Tomsk zones [29].

Basin formation began in the Middle Devonian, during the early stages of Hercynian orogeny, and was accompanied by the ingression of a marine basin [30]. Marine sedimentation continued until the Visean. Starting from the Serpukhovian, several phases of folding changed the depositional environment from marine to continental, initiating the accumulation of clastic and coal-bearing deposits. Subsequent tectonic uplift led to block deformation and partial erosion of the previously deposited sequences. The present configuration of the basin was established in the Early Cretaceous, following tectonic stability of the region [31].

General Characteristics of the Coal-Bearing Succession. The upper part of the Carboniferous and the entire Permian system in the Kuznetsk Basin consists of continental clastic and coal-bearing deposits

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 May 2025 doi:10.20944/preprints202505.0345.v1

with a total thickness of 7000–8000 m. The greatest thicknesses are observed in the central and western areas of the basin (Figure 1C), where the most complete stratigraphic sections are located.

Lithologically, the succession includes sandstones, siltstones, and mudstones, containing both thick coal seams and thin carbonaceous interbeds. Subordinate occurrences of gritstone and conglomerate lenses are typically associated with the base of sedimentary cycles. The average coal content in the succession ranges from 1 to 6%, although it may reach up to 14.5% in certain formations [31].

The coal-bearing succession is divided into the Balakhonka and Kolchugino Groups, which in turn contain subordinate subgroups, formations, and regional stages. The boundary between the two groups is defined lithologically by the transition from coal-bearing strata with productive coal seams to a thick (up to 1000 m) barren interval (Kuznetsk Subgroup) [20]. Biostratigraphically, this boundary coincides with the replacement of two major floral assemblages: the Balakhonka flora (dominated by cordaitoids) is replaced by the Kolchugino flora (characterised by ferns, pteridosperms, and cordaitoids) [10,19,20]. Our recently published radioisotopic data indicate that the transition from Balakhonka to Kolchugino floras occurred in the late Kungurian [13].

The Balakhonka Group comprises siliciclastic and coal-bearing strata ranging in thickness from 1300 to 3200 m and corresponds to the Pennsylvanian (Lower Balakhonka Subgroup) and Cisuralian (Upper Balakhonka Subgroup).

The Lower Balakhonka Subgroup is 900–980 m thick in the Kemerovo reference area. It consists predominantly of sandstones (39%), siltstones (38%), mudstones (19%), and coals (2%), with minor lenses of gritstone and conglomerate, along with carbonate and sulphide concretions. The coal content is low, with numerous but thin coal seams. Fine-grained sandstones dominate, frequently interbedded with siltstones to form rhythmic, millimetre-scale lamination.

The Upper Balakhonka Subgroup, 700 to 2000 m thick, comprises three formations (Fms): Promezhutochnaya (Transitional), Ishanova, and Kemerovo. In the type section (Kemerovo region), the subgroup is 700–1000 m thick and consists of sandstones (50%), siltstones (40%), mudstones (6%), and coals (4%), with minor occurrences of gritstones and concretions. The subgroup is characterised by pronounced lateral and vertical variations in thickness and lithological composition, including substantial heterogeneity in coal content and type across the basin [31].

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 May 2025 doi:10.20944/preprints202505.0345.v1

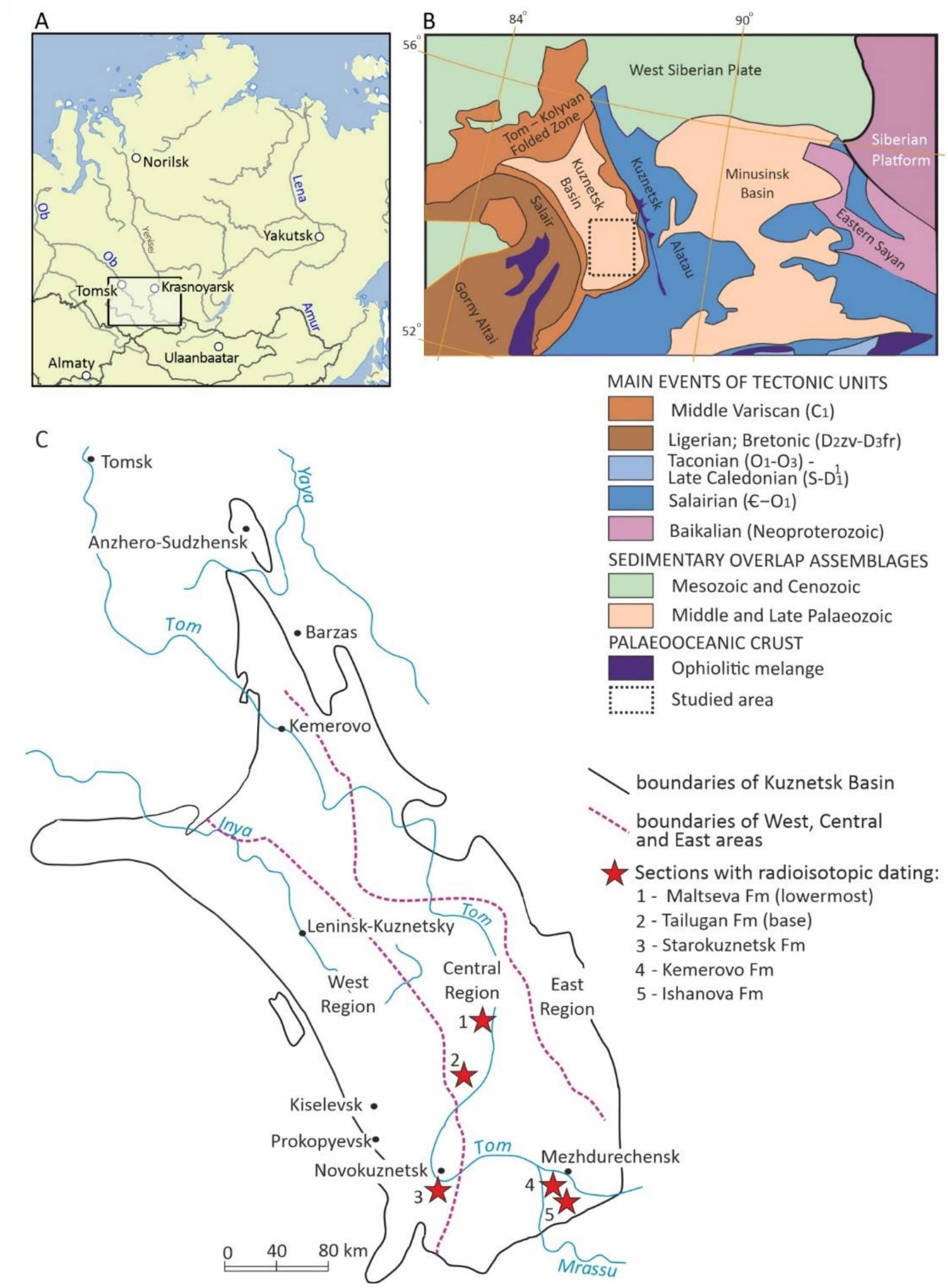


Figure 1. Overview map (A) with outlines of the tectonic scheme (B) showing the position of the study area within the Altai–Sayan fold belt, and (C) the locations of studied sections; simplified from [32–34].

The Kolchugino Group, up to 6000 m thick, spans the upper part of the Cisuralian and the entire Guadalupian and Lopingian series of the Permian system. It includes seven Fms: Starokuznetsk and Mitina (Cisuralian); Kazankovo-Markina, Uskat, and Leninsk (Guadalupian); and Gramoteino and Tailugan (Lopingian).

The lower boundary of the group is lithological defined in the roof of the upper productive coal seam of the Upper Balakhonka subgroup (coal seam Aralicheva I), and generally corresponds to a subregional depositional hiatus. The upper boundary is marked by the replacement of coal-bearing strata with volcanogenic and siliciclastic rocks of the Abinsk Group, mainly of Triassic age. In complete sections, a gradual transition from the coal-bearing Tailugan Fm to the tuffaceous–clastic Maltseva Fm is observed, making the boundary between the Kolchugino and Abinsk Groups transitional and conventional.

Pyroclastic material and associated clay interbeds – including tuffs, tuffites, montmorillonite clays, and kaolinitic tonsteins – are important components of the Permian coal-bearing strata of the

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 May 2025 doi:10.20944/preprints202505.0345.v1

Kuznetsk Basin [35–37]. These clays, primarily composed of kaolinite and montmorillonite, are widely interpreted as alteration products of volcanic ash. Among them, tonsteins – hard, usually light-coloured, kaolinite-rich layers commonly found within coal seams – are of particular interest due to their mineral composition and suitability for high-precision geochronology.

The origin of these ash-derived layers is linked to volcanic activity in surrounding fold belts [38]. In siliciclastic settings, volcanic ash was transformed into plastic montmorillonite clays, whereas in swampy peat-forming environments, it formed kaolinitic tonsteins. These are distinguishable from host coals by their light colour, lack of bedding, and occasional presence of idiomorphic zircon grains.

The mineralogical and geochemical characteristics of these pyroclastic layers, including rare earth and radioactive element concentrations, have been examined in detail in several studies [39,40].

Palaeobiogeographic context: Angaraland. The close palaeogeographic position of the Kuznetsk Basin to the Siberian Platform during the Late Palaeozoic resulted in remarkable floral and faunal similarities between these regions. This vast area was characterised by unique, largely endemic plant and animal assemblages that differed significantly from those of Euramerica (Laurussia) and Gondwana. The high degree of floral and faunal endemism formed the basis for defining a separate palaeobiogeographical province – the Angaran Realm (or Angaraland), encompassing biotically related regions across the Siberian palaeocontinent [24].

The Kuznetsk Basin is traditionally considered as the reference region of Angaraland. The Carboniferous and Permian floral and faunal assemblages preserved in the basin provide a framework for reconstructing the evolutionary history of continental ecosystems throughout Angaraland and are widely used in interregional biostratigraphic correlations [10,15,18–20].

Despite the pronounced floral and faunal endemism of Angaraland, available data on the distribution of certain taxonomic groups among terrestrial plants, conchostracans, non-marine ostracods and bivalves, and freshwater fishes suggest episodes of intermittent biotic exchange between Angaraland, Euramerica and Gondwana. These exchanges likely occurred during discrete intervals, enabled by the temporary opening of migration corridors [12,17,19,41].

Changes in the Permian stratigraphy. The International Stratigraphic Scale of the Permian was revised in 2004, introducing a threefold division: the Cisuralian, Guadalupian, and Lopingian series. Over the past two decades, considerable progress has been made in defining global chronostratigraphic boundaries. This includes the formal ratification of Global Stratotype Sections and Points (GSSPs) for most Permian stages, the acquisition of precise radioisotopic age constraints, and refinement of the boundaries with both the Carboniferous and Triassic systems [1–3].

Corresponding updates have been incorporated into the General Stratigraphic Scale of Russia (GSSR), albeit with certain regional distinctions. While the Cisuralian series corresponds to its international counterpart in both name and extent, the middle and upper parts of the Permian are represented by the Biarmian and Tatarian series, respectively – units that diverge from the International Chart in both terminology and temporal range [22,23].

The revision of the International Permian timescale coincided with a decline in geological mapping activity, both within the Kuznetsk Basin and more widely in the coal-bearing regions of the Altai-Sayan fold belt. As a result, these updates have not been adequately reflected in regional stratigraphy.

The regional stratigraphic scheme of the coal-bearing strata of the Kuznetsk Basin, formally adopted in 1982 [7] and only slightly revised thereafter [8], remains the main working framework for both the Kuznetsk Basin and adjacent regions [18–20]. The scheme is highly detailed, comprising groups, subgroups, formations and regional stages defined on the basis of floral and faunal evidence. Its resolution is supported by extensive data from cores of thousands of exploration wells, as well as from numerous mine sections and natural outcrops. However, much of this empirical knowledge is becoming outdated and is increasingly in need of revision using modern techniques. The last comprehensive summary of regional stratigraphic research was published over three decades ago in the volume 'Kuzbass – A Key Region in the Stratigraphy of Angaraland...' [20].

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 May 2025 doi:10.20944/preprints202505.0345.v1

Despite updates to the International Timescale, current State geological mapping of the Kuznetsk Basin and adjacent coal-bearing regions [42] continue to be based on the 1982–1996 regional stratigraphic scheme [7,8]. In some cases, i.e. the Geological Map of the Kuznetsk Basin [43], the stratigraphic subdivision of the Permian has been aligned with the International Timescale and/or the GSSR. However, this alignment is largely formal, achieved by 'mechanically' transferring the threefold division of the Permian into the framework of the 1982–1996 regional scheme [44].

Thus, the modern International Chronostratigraphic Scale and the outdated regional scheme coexist in parallel within regional practice. This dual framework requires refinement using independent methods, primarily high-precision radioisotopic dating.

The problem of stratigraphic continuity. The Late Palaeozoic coal-bearing strata of the Kuznetsk Basin are generally considered by most researchers to be a continuous sedimentary record, interrupted only by a single local unconformity at the boundary between the Balakhonka and Kolchugino groups [19,45]. The duration of this unconformity is usually estimated to be much shorter than that of the stratigraphic units it separates [8].

Since the early 1990s, it has been argued that palaeontologists have underestimated potential hiatuses in the coal-bearing succession. For example, Sivtchikov [46] noted that efforts to construct an artificially continuous sequence of faunal and floral assemblages often resulted in incorrect taxonomic definitions and unreliable correlations. More recently, using radioisotopic dating in the adjacent Minusinsk Basin, we estimated the duration of one such hiatus to be approximately 7 Ma [47].

3. Materials

The tonstein samples used for zircon extraction and new radioisotopic dating derive from the Ishanova Fm, coal seam XXX (sample G23-18), South Mezhdurechensk coal field, and the Kemerovo Fm, coal seam VI (sample G23-15), Mezhdurechensk coal field (Figures 1, 2).

This study also considers previously published $^{206}Pb/^{238}U$ age data: (a) Maltseva Fm, volcanic ash beds in the lower part of the formation (252.78 ± 0.06 Ma, 252.65 ± 0.08 Ma and 252.33 ± 0.08 Ma) [11], (b) Tailugan Fm, tonsteins in the lowermost coal seam 78 (257.0 ± 1.3 Ma, 256.6 ± 0.4 Ma) [12]; (c) Starokuznetsk Fm, volcanic ash bed in the middle part (276.9 ± 0.4 Ma) [13].

The material used for biostratigraphic analysis and reconstruction of the sequence of biotic events was studied using original field collections and museum specimens examined between 2022 and 2025. Information on the main collections and fossil preservation is given below.

The ostracods come from the monographic collections of M.O. Mandelstam, stored in the Aprelevka branch of the All-Union Research Geological Petroleum Institute, coll. 223, 233, 238, 245, 265, 283, 251; mostly represented by single valves, molds and imprints; the preservation of the material is usually poor.

Insects were studied from original collections and material housed in the Paleontological Institute of the Russian Academy of Sciences (PIN RAS), Moscow. Examined specimens include: coll. 742, 840, 1079 (Lower Balakhonka); coll. 504, 679, 966, 1197, 1424 (Upper Balakhonka); coll. 1292 (Ishanova Fm); coll. 503, 598, 746, 1283, 1435, 5922 (Starokuznetsk Fm). Insect remains are mostly represented by isolated elytra, more rarely by body fragments of apterygotes and disarticulated parts (legs, sclerites) of pterygote orders.

Non-marine bivalves were studied using material from several institutional collections: the Central Scientific Research Geological Prospecting Museum (CSRGP Museum), St. Petersburg (D.M. Fedotov coll. 4672); the Geological Museum of the Territorial Geological Information Fund (GMTGIF), Novokuznetsk (P.A. Tokareva coll. 1342); and the Central Siberian Geological Museum, Novosibirsk (O.A. Betekhtina coll. 295).

Fish remains were examined from the collections of the CSRGP Museum (coll. 2409) and the PIN RAS (coll. 612, 1288, 5784, 5797). The material includes abundant isolated scales, teeth, bones, and complete skeletons.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 May 2025 doi:10.20944/preprints202505.0345.v1

Plant remains were studied from the collections of the CSRGP Museum (coll. 573, 4898, 5374, 6307, 8269, 9247, 9259) and the GMTGIF (coll. 2553, 2579, 2771). The assemblages are represented by mineralised wood fragments and impressions of vegetative and reproductive organs.

4. Methods and Approaches

A detailed description of the methodology used for U–Pb radioisotopic dating of zircon is provided in our previous publications [12,13,47]. In the present study, the Chemical Abrasion–Isotope Dilution–Thermal Ionisation Mass Spectrometry (CA-IDTIMS) was employed to obtain high-precision ages from individual zircon grains. Laser Ablation–Inductively Coupled Plasma–Mass Spectrometry (LA-ICP-MS) was used for rapid screening of zircon age populations based on large sample sets.

The methodology for estimating sedimentation rates (in m/Ma) for coal and siliciclastic deposits, which forms the basis for calculating the expected duration of geological unit accumulation, is described in detail in our previous works [12,48]. In this study, the coal accumulation rate is assumed to be 0.025 mm/year, which is close to the lowest values reported [12,49]. At this rate, a 100-metre-thick coal seam would require approximately 4 million years to accumulate. Assuming a compaction ratio of 10:1 for peat to coal conversion, the inferred rate of peat accumulation is 0.25 mm/year. This estimate is comparable to observed peat accumulation rates in Holocene mires of modern Europe and Siberia [50,51]. According to calculations, over the past 9200–8780 years, the average annual rate of vertical peat accumulation in Western Siberia ranged from 0.21 to 0.57 mm/year [52].

Field observations suggest that most siliciclastic sediments in the coal-bearing succession of the Kuznetsk Basin were deposited rapidly, during avalanche-like events comparable to modern mudflows – essentially instantaneously in geological terms [30]. Nevertheless, in this study we do not disregard the duration of siliciclastic accumulation and assume a rate of 0.2 mm/year – the minimum value recorded for modern siliciclastic deposition in the Gulf of Maine on the Atlantic coast of North America [53]. At this rate, and assuming uninterrupted deposition, approximately 200 m of sediment would accumulate over one million years.

Total content of depleting microcomponents in coal (ΣDm). This term refers to the cumulative content of coal microcomponents – primarily fusinite – that do not become plastic when heated, do not melt or swell, and do not release liquid or gaseous products [54]. Fusinite, one of the major inertinite macerals, is formed from woody material either by partial microbial oxidation of organic matter under aerobic conditions or as a result of wildfire and/or associated thermal alteration of peat. The wildfire-related origin is currently the prevailing interpretation among researchers, especially palaeoecologists (for a detailed review, see [55]). In general, peat-forming plant communities that contribute woody material increase ΣDm due to higher fusinite content, regardless of its specific origin. Units of ΣDm are expressed in wt%, with values normalised to the maximum observed content on an ash-free basis. At this rate, and assuming uninterrupted deposition, approximately 200 metres of sediment would accumulate in one million years.

Biotic events were identified based on key fossil localities within formations and subunits, and their levels and ranges were then correlated with the regional scheme.

5. Results

5.1. Radioisotopic Dating

Five radioisotope dated levels are currently recognised within the Permian succession of the Kuznetsk Basin. Three of these – located within the Maltseva, Tailugan and Starokuznetsk Fms – have been published previously [11–13]. The present study provides the first U–Pb age constraints for two additional levels, within the Ishanova and Kemerovo formations (Figure 2).

Ishanova Fm. High-precision CA-ID-TIMS dating of zircon from a kaolinitic tonstein layer within coal seam XXX (sample G23-18), located in the lower part of the Ishanova Fm, yielded an age of 292.00 ± 0.43 Ma. Complementary LA-ICP-MS U–Pb analyses of the same sample produced consistent

 doi:10.20944/preprints202505.0345.v1

results. Two main zircon age populations were identified: one at ~323 Ma and a second at ~292 Ma. The younger cluster yielded a concordant 206Pb/238U age of 292.5 ± 1.8 Ma (n = 22).

The CA-ID-TIMS age of 292.00 ± 0.43 Ma suggests that coal seam XXX, and thus the lower boundary of the Ishanova Formation – stratigraphically positioned at the base of coal seam XXXI – correlates with the middle Sakmarian.

Kemerovo Fm. High-precision CA-ID-TIMS dating of zircon from a kaolinitic tonstein layer within coal seam VI (sample G23-15), situated in the middle part of the Kemerovo Fm, yielded an age of 285.6 ± 0.4 Ma. This age indicates that the corresponding stratigraphic level falls within the upper Artinskian.

LA-ICP-MS U–Pb dating of a sedimentary interbed from coal seam XI (sample G23-1), initially interpreted as a tonstein, revealed a wide range of zircon ages. The sample is dominated by Phanerozoic zircons, while Precambrian grains occur only sporadically (~1571, ~748, and ~595 Ma). Among the Palaeozoic zircons, Cambrian–Ordovician ages are most frequent (74%, 29 grains), with statistically significant peaks at ~524, ~491, and ~456 Ma. Devonian zircons (25%, 10 grains) form a distinct age cluster at ~406 Ma. One younger grain yielded an age of ~334 Ma.

All zircons are prismatic crystals or fragments measuring 150–200 μm, suggesting a relatively proximal source area. Cathodoluminescence imaging shows well-developed oscillatory zoning, typical of magmatic zircons. This interpretation is further supported by Th/U ratios between 0.1 and 1.0. The broad and polymodal age distribution clearly indicates that the sample represents a detrital sedimentary layer rather than a primary tonstein.

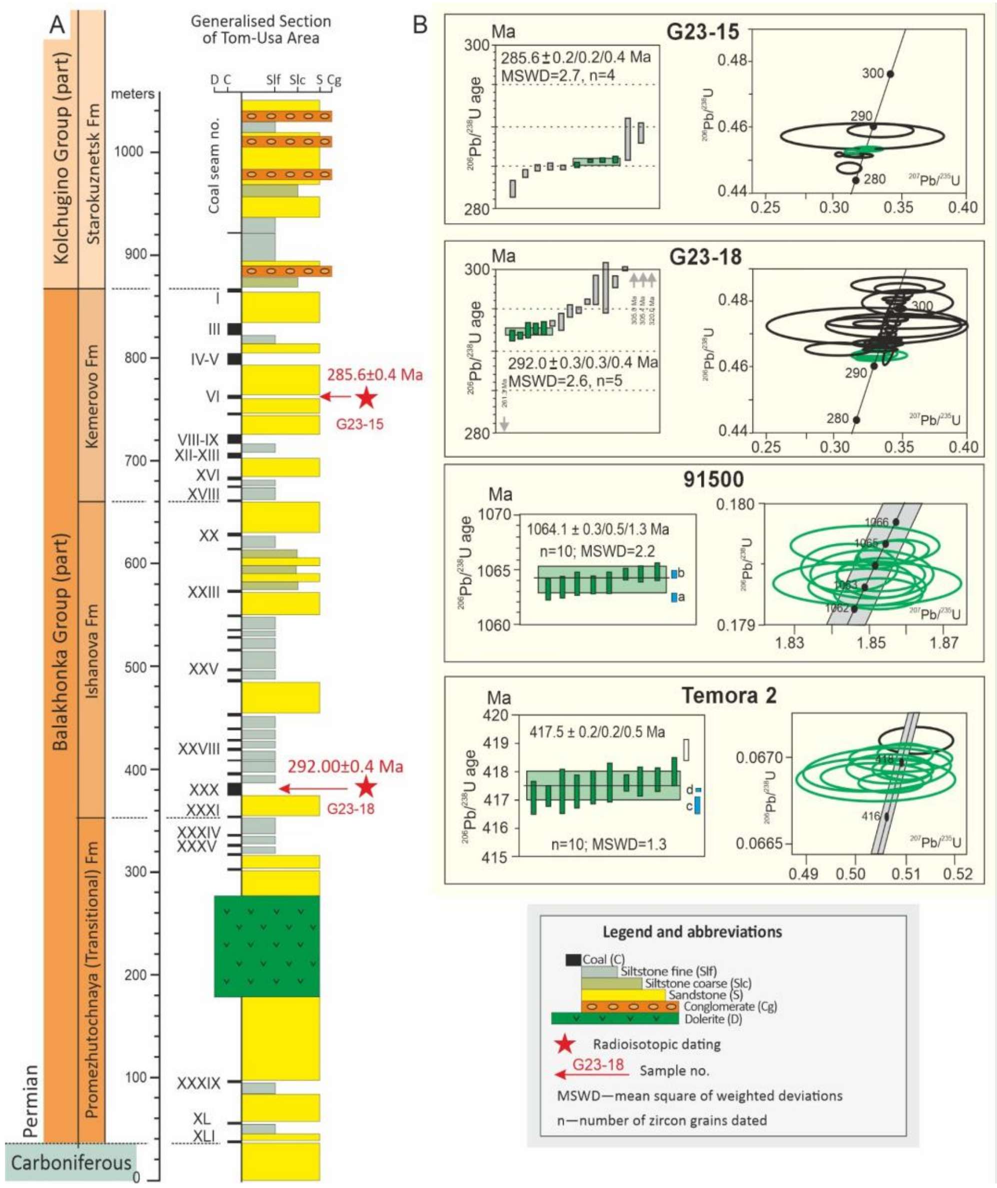


Figure 2. Generalised stratigraphic section of the Upper Balakhonka Subgroup (Cisuralian) of the Kuznetsk Coal Basin (A). Star symbols indicate new radioisotopic datings. (B) Single-zircon-grain U-Pb CA-ID-TIMS analyses shown as 206Pb/238U weighted mean dates (left column) and Concordia diagrams (right column) for both samples, G23-15 and G23-18, and two secondary standards, 91500 and Temora 2, analysed in parallel with the unknowns. In the weighted mean plots, each vertical bar represents a single zircon analysis with its 2σ analytical (internal) uncertainty; grey bars were excluded from the weighted mean calculation. Vertical green boxes denote the weighted mean age with its z-component uncertainty. The uncertainty of the weighted mean CA-ID-TIMS dates is reported as ± x/y/z, where x = 2σ internal, y = 2σ external (including tracer calibration), and z = 2σ external (including 238U decay constant uncertainty) [56]. Blue bars for the two zircon standards indicate published ages and their uncertainties (a – [57]; b – [56]; c – [58]; d – [59]). In the Concordia diagrams, green ellipses represent data points used in the 206Pb/238U weighted mean calculation; black ellipses were excluded.

The newly obtained and previously published radioisotope dates from tonsteins have been used to update the regional Permian scheme. These data provide a more accurate representation of the stratigraphic succession and its defining characteristics (Figure 3). For clarity, the updated scheme is correlated with the 2024 ICC. Figure 3 also displays interval-based information on coal content (%), number of coal seams and their cumulative thickness, total content of depleting microcomponents (ΣDm), and the total thickness of each stratigraphic unit.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 May 2025 doi:10.20944/preprints202505.0345.v1

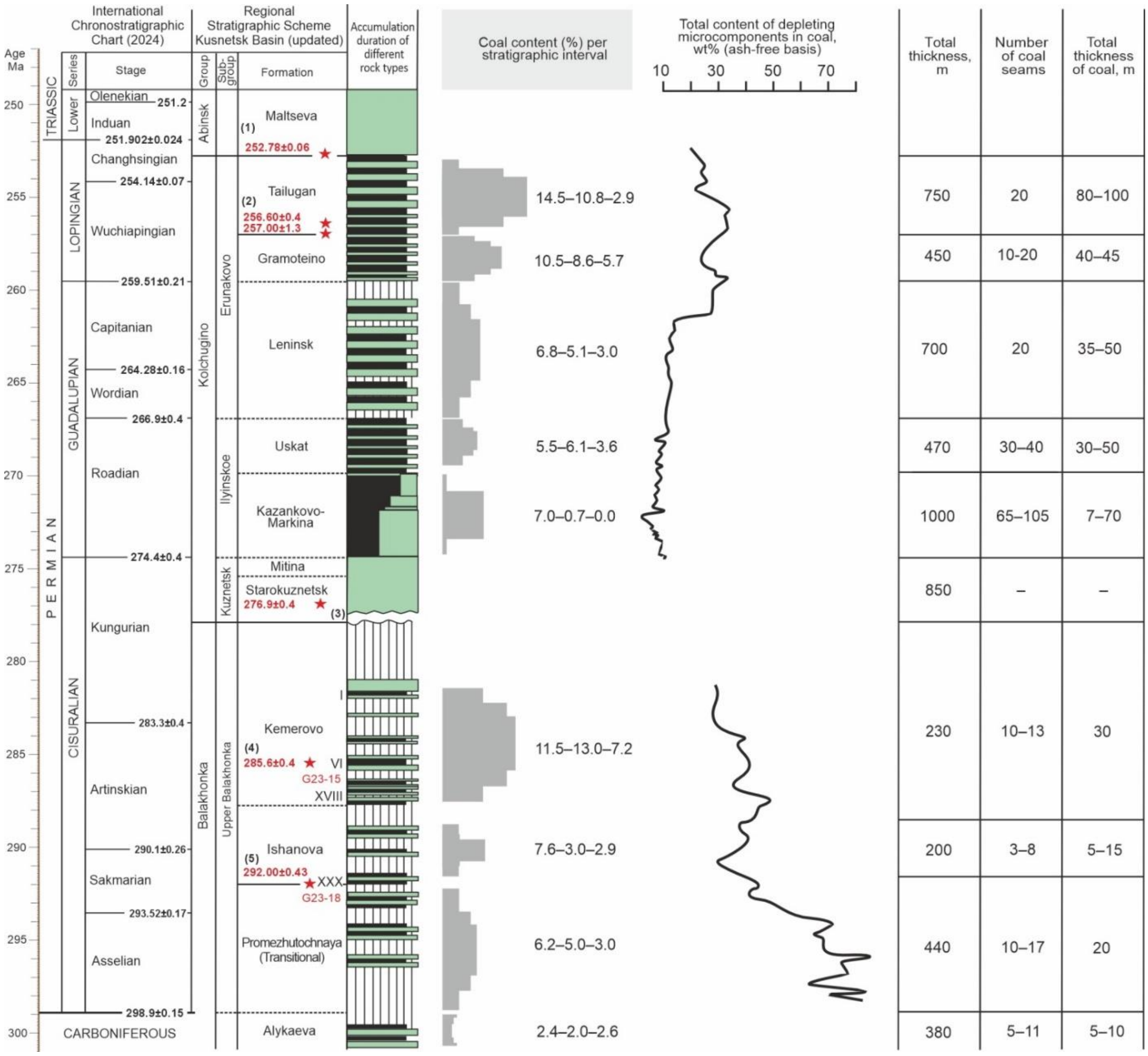


Figure 3. Updated Regional Stratigraphic Scheme of the Permian in the Kuznetsk Basin. Accumulation duration of different rock types – estimated time spans of deposition of siliciclastic (green) and coal (black) deposition; Coal content (%) is shown per stratigraphic interval for the western, central, and eastern parts of the basin [31]; Total content of depleting microcomponents in coal, wt% (ash-free basis, normalised) – values are normalised to the maximum observed content on an ash-free basis (simplified after [60]; Table at right [31]: Total thickness, m – corresponds to stratotype sections of each stratigraphic unit; Number of coal seams and Total thickness of coal, m, are given for the entire basin.

5.2. Coal Accumulation

Coal accumulation patterns show marked contrasts between the early and middle–late Permian intervals. Although both successions are of comparable duration (c. 20 Ma), they differ significantly in coal seam development. The early Permian sequence (total thickness 870 m) contains approximately 60 coal seams, with a cumulative coal thickness of up to 95 m. In contrast, the middle-late Permian sequence (c. 3000 m thick) comprises around 200 coal seams, with a cumulative thickness of up to 320 m. This represents more than a threefold increase in both the number and thickness of seams.

The available data indicate two distinct phases of coal accumulation, reflecting contrasting sedimentary regimes. These phases are separated by a long (≥ 4 Ma) depositional hiatus, partly represented by the Kuznetsk Group coal-barren interval (Figure 3).

 doi:10.20944/preprints202505.0345.v1

The total content of depleting microcomponents in coal (ΣDm) also exhibits distinct values and trends between the early Permian and middle-late Permian intervals. The early Permian interval is characterised by generally elevated ΣDm values with a decreasing trend upwards. In contrast, the middle-late Permian interval shows predominantly lower ΣDm values that gradually increase upward, culminating in a pronounced rise near the Guadalupian–Lopingian boundary (Figure 3).

The Accumulation Duration of Different Rock Types panel of Figure 3, illustrates the estimated durations of coal and siliciclastic deposition. The height of each shaded bar reflects the time span of accumulation, calculated using the sedimentation rates assumed in this study: 0.025 mm/year (25 m/Ma) for coal and 0.2 mm/year (200 m/Ma) for siliciclastic rocks.

Calculations indicate that in the upper part of the succession (Gramoteino and Tailugan Fms), the observed thicknesses of coal and siliciclastic intervals are broadly consistent with near-continuous sedimentation. For example, based on the assumed sedimentation rates, the 4.2 Ma duration of the Tailugan Fm would allow the accumulation of approximately 100 m of coal (4.2 Ma × 25 m/Ma) and 840 m of siliciclastics (4.2 Ma × 200 m/Ma). These values closely match the observed coal thickness (80–100 m) and the siliciclastic component (650–670 m).

For the Gramoteino Fm, the estimated thicknesses are ~60 m of coal (2.5 Ma × 25 m/Ma) and ~500 m of siliciclastics (2.5 Ma × 200 m/Ma), slightly exceeding the observed values of 40–45 m and 400 m, respectively. This discrepancy likely reflects current uncertainty regarding the exact position of the lower boundary of the Gramoteino Fm.

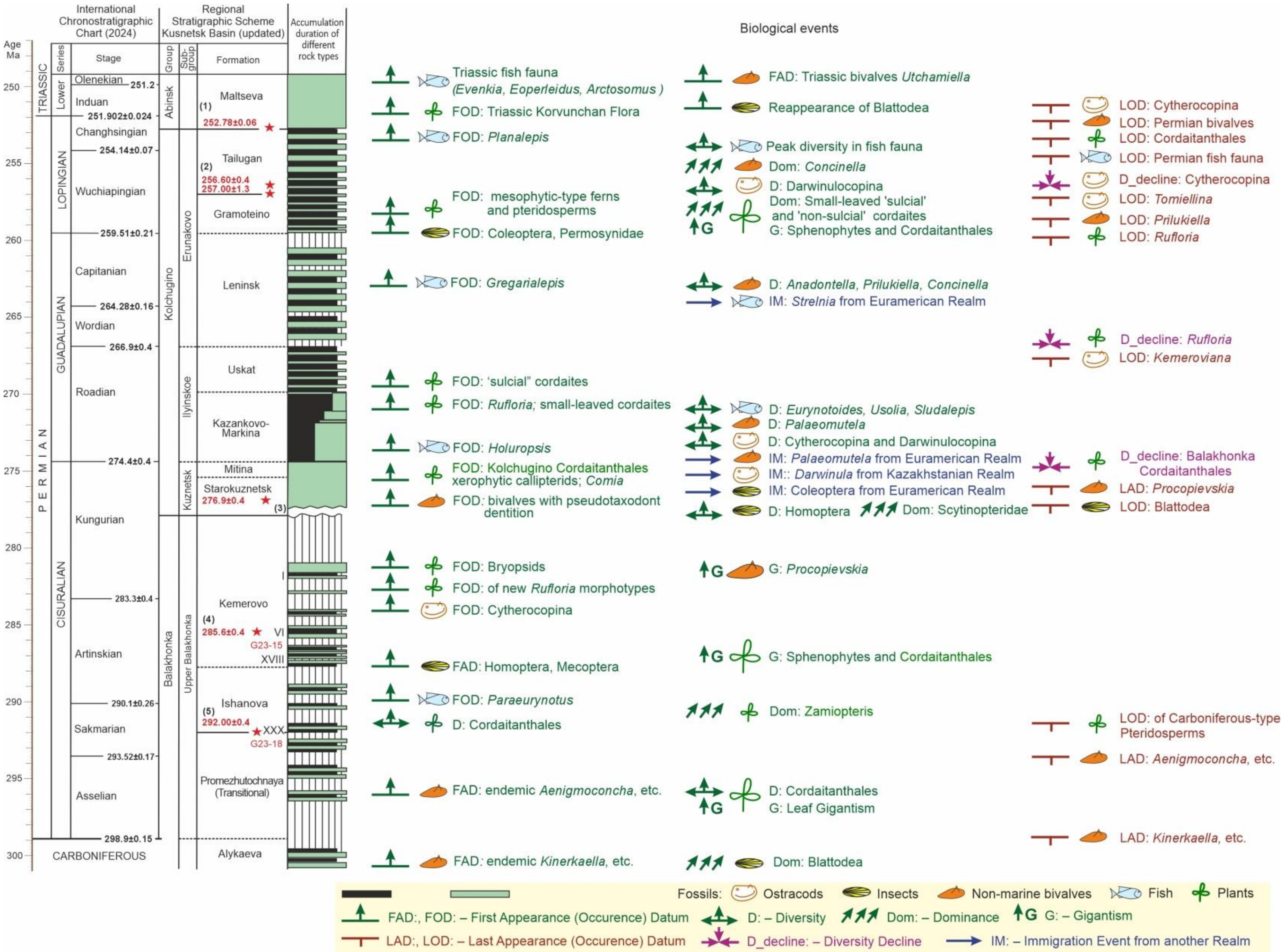
Discontinuous sedimentation and/or the most prolonged stratigraphic gaps – reducing the completeness of the geological record – are evident in the early Permian of the Kuznetsk Basin. A representative example is the Promezhutochnaya (Transitional) Fm. Its lower boundary approximately corresponds to the Carboniferous–Permian transition (298.9 ± 0.15 Ma) [21], while its upper boundary is inferred to be slightly older ~292.00 Ma, according to the new CA-ID TIMS age from the base of the overlying Ishanova Fm. Assuming uninterrupted accumulation over a span of ~6.9 Ma, the expected thicknesses would be ~165 m of coal (6.9 Ma × 25 m/Ma) and ~1380 m of siliciclastics (6.9 Ma × 200 m/Ma). In contrast, the observed values – ~20 m of coal and ~440 m of siliciclastics – are less than one-third of the predicted totals, indicating probable significant stratigraphic gaps likely due to erosion, non-deposition, or both.

For the upper part of the Kemerovo Formation – from coal seam VI to the top of coal seam I – the estimated depositional time is about 7.5 Ma (Figure 3). Based on the assumed sedimentation rates, this interval could theoretically accommodate up to 180 m of coal (7.5 Ma × 25 m/Ma) and 1500 m of siliciclastics (7.5 Ma × 200 m/Ma). The observed thicknesses are approximately 30 m of coal and 200 m of siliciclastics, indicating that the preserved strata in this interval are 6–7 times thinner than the theoretical estimates.

5.3. Biotic Events

Biotic events aligned with the updated Permian Regional Stratigraphic Scheme of the Kuznetsk Basin reveal a markedly uneven temporal distribution (Figure 4). The highest concentration of events is associated with the coal-free Kuznetsk Group (Late Kungurian; Starokuznetsk and Mitina Fms) and, as expected, with the Permian–Triassic boundary interval.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 May 2025 doi:10.20944/preprints202505.0345.v1



Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 May 2025 doi:10.20944/preprints202505.0345.v1

Figure 4. Major biotic events aligned with the updated Permian Regional Stratigraphic Scheme of the Kuznetsk Basin. Biotic events: the left column shows the first appearances or occurrences (FADs or FODs) of specific fossil groups at corresponding stratigraphic levels; the middle column indicates episodes of dominance, diversification, gigantism, or immigration; the righ t column marks extinction levels (LADs or LODs) as well as diversity declines.

 doi:10.20944/preprints202505.0345.v1

Vegetation and invertebrate gigantism – notably among Cordaitanthales, Sphenophytes, and non-marine bivalves – is recorded in three early Permian Fms: the Promezhutochnaya (Transitional), Ishanova, and Kemerovo, as well as in the late Permian Gramoteino Fm.

Faunal migrations – including ostracods, bivalves, and possibly fishes, whose diversity markedly increased during this time – are recorded within the coal-free interval of the Kuznetsk Group, corresponding to the Late Kungurian. This interval also marks the first appearance of xerophytic callipterids.

The dominance of drought-tolerant, small-leaved 'sulcial' cordaitoids with thin furrows along the veins on the upper side of the leaf and numerous false veins is characteristic of the Lopingian strata.

The Permian–Triassic boundary is marked by a profound biotic turnover across all fossil groups – plants, ostracods, insects, non-marine bivalves, and fishes. Of particular significance is the floral transition: the Permian Kolchugino Flora gives way to the Triassic Korvunchan Flora, which encompasses nearly all major lineages of early Mesozoic higher plants.

6. Discussion

The U-Pb CA-IDTIMS radioisotope ages obtained in this study provide, for the first time, a direct correlation between the Permian Regional Stratigraphic Scheme of the Kuznetsk Basin and the International Chronostratigraphic Chart (2024) [21]. Sedimentological and biotic data integrated into the revised stratigraphic framework enable reconstruction of the temporal sequence of regional depositional settings and their comparison with the global event record.

The correlation is illustrated in Figure 5. Compared with the official 1982–1996 Regional Stratigraphic scheme [7,8], which is also shown in Figure 5 for reference, the updated framework exhibits several important differences, which are outlined below.

The lower boundaries of most regional units have been shifted to older stratigraphic levels. This adjustment is directly supported by new U–Pb radioisotopic ages for five Fms – Ishanova, Kemerovo, Starokuznetsk, Tailugan, and Maltseva. For adjacent units lacking direct age constraints, boundary positions were inferred from their relative stratigraphic context. As a result, correlations between regional Fms and stages of the ICC have been significantly modified. Importantly, the downward shift of the unit boundaries are consistent with previous biostratigraphic interpretations proposed by Siberian palaeontologists [19,61]. In the updated framework, the lower boundaries of units constrained by radioisotopic data no longer coincide with ICC stage boundaries, thereby probably reducing their convention and enhancing precision (Figure 5).

The early Permian (Cisuralian) part of the revised framework now includes five regional units, reflecting the reassignment of the Kuznetsk Group – comprising the Starokuznetsk and Mitina Fms – to the upper Kungurian (corresponding to the Ufimian regional stage of the GSSR). This interpretation of the stratigraphic position of the Kuznetsk Group is supported by both radioisotope data and biostratigraphic evidence [13,19,61].

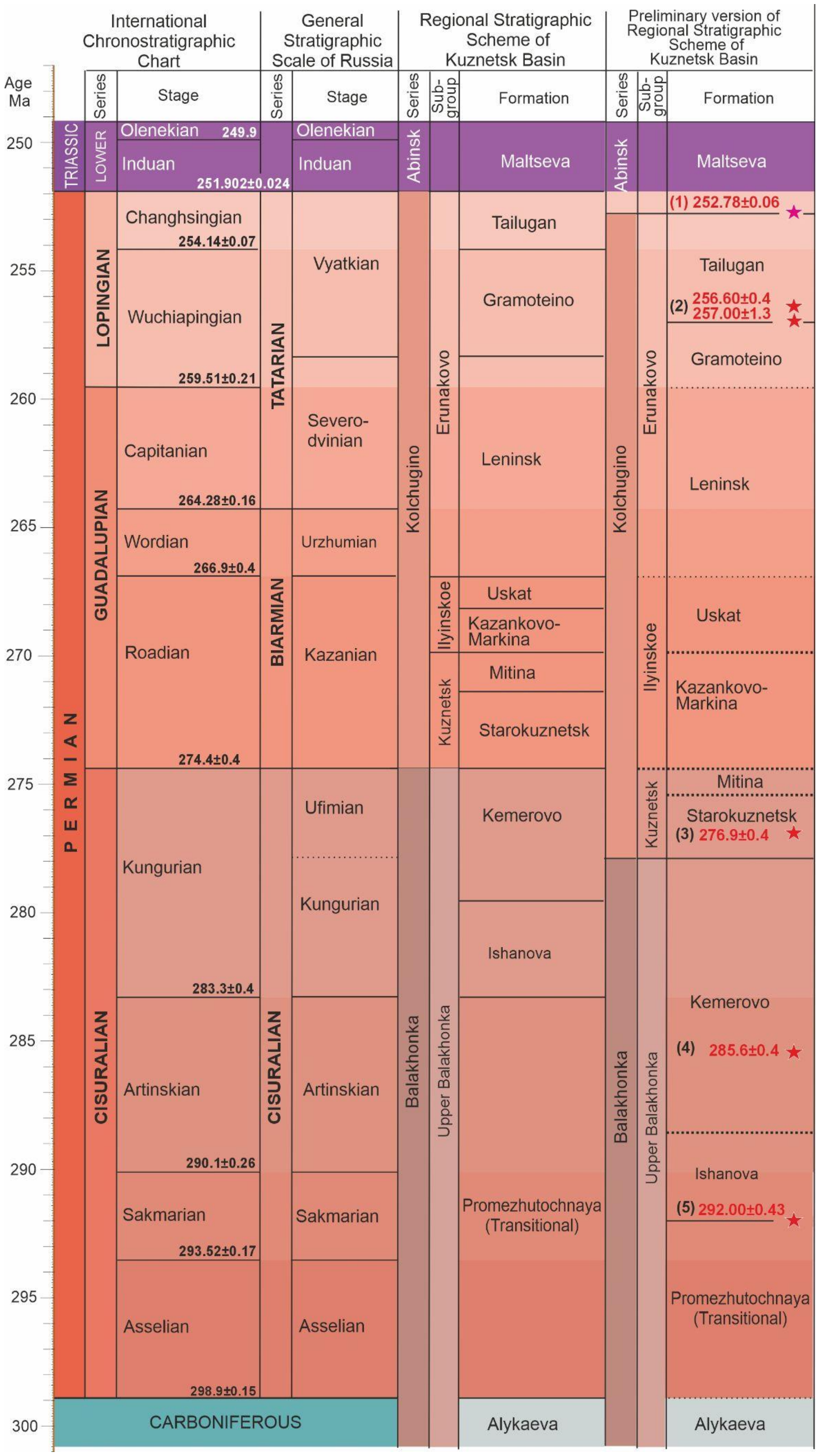


Figure 5. Permian regional stratigraphic scheme of the Kuznetsk Basin, updated based on available radioisotopic dating and correlated with the International Chronostratigraphic Chart (2024) [21] and the General Stratigraphic Scale of Russia (2019) [22]; the 1982–1996 regional stratigraphic scheme [7,8] is also shown for comparison. Radioisotopic dates marked with star symbols are based on: (1) [11]; (2) [12]; (3) [13]; (4, 5) this study.

In the Lopingian (upper) interval of the regional stratigraphic scheme, the most significant revisions involve the Tailugan and Maltseva Fms. Radioisotopic dating indicates a Wuchiapingian

 doi:10.20944/preprints202505.0345.v1

age for the base and most part of the Tailugan Fm [12], and a Changhsingian age for the basal strata of the Maltseva Fm [11].

Several issues remain unresolved and require further investigation. First, many Fms – including the Promezhutochnaya (Transitional), Mitina, Kazankovo-Markina, Uskat, Leninsk, and Gramoteino – currently lack radioisotope age constraints, making their stratigraphic position and extent provisional. Second, the duration of individual Fms varies considerably, from as little as ~1 Ma (Mitina Fm) to as much as ~9 Ma (Kemerovo Fm).

Stratigraphic hiatus and its relationship to tectonics, volcanism and climate. The new radioisotope age constraints and revised regional scheme highlight the probability of stratigraphic discontinuities and an incomplete sedimentary record, especially in the lower part of the Permian coal-bearing succession (Figures 3 and 4).

Direct evidence of an incomplete stratigraphic record – extending even into the coal seams – is provided by our LA-ICPMS and CA-IDTIMS U–Pb zircon dating of a siliciclastic interbed within coal seam XI (Kemerovo Fm). The analysis revealed both Precambrian (~1571, ~748, and ~595 Ma) and Early Palaeozoic (~524, ~491, and ~456 Ma) zircon grains within a thin layer, indicating that the sedimentary material was significantly reworked and derived from older, previously exposed and eroded source areas.

The occurrence of reworked siliciclastic layers within coal seams highlights episodes of erosion that temporarily disrupted peat accumulation and introduced hidden gaps into the geological record. These interruptions, often overlooked, may record the interplay of local environmental shifts and broader regional controls on sedimentation and preservation (Figure 6).

Tectonic activity plays a key role among the factors influencing erosion, as it can directly affect landscape stability and indirectly control peat accumulation and clastic supply. Its impact is particularly evident in the early Permian part of the coal-bearing succession, where signs of erosion and gaps in sedimentation are most pronounced.

The early Permian part of the coal-bearing succession is generally composed of poorly sorted siliciclastic rocks composed mainly of quartz (>40–45%), clasts of effusive volcanic rocks and their tuffs (15–25%), as well as feldspars, siliceous rocks, and plagioclase feldspars [62]. Against this background, certain stratigraphic intervals within the Promezhutochnaya (Transitional) and Ishanova Fms contain thick (up to 120 m) packages of volcaniclastic sandstones and siltstones. These rocks are characterised by a dominance (>50%) of angular clasts of effusive rocks and their tuffs, weak cementation, and characteristic greenish colour [63]. The volcanic and tuffaceous material is interpreted as product of erosion from lower to middle Devonian volcanic complexes exposed in the surrounding highlands [31]. The predominance of effusive and tuffaceous rock fragments, combined with poor sorting, green colour, and weak lithification, suggests rapid sediment transport and high accumulation rates, likely associated by fluvial avulsions or short-lived depositional pulses [64].

Volcanism in the uppermost part of the coal-bearing succession of the Kuznetsk Basin, near the Permian–Triassic boundary, has been well documented in numerous studies [65,66], which link it to the activity of the Siberian Large Igneous Province (LIP) [67,68] . Regionally, it is expressed by an increased content of volcanogenic material in the uppermost part of Tailugan Fm, as well as by the presence of at least two basalt units – probably lava flows, each several metres thick – within the Maltseva Fm [64].

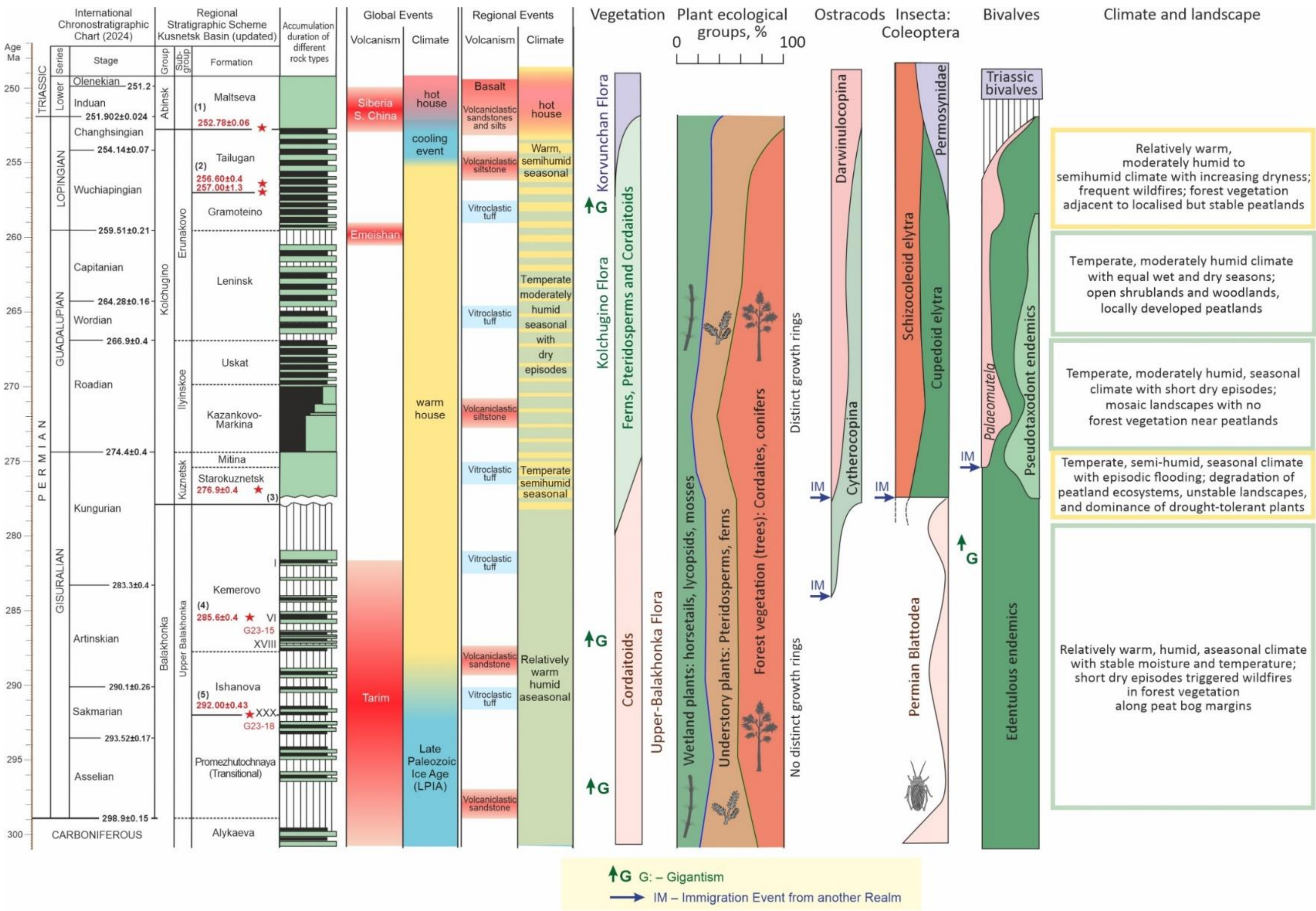


Figure 6. Synopsis of regional volcano-tectonic, biotic, and palaeoclimate events in comparison with global Permian record. Global events adapted from [6,69,70].

 doi:10.20944/preprints202505.0345.v1

Sills associated with the development and emplacement of the Siberian LIP and trap magmatism are widespread along the margins of the Kuznetsk Basin, particularly in areas adjacent to surrounding fold belts (e.g., the Tom–Usa region). Intrusions of hypabyssal mafic sills (diabase and dolerite; see Figure 2) are common within the Promezhutochnaya (Transitional), Ishanova, and Kemerovo Fms. Their thickness is highly variable, locally reaching up to 120 m, and they often split into several tabular bodies 20 to 40 m thick. Radioisotopic K–Ar dating suggests emplacement ages between 209 and 270 Ma [31].

To better understand the causes of stratigraphic discontinuities, it is necessary to consider the palaeoclimatic conditions that influenced the sedimentation dynamics, erosion, and peat-forming environments within the basin.

Permian Palaeoclimate: Regional Trends and Phases. The Permian climate history of the Kuznetsk Basin reveals a progression from humid and relatively stable conditions in the Cisuralian to increasingly dry and unstable regimes in the Lopingian. Shifts in climate are reflected in changes in coal accumulation patterns, vegetation and faunal composition, and the intensity of wildfire activity. These trends are summarised in Table 1, which integrates sedimentological and biotic indicators (Figures 3 and 4) to characterise the prevailing settings during different time intervals.

Early Permian, Asselian, Sakmarian, and early Kungurian coal-bearing succession (Promezhutochnaya (Transitional), Ishanova, and Kemerovo Fms). Climate during this phase was relatively warm and humid, with minimal annual temperature variability. This interpretation is supported by the absence of distinct growth rings in fossil wood, the dominance of cockroaches (Blattodea) in insect assemblages, and the widespread distribution of peatlands [71–73]. The gigantism observed in plants and non-marine bivalves suggests long-term ecological stability in both terrestrial and freshwater ecosystems, as well as probably elevated atmospheric oxygen levels [74].

High fusinite content in coal indicates frequent wildfire activity, likely associated with short dry episodes and the proximity of forest vegetation to peat mires. Together with elevated oxygen levels, these factors would have favoured ignition and the incorporation of charred material into accumulating peat. This pattern is consistent with observations from the Xingtai Coalfield (Middle Permian) in the North China Basin, where wildfires occurred despite generally humid conditions [75].

Early Permian, Late Kungurian coal-free succession (Starokuznetsk and Mitina Fms). Climate was temperate, semi-humid, with pronounced seasonality, and an unstable hydrological regime, including periodic flooding. Long periods of relatively warm and dry conditions were probably interrupted by short humid episodes. Peat accumulation was either suppressed or disrupted by erosion. The appearance of xerophytic callipterids – migrants from lower latitudes – in the plant assemblage suggests increasing drought stress [76]. Other indicators of dry climate include narrowing of sphenopsid stems, reduced leaf size in cordaitaleans, thicker leaf textures, and denser venation patterns [19].

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 May 2025 doi:10.20944/preprints202505.0345.v1

Stratigraphic interval	Sedimentary and Biotic Features	Interpretation of setting	Climate interpretation	Landscape and sedimentary environments
Late Permian, **Wuchiapingian – Changhsingian** coal-bearing succession (Gramoteino and Tailugan Fms)	**Sedimentary:** – Coal accumulation: 30–40 seams, 80–100 m total thickness; – Elevated content (25–30 wt%) of depleting microcomponents, including fusinite, in coal. **Biotic:** – DOM: 'sulcial' cordaitoids with thin furrows along the veins on the upper side of the leaf and numerous false veins, as well as Mesozoic-type pteridosperms; – Monogeneric assemblages of non-marine bivalves; – Peak diversity of fish and insects in the later half of the phase; – Notable decline in xylophagous Coleoptera;	– Local but intense peat accumulation in stable ecological niches – High wildfire frequency – Frequent seasonal drought – Ecological instability and stress, leading to biocoenotic simplification – Temporary improvement of conditions in freshwater ecosystems – Catastrophic change in terrestrial and aquatic environments	Humid Intercalated wet and dry seasons Dryness Seasonality Global hot house at the end of phase	***Dry uplands:*** – reduced vegetation cover; – simplified plant communities; – dominance of 'sulcial' cordaitoids and Mesozoic-type pteridosperms; – pronounced dryness; – frequent wildfires.. ***Transitional zone:*** – open woodlands and shrublands; – flammable biomass actively transported into peatlands; – widespread wildfires; – Peak insect diversity prior to the end-Permian crisis, with diminishing distinctions between regional entomofaunas. ***Peatlands:*** – localised but stable peat accumulation; – frequent wildfires, with potential gaps in peat accumulation and erosion; – proximity of forest vegetation to peatlands. ***Freshwater systems (lakes and channels):*** – monogeneric non-marine bivalve assemblages indicate ecological degradation of aquatic systems; – peak fish diversity in the latter part of the phase suggests temporary environmental stabilisation prior to extinction events;

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 May 2025 doi:10.20944/preprints202505.0345.v1

	– Extinction of cordaitoids, other Permian plants, ostracods, non-marine bivalves, and fishes at the end of the phase.			– the phase concludes with the extinction of Permian plants, invertebrates, and fishes. ***Fluvial systems:*** accumulation of clastic sediments; widespread erosion.
Middle Permian, **Wordian–Capitanian** coal-bearing succession (Leninsk Fm)	**Sedimentary:** – Coal accumulation represented by ~20 seams, with a total thickness of 35–50 m; – Low content (<10 wt%) of depleting microcomponents (including fusinite) in most of the interval; – Sharp increase in fusinite content to 25–30 wt% near the top of the section. **Biotic:** – LAD: *Rufloria*; – presence of distinct growth rings in fossil wood; – Im: fish from Euramerica; – FAD: new fish genera.	– Fragmented and unstable peatlands – Relatively high humidity for most of the phase – Intensifying dryness and more frequent wildfires towards the end of the stage.	Humid Humid Episodic dry phases Declining humidity and increasing dryness Seasonality Intermittent wet phases, floods, and ephemeral water bodies	***Dry uplands:*** – sparse vegetation dominated by xerophytic forms (cordaitoids, callipterids); – trees with well-defined growth rings. ***Transitional zone:*** – open shrublands and woodlands; – partial preservation of woody vegetation. ***Peatlands:*** – locally developed; – unstable peat accumulation; – probable periodic drying; – wildfires rare in the early phase, becoming more frequent toward the end. ***Freshwater systems (lakes and channels):*** – likely increased seasonal water-level fluctuations; – episodic hydrological connections between neighbouring biogeographical provinces. ***Fluvial systems:*** accumulation of clastic sediments; widespread erosion.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 May 2025 doi:10.20944/preprints202505.0345.v1

Middle Permian, **Roadian** coal-bearing succession (Kazankova-Markina and Uskat Fms)	**Sedimentary:** – Coal accumulation: 95–145 seams; total thickness 35–120 m; – Low content (<10 wt%) of depleting microcomponents, including fusinite, in coal. **Biotic:** – FOD of the subgenus *Rufloria*; DOM of *Tungussocarpus;* – Small-leaved and 'sulcial' cordaitoids; callipterids (*Callipteris*); – Presence of distinct growth rings in fossil wood; – FOD of Permochoristidae (Mecoptera); – LOD of Palaeoptera (except Odonata), Archescytinidae; – Decline in Homoptera abundance; dominance of Prosbolidae among Homoptera; – Development of coarse elytral sculpture and thickening in Coleoptera (DOM: Schizocoleidae; Rhombocoleidae); – DOM: ostracods and non-marine bivalves that had previously migrated into the basin; – D: freshwater fishes.	Vigorous plant growth; peatlands with anaerobic conditions favourable for peat accumulation; Rare and/or low-intensity wildfires; Absence of forest vegetation in proximity to peatlands; Peat-forming and wetland ecosystems; Dry episodes; Mosaic of peatlands interspersed with open woodlands or/and shrublands; Seasonal variation in temperature and humidity; Seasonal conditions with stable biotic communities; Stable freshwater environments; High resilience of aquatic ecosystems.	Humid Humid Seasonal short dry episodes Seasonality Stability	***Dry uplands:*** – small-leaved, 'sulcial' cordaitoids and callipterids adapted to drought; – colonisation by drought-tolerant insect groups; – strongly seasonal climate; – infrequent wildfires. ***Transitional zone:*** – lowland areas with open woodlands or/and shrublands; – patchy vegetation cover; – low woody productivity; – abundance of Mecoptera (Permochoristidae), dominance of Prosbolidae and schizophoroid beetles. ***Peatlands:*** – active peat accumulation; – peat-forming vegetation; – stable humidity, absence of wildfires; – resilient ecosystem, sensitive to climatic seasonality. ***Freshwater systems (lakes and channels):*** – stable hydrological regime with seasonal fluctuations.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 May 2025 doi:10.20944/preprints202505.0345.v1

				Fluvial systems (perennial and intermittent): accumulation of clastic sediments; widespread erosion.
Early Permian, **Late Kungurian** coal-free succession (Starokuznetsk and Mitina Fms)	**Sedimentary:** – Coal accumulation virtually absent or removed by erosion. **Biotic:** – FAD: xerophytic callipterids; – LOD: Blattodea; – Dom: Hemiptera: Homoptera; Mecoptera, and Grylloblattodea; – Im: ostracods from Kazakhstan; – Im: bivalves from Euramerica; – Im: Coleoptera from Euramerica; – FAD: new fish genera.	Peat failed to accumulate or was eroded by seasonal floods. Plants adapted to drought and intense solar radiation. Loss of humid, shaded forest biotopes; disappearance of forest ecosystems Insects associated with seasonally active plant communities. Emergence of temporary hydrological routes between biogeographical provinces. Transformation of ecosystems and changes in freshwater environments.	Water balance disturbance; unstable moisture Progressive dryness; rising temperatures; decreasing precipitation Intensification of dryness Seasonal climate with a short wet period Intermittent wetting; flood events; ephemeral water bodies Temporary and permanent well-aerated water bodies	***Dry uplands:*** – xerophytic callipterids with narrow, folded leaves; narrowing of sphenopsid stems; – moisture deficit and unstable hydrological conditions. ***Open lowland landscapes:*** – sparse woodland, shrub vegetation, mosaic plant communities; –dominance of Homoptera (indicative of seasonal biocenoses); insects active during short wet intervals. ***Swampy areas and ephemeral channels:*** – minimal peat accumulation; – frequent erosion and reworking of sediments; – predominantly clastic deposition; – seasonal flooding and ephemeral water bodies; ***Freshwater systems (lakes and channels):*** – immigration of freshwater invertebrates from other palaeobiogeographic provinces; – temporarily stable aquatic environments. ***Fluvial systems (perennial and intermittent):*** accumulation of clastic sediments; widespread erosion.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 May 2025 doi:10.20944/preprints202505.0345.v1

Early Permian, **Asselian, Sakmarian, and early Kungurian** coal-bearing succession (Promezhutochnaya (Transitional), Ishanova, and Kemerovo Fms)	**Sedimentary:** – Coal accumulation: 20–40 seams with a total thickness of 55–65 m; – High content of depleting microcomponents (ΣDm <30–70 wt%), including fusinite. **Biotic:** – Plant gigantism; – Absence of growth rings in fossil wood; – Gigantism: non-marine bivalves; – Dom: Blattodea.	Active vegetation growth; extensive peat-forming wetlands under persistently anaerobic conditions Periodic droughts triggering wildfire events Presence of forested vegetation in proximity to peatlands Absence of climatic stressors (e.g. frost, drought) Continuous, non-seasonal plant growth throughout the year Well-developed freshwater ecosystems with stable water supply	Humid and stable regime Short dry episodes Warm, humid, and stable Little or no evidence of seasonality	***Wet lowland forested plains:*** – presence of giant trees (lacking growth rings); – high biomass productivity; – development of forest litter supporting Blattodea dominance. ***Transitional zone:*** – forests adjoin peatlands; – accumulation of woody debris as habitat for cockroaches and a potential source of combustible material during wildfires. ***Peatlands:*** – persistently wet, anoxic conditions; – occurrence of charred plant remains and fusinite, indicating recurrent wildfire activity. ***Freshwater systems (lakes and channels):*** – habitats for non-marine bivalves and fish; – stable water levels, not prone to desiccation; – proximity to wetlands, with potential input of carbonaceous material to peatlands ***Fluvial systems:*** accumulation of clastic sediments; widespread erosion.

Note. D: – Diversity; DOM: – Dominance; FAD: (FOD:) – First Appearance (Occurence) Datum; LAD: (LOD:) – Last Appearance (Occurrence) Datum; Im: – Immigration Event from another Realm; ΣDm – Total content of depleting microcomponents in coal, wt% (ash-free basis, normalised).

 doi:10.20944/preprints202505.0345.v1

Evidence of episodic connections with neighbouring biogeographical provinces is provided by the immigration of freshwater ostracods (from Kazakhstan) and non-marine bivalves (from Euramerica), suggesting temporary hydrological routes during wetter phases. Insect assemblages also reflect climate variability. Thermophilic Blattodea are completely absent (reappearing only in Maltseva Fm), while the fauna is dominated by Hemiptera (Homoptera), Mecoptera and Grylloblattodea [73], taxa probably associated with riparian vegetation and understorey habitats. Among the Homoptera, the hydrophilic Scytinopteridae dominate. These insects are thought to have been adapted to moist, marginal environments and may have been capable of temporary submersion [77,78]. The phase marks the first major expansion of Coleoptera, dominated by xylophagous Permocupedidae with distinct cupedoid elytra [79]. Flood-induced erosion probably produced spatially heterogeneous and dynamic landscapes.

Middle Permian, Roadian coal-bearing succession (Kazankovo-Markina and Uskat Fms). Climate was temperate, moderately humid and seasonal, with short dry episodes. This is supported by the presence of growth rings in fossil wood, the coexistence of xerophytic and hydrophytic plant forms, and the persistence of long-lived peat-forming wetlands.

Insects show a transition from typical early Permian assemblages to the Late Permian ones. In particular, the large open-habitat Palaeoptera disappear almost completely. Among the Mecoptera, the Permochoristidae became dominant [73]. Within Homoptera the Prosbolidae dominate – a group inhabiting a variety of plant hosts, including cordaitaleans [77]. Among Coleoptera, there is an increase in forms with schizophoroid-type elytra (families Schizocoleidae, Rhombocoleidae) and a decrease in cupedoid types (families Permocupedidae, Taldycupedidae) [79]. The dominance of schizophoroid beetles – characterised by thick, coarsely sculptured elytra – along with the absence of moisture-dependent Archescytinidae and the reduced presence of Scytinopteridae (Hemiptera: Homoptera), supports the interpretation of episodic dry conditions [73,79].

Peat-forming wetlands indicate stable, though seasonally variable, humidity. The mire vegetation was dominated by small-leaved *Rufloria*, together with mosses such as *Polyssaievia* and other moisture-dependent taxa. The low fusinite content in coal (<10%) suggests infrequent wildfire activity and the absence of extreme droughts. Freshwater ecosystems appear to have been stable and diverse, supporting rich assemblages of ostracods, non-marine bivalves, and fishes – including migrants from neighbouring biogeographical provinces. Taken together, the evidence points to a heterogeneous landscape of peatlands, open woodlands, and sustained water bodies, developed under a moderately humid climate with well-defined, though not extreme, seasonality.

Middle Permian, Wordian–Capitanian coal-bearing succession (Leninsk Fm). Climate was temperate, moderately humid, with equal wet and dry seasons. Peat accumulation slightly declined, suggesting localised peatlands. For most of the phase, fusinite content in coal remained low (<10%), indicating persistently high humidity, at least seasonally. A sharp increase in fusinite content (up to 25–30 wt%) in the upper part of the Leninsk Fm indicates increasing dryness and more frequent wildfires.

The near disappearance of *Rufloria* [80] and the spread of xerophytic forms – including callipterids and small-leaved cordaitoids – reflect the trend to the degradation of peatland ecosystems. Nevertheless, well-defined annual growth rings in fossil wood [72,81] confirm the persistence of a seasonal climate. Fish migrations from Euramerica and the appearance of new genera may be linked to the formation of water bodies that connected adjacent biogeographical provinces. Overall, the Wordian–Capitanian climate represents a transitional phase towards the increasingly dry semi-humid conditions of the Late Permian.

Late Permian, Wuchiapingian–Changhsingian coal-bearing succession (Gramoteino and Tailugan Fms). Climatic conditions were strongly seasonal, with a clear trend toward progressive dryness. These changes favoured increasing ecological instability and widespread ecosystem degradation [82]. Biotic communities became structurally simplified, r-selection intensified, specialist taxa declined, polymorphism was reduced, and opportunistic species capable of rapidly colonising unstable or vacant ecological niches became increasingly dominant.

 doi:10.20944/preprints202505.0345.v1

High fusinite contents (25–30 wt%) in coal seams – particularly in seams 78 and 88 of the Tailugan Fm – indicate frequent wildfire activity [83], driven by alternating wet and dry seasons and the proximity of forest areas to peatlands. Although the coal-forming regime persisted, peat accumulation was spatially restricted to relatively stable local environments.

The structure of the vegetation differed markedly between the beginning and end of this phase. The earlier interval is characterised by the widespread occurrence and gigantism with both of sparsely veined and 'sulcial' leaves of cordaitoids, together with sphenopsids with large stems and leaf whorls of the *Annularia*. Leaf mosses, diverse pteridosperms (*Comia*, *Permocallipteris*), proto-ginkgophytes (*Psygmophyllum* [syn. *Iniopteris*], *Rhipidopsis*), and cycadophyte foliage (*Yavorskyia*) were also common [84,85]. In contrast, the later part of the phase is dominated by xerophytic, small-leaved 'sulcial' cordaitoids and Mesozoic-type pteridosperms. Leaf mosses disappear, pointing to a shortened growing season and increasingly unstable, seasonally dry conditions.

At the beginning of this phase, an increase in the rate of new insect family origination is observed, leading to a peak in taxonomic diversity and the blurring of distinctions between regional entomofaunas [77]. In the later part of the phase, a reduction in insect body size is documented – especially in Coleoptera – along with a declining role of xylophagous taxa. This trend is reflected in the dominance of primitive schizophoroid beetles over the increasingly rare cupedoids [79].

Freshwater ecosystems were dominated by monogeneric bivalve assemblages, indicating ecological degradation. The second half of the phase records a peak in fish diversity [86], probably associated with a short-lived episode of environmental stabilisation in aquatic habitats.

The final part of the phase records signals of a major biotic crisis (Figures 4 and 6), marked by the disappearance of most characteristic Permian floral and faunal groups. These patterns align with the global trends associated with the end-Permian mass extinction.

7. Conclusions

High-precision U–Pb radioisotope ages obtained using CA-IDTIMS and LA-ICP-MS methods from five stratigraphic levels – including new results for the Ishanova and Kemerovo Fms – provide robust age constraints for key units within the Permian succession of the Kuznetsk Basin. These results are independently supported by biostratigraphic data from both previous and present studies.

The new radioisotopic dates allow, for the first time, direct correlation of regional units with the International Chronostratigraphic Chart (2024), revealing significant discrepancies in previous correlations, particularly at the Cisuralian–Guadalupian boundary and within the Late Permian interval.

A comparison with the official 1982–1996 regional stratigraphic scheme reveals major inconsistencies in the age and duration of several units. In response, a revised scheme is proposed, integrating both biostratigraphic and radioisotopic data.

Estimates of sedimentation rates and cumulative durations of coal-bearing intervals were used to assess the extent and timing of stratigraphic gaps. The results show that the greatest cumulative duration of hiatuses occurs within the Cisuralian, particularly in the late Kungurian.

Palaeobiological data reflect distinct climatic phases during the Permian: a relatively warm and humid Asselian–Sakmarian, a semi-humid late Kungurian, a temperate and moderately humid Guadalupian, and an increasingly dry Lopingian. These reconstructions are broadly consistent with global climate record, but also show regional variations – in particular, prevailing temperate humid or moderately humid conditions corresponding to the middle latitude position of the basin during the Permian.

The application of U–Pb radioisotopic dating, combined with sedimentation rate analysis, has proven to be an effective tool for verifying and refining regional stratigraphic frameworks. This integrated approach allows not only for the more accurate definition of unit boundaries, but also for the integration of regional data into a global chronostratigraphic context.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 May 2025 doi:10.20944/preprints202505.0345.v1

References

1. *Geologic Time Scale 2020*. Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; 1144 p.
2. Ogg, J.G.; Ogg, G.; Gradstein, F.M. *A Concise Geologic Time Scale*; Elsevier: Amsterdam, The Netherlands, 2016; 240 p.
3. Henderson, C.M.; Shen, S.Z. Chapter 24 – The Permian Period. In *Geologic Time Scale 2020*; Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; Volume 2, pp. 875–902.
4. Lucas, S.G.; Schneider, J.W.; Cassinis, G. Non-marine Permian bios-tratigraphy and biochronology: An introduction. In *Non-Marine Permian Biostratigraphy and Biochronology*; Lucas, S.G., Cassinis, G., Schneider, J.W., Eds.; Geological Society of London, Special Publications, London, UK, 2006; Volume 265(1), pp. 1–14.
5. Menning, M.; Alekseev, A.S.;Chuvashov, B.I.; Davydov, V.I.; Devuyst, F.-X.; Forke, H.C.; Grunt, T.A.; Hance, L.; Heckel, P.H.; Izokh, N.G.; Jin, Y.G.; Jones, P.J.; Kotlyar, G.V.; Kozur, H.W.; Nemyrovska, T.I.; Schneider, J.W.; Wang, X.D.; Weddige, K.; Weyer, D.; Work, D.M. Global time scale and regional stratigraphic reference scales of Central and WestEurope, East Europe, Tethys, South China, and North America as used in the Devonian–Carboniferous–Permian Correlation Chart 2003 (DCP2003). *Palaeogeography, Palaeoclimatology, Palaeoecology* **2006**, *240*(1–2), 318–372.
6. Schneider, J.W.; Lucas, S.G.; Scholze, F.; Voigt, S.; Marchetti, L.; Klein, H.; Opluštil, S.; Werneburg, R.; Golubev, V.K.; Barrick, J.E.; Nemyrovska, T.; Ronchi, A.; Day, M.; Silantiev, V.; Rößler, R.; Saber, H.; Linnemann, U.; Zharinova, V.; Shen, S. Late Paleozoic–early Mesozoic continental biostratigraphy – Links to the Standard Global Chronostratigraphic Scale. *Palaeoworld* **2020**, *29*, 186–238.
7. *Decisions of the All-Union Conference on the Development of Unified Stratigraphic Schemes for the Precambrian, Paleozoic and Quaternary Systems of Central Siberia (Novosibirsk, 1979). Part 2 (Middle and Upper Paleozoic)*; SRIGGMRM: Novosibirsk, Russia, 1982; 129 p. (In Russian)
8. Budnikov, I.V. Decision of the Meeting on the stratigraphy of the Upper Paleozoic deposits of Kuzbass. In *Kuznetsk Basin – Key Region in Stratigraphy of the Angarida Upper Paleozoic*; Budnikov, I.V., Ed.; YuzhSibgeolkom: Novosibirsk, Russia, 1996; Volume 2, pp. 93–94. (In Russian)
9. Schmitz, M.D.; Singer, B.S.; Rooney, A.D. Radioisotope Geochronology. In *Geologic Time Scale 2020*; Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; Volume 1, pp. 193–209.
10. Kotlyar, G.V.; Pukhonto, S.K.; Burago, V.I. International correlation of continental and marine Permian deposits of the Northeast of Russia, the Southern of the Far East, Siberia and the Pechora Ural Region. *Pac. Geol.* **2018**, *37*, 3–21. (In Russian with English Abstract)
11. Davydov, V.I.; Karasev, E.V.; Nurgalieva, N.G.; Schmitz, M.D.; Budnikov, I.V.; Biakov, A.S.; Kuzina, D.M.; Silantiev, V.V.; Urazaeva, M.N.; Zharinova, V.V.; Zorina, S.O.; Gareev, B.I.; Vasilenko, D.V. Climate and biotic evolution during the Permian-Triassic transition in the temperate Northern Hemisphere, Kuznetsk Basin, Siberia, Russia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2021**, *573*, 110432.
12. Silantiev, V.V.; Gutak, Ya.M.; Tichomirowa, M.; Kulikova, A.V.; Felker, A.S.; Urazaeva, M.N.; Porokhovnichenko, L.G.; Karasev, E.V.; Bakaev, A.S.; Zharinova, V.V.; Naumcheva, M.A. First radiometric dating of tonsteins from coal-bearing succession of the Kuznetsk Basin: U-Pb geochronology of the Tailugan Formation. *Georesursy=Georesources* **2023a**, *25*, 203–227.
13. Silantiev, V.V.; Gutak, Ya.M.; Tichomirowa, M.; Käßner, A.; Kutygin, R.V.; Porokhovnichenko, L.G.; Karasev, E.V.; Felker, A.S.; Bakaev, A.S.; Naumcheva, M.A.; Urazaeva, M.N.; Zharinova, V.V. U-Pb Dating of the Kolchugino Group Basement (Kuznetsk Coal Basin, Siberia): Was the Change in Early–Middle Permian Floras Simultaneous at Different Latitudes in Angaraland? *Geosciences* **2024a**, *14*, 21.
14. Meyen, S.V. The Carboniferous and Permian floras of Angaraland: (a synthesis). *Biol. Mem.* **1982**, 7, 1–109.
15. Meyen, S.V.; Afanasieva, G.A.; Betekhtina, O.A.; Durante, M.V.; Ganelin, V.G.; Gorelova, S.G.; Graizer, M.I.; Kotlyar, G.V.; Maximova, S.V.; Tschernjak, G.E.; et al. Angara and surrounding marine basins. In *The Carboniferous of the World. III. The Former USSR, Mongolia, Middle Eastern Platform, Afganistan & Iran*; Diaz, C.M., Wagner, R.H., Winkler Prins, C.F., Granados, L.F., Eds.; I.T.G.M.E.: Madrid, Spain; N.N.M.: Leiden, The Netherlands, 1996; pp. 180–237.

16. Oshurkova, M.V. Paleoecological parallelism between the Angaran and Euramerican phytogeographic provinces. *Rev. Palaeobot. Palynol.* **1996**, *90*, 99–111.
17. Silantiev, V.V. Permian Nonmarine Bivalve Mollusks: Review of Geographical and Stratigraphic Distribution. *Paleontol. J.* **2018**, *52*, 707–729.
18. Budnikov, I.V.; Kutygin, R.V.; Shi, G.R.; Sivtchikov, V.E.; Krivenko, O.V. Permian stratigraphy and paleogeography of Central Siberia (Angaraland) – A review. *J. Asian Earth Sci.* **2020**, *196*, 104365.
19. Betekhtina, O.A.; Gorelova, S.G.; Dryagina, L.L.; Danilov, V.I.; Batyaeva, S.P.; Tokareva, P.A. *Upper Paleozoic of Angarida*; Zhuravleva, I.T., Ilyina, V.I., Eds.; Nauka: Novosibirsk, Russia, 1988; 265 pp. (In Russian)
20. Budnikov, I.V. *Kuznetsk Basin – Key Region in Stratigraphy of the Angarida Upper Paleozoic*; YuzhSibgeolkom: Novosibirsk, Russia, 1996b; Volume 1, pp. 1–122; Vol. 2, pp. 1–109. (In Russian)
21. International Chronostratigraphic Chart. Permian Timescale. Subcommission on Permian Stratigraphy. Available online: https://permian.stratigraphy.org/timescale (accessed on 19 April 2025).
22. Zhamoida, A.I. *Stratigraphic Guide of Russia*, 3rd ed.; Corrected and supplemented; VSEGEI: St. Petersburg, Russia, 2019; 96 p. (In Russian)
23. Kotlyar, G.V.; Golubev, V.K., Silantiev, V.V. General stratigraphic scale of the Permian system: current state of affairs. In *General Stratigraphic Scale of Russia: current state and ways of perfection*, All-Russian meeting, Institute of RAS, Moscow, Russsia, May 23-25, 2013; GIN RAS: Moscow, Russia, 2013; pp. 187–195.
24. Vakhrameev, V.A.; Dobruskina, I.A.; Zaklinskaya, E.D.; Meyen, S.V. Paleozoic and Mesozoic floras of Eurasia and Phytogeography of This Time. In *Proceedings GIN*; Nauka: Moscow, Russia, 1970; Issue 208, 431 p. (In Russian)
25. Meyen, S.V. Carboniferous and Permian floras of the Angarides (review). In *Theoretical Problems of Paleobotany*; Meyen, S.V., Ed.; Nauka: Moscow, Russia, 1990; pp. 131–223.
26. Amler M.R.W.; Silantiev V.V. A global review of Carboniferous marine and non-marine bivalve biostratigraphy. *Geological Society London, Special Publications* **2021**, *512*(1), 893–932.
27. Buslov, M.M.; Watanabe, T.; Fujiwara, Y.; Iwata, K.; Smirnova, L.V.; Safonova, I.Y.; Semakova, N.N.; Kiryanova, A.P. Late Paleozoic faults of the Altai region, Central Asia: Tectonic pattern and model of formation. *J Asian Earth Sci.* **2004**, *23*(5), 655–71.
28. Buslov, M.M. Tectonics and geodynamics of the Central Asian Foldbelt: The role of Late Paleozoic large-amplitude strike-slip faults. *Russ Geol Geophys.* **2011**, *52*(1), 52–71. http://dx.doi.org/10.1016/j.rgg.2010.12.005
29. Gutak, Ya.M. Development of Structure of the West Part of the Altay-Sayan Orogen (the Mesozoic Stage). *Geosfernye issledovaniya = Geosphere Research* **2021**, *1*, 123–129. (In Russ.) https://doi.org/10.17223/25421379/18/10
30. Gutak, Ya.M.; Antonova, V.A.; Bagmet, G.N.; Gabova, M.F.; Savitskiy, V.R.; Tolokonnikova, Z.A. *Essays on the historical geology of the Kemerovo region*; Nauka: Novokuznetsk, Russia, 2008; 132 p.
31. Yuzvitsky, A.Z. Kuznetsk Coal Basin. In *Coal Basins and Deposits of Western Siberia (Kuznetsk, Gorlovsky, Zapadno-Sibirsky Basins, Deposits of the Altai Territory and the Republic of Altai)*; Geoinformtsentr: Moscow, Russia, 2003; Volume 2, pp. 7–46. (In Russian)
32. Parfenov, L.M.; Khanchuk, A.I.; Badarch, G.; Miller, R.J.; Naumova, V.V.; Nokleberg, W.J.; Ogasawara, M.; Prokopiev, V.; Yan, H. Geodynamics Map of Northeast Asia; Scientific Investigations Map 3024. Scale 1:5 000 000; 2 sheets; U.S. Geological Survey: Reston, VA, USA, 2013.
33. Tectonic Map of Northern-Central-Eastern Asia and Adjacent Areas; Scale 1:2 500 000. In *Atlas of Geological Maps of Northern-Central-Eastern Asia and Adjacent Areas*; Petrov, O.V.; Leonov, Y.G., Tingdong, L., Tomurtogoo, O., Eds.; VSEGEI Publishing House: St. Petersburg, Russia, 2014. Available online: https://karpinskyinstitute.ru/ru/info/inter-proj/tect-asia2500/ (accessed on 20 April 2025).
34. Petrov, O.V.; Khanchuk, A.I.; Shokalsky, S.P.; Babin, G.A.; Pospelov, I.I. Principles of tectonic mapping of Asia and the Arctic, scales 1:2 500 000–1:5 000 000. *Geodyn. Tectonophys.* **2021**, *12*, 173–198.
35. Van, A.V. The role of pyroclastic material in coal-bearing deposits of the Kuznetsk basin. *Sov. Geol.* **1968**, *4*, 129–138. (In Russian)

36. Van, A.V.; Kazanskiy, Yu.P. *Volcanic Material in Sediments and Sedimentary Rocks*; Nauka: Novosibirsk, Russia, 1985; 128 p. (In Russian)
37. Chernovyants, M.G. *Tonsteins and Their Use in the Study of Coalbearing Formations*; Nedra: Moscow, Russia, 1992; 144 p. (In Russian)
38. Kazanskiy, Yu.P.; Van, A.V. Using of tephrochronology for subdivision and correlation of Upper Paleozoic deposits of Kuzbass. In *Kuznetsk Basin – Key Region in Stratigraphy of the Angarida Upper Paleozoic*; Budnikov, I.V., Ed.; YuzhSibgeolkom: Novosibirsk, Russia, 1996; Volume 2, pp. 31–37. (In Russian)
39. Arbuzov, S.I.; Spears, D.A.; Vergunov, A.V.; Ilenok, S.S.; Mezhibor, A.M.; Ivanov, V.P.; Zarubina, N.A. Geochemistry, mineralogy and genesis of rare metal (Nb-Ta-Zr-Hf-Y-REE-Ga) coals of the seam XI in the south of Kuznetsk Basin, Russia. *Ore Geol. Rev.* **2019a**, *113*, 103073.
40. Arbuzov, S.I.; Vergunov, A.V. Volcanogenic Pyroclastics as a Factor in the Formation of Nb(Ta)-Zr(Hf)-REE-Ga Mineralisation in Coals (the Case of Siberia). In *Large Igneous Provinces through earth history: mantle plumes, supercontinents, climate change, metallogeny and oil-gas, planetary analogues*, Abstract Volume of the 7th International Conference; CSTI Publishing house: Tomsk, Russia, 2019b, pp.177–178. (In Russian) https://doi.org/10.17223/9785897024568
41. Bakaev, A.S. Revision of Permian Ray-Finned Fishes from the Kazankovo-Markino Formation of the Kuznetsk Basin. *Paleontol. J.* **2023**, *57*, 335–342.
42. Legend of the Kuzbass Series of the State Geological Map of the Russian Federation. Scale 1:200,000, Second edition; Novokuznetsk, 1999. (In Russian)
43. Babin, G.A. State Geological Map of the Russian Federation, Scale 1:1,000,000 (Third Generation). Altai-Sayan Series, Sheet N-45 – Novokuznetsk, Explanatory Note; VSEGEI: Saint Petersburg, Russia, 2007; 665 p. (In Russian)
44. Yarkova, N.M.; Shestakova, O.E. Stratigraphy of the Carboniferous–Permian succession of the Kuznetsk Basin. In *Modern Problems in Mining and Methods for Modeling Mining and Geological Conditions in the Development of Mineral Deposits*; Kuzbass State Technical University: Kemerovo, Russia, 2015; pp. 1–5. (In Russian)
45. Gorelova, S.G.; Budnikov, I.V. Main stages of studying the stratigraphy of the Upper Palaeozoic of Kuzbass. In *Kuznetsk Basin – Key Region in Stratigraphy of the Angarida Upper Paleozoic*; Budnikov, I.V., Ed.; YuzhSibgeolkom: Novosibirsk, Russia, 1996; Volume 1, pp. 7–12. (In Russian)
46. Sivtchikov, V.E.; Donova, N.B. Stratigraphic subdivision of the Upper Palaeozoic deposits of the South Minusinsk Depression. *Lethaea Ross. Russ. Palaeobot. J.* **2016**, *13*, 1–46.
47. Silantiev, V.V.; Arbuzov, S.I.; Tichomirowa, M.; Käßner, A.; Izmailova, A.K.; Ilenok, S.S.; Soktoev, B.R.; Nurgalieva, N.G.; Gutak, Y.M.; Felker, A.S.; Porokhovnichenko, L.G.; Eliseev, N.A.; Zharinova, V.V.; Nurieva, E.M.; Urazaeva, M.N. First U-Pb (CA-ID-TIMS) Dating of the Uppermost Permian Coal Interval in the Minusinsk Coal Basin (Siberia, Russia) Using Zircon Grains from Volcanic Ashfalls. *Minerals* **2024b**, *14*, 982. https://doi.org/10.3390/min14100982
48. Silantiev, V.V.; Validov, M.F.; Miftakhutdinova, D.N.; Nourgalieva, N.G.; Korolev, E.A.; Ganiev, B.G.; Lutfullin, A.A.; Shumatbaev, K.D.; Khabipov, P.M.; Sudakov, V.A.; Akhmadullina, Ju.A.; Golod, K.A.; Leontiev, A.A.; Shamsiev, R.R.; Nikonorova, D.A.; Krikun, S.S.; Noikin, M.V.; Abdullina, E.A. Visean terrigenous sediments of the South Tatar Arch – multifacial filling of the karst surface of the Tournaisian carbonate platform. *Georesursy = Georesources* **2023b**, *25*(4), 3–28. (In Russian)
49. Ayaz, S.A.; Martin, M.; Esterle, J.; Amelin, Y.; Nicoll, R.S. Age of the Yarrabee and accessory tuffs: implications for the upper Permian sediment-accumulation rates across the Bowen Basin. *Aust. J. Earth Sci.* **2016**, *63*(7), 843–856.
50. Karpenko, L.V.; Prokushkin, A.S. Genesis and history of the postglacial evolution of forest bog in the valley of the Dubches River. *Siberian Journal of Forest Science* **2018**, *5*, 33–44. (In Russian)
51. Volkova, E.M.; Pel'gunova, L.A.; Kochkina, A.V. The dynamic of development of mires in karst depressions and accumulation of chemical elements in peat deposits. *Izvestiya Tul'skogo gosudarstvennogo universiteta. Estestvennye nauki* **2014**, *4*, 158–173. (In Russian)
52. Bakhnov, V.K. *Biogeochemical Aspects of the Mire-Forming Process*; Nauka: Novosibirsk, Russia, 1986; 192 p.
53. Kukal, Z. *Geology of Recent Sediments*; Academic Press: London, UK, 1971; 490 p.

54. Skursky, M.D. On the material composition of coals. *Journal of mining and geotechnical engineering* **2022**, *1*(16), 31–82. http://dx.doi.org/10.26730/2618-7434-2022-1-31-82
55. Sun, Y.-Z. Review and update on the applications of inertinite macerals in coal geology, paleoclimatology, and paleoecology. *Palaeoworld* **2024**, *33*(6), 1449–1463.
56. Schoene, B.; Crowley, J.L.; Condon, D.C.; Schmitz, M.D.; Bowring, S.A. Reassessing the uranium decay constants for geochronology using ID-TIMS U–Pb data. *Geochim. Cosmochim. Acta.* **2006**, *70*, 426–445.
57. Wiedenbeck, M.; Alle, P.; Corfu, F.; Griffin, W.L.; Meier, M.; Oberli, F.; Von Quadt, A.; Roddick, J.C.; Spiegel, W. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. *Geostand. Newsl.* **1995**, *19*, 1–23.
58. Black, L.P.; Kamo, S.L.; Allen, C.M.; Davis, D.W.; Aleinikoff, J.N.; Valley, J.W.; Mundil, R.; Campbell, I.H.; Korsch, R.J.; Williams, I.S.; Foudoulis, C. Improved 206Pb/238U microprobe geochronology by the monitoring of a trace-element related matrix effect; SHRIMP, ID-TIMS, ELA-ICP-MS and oxygen isotope documentation for a series of zircon standards. *Chem. Geol.* **2004**, *205*, 115–140.
59. Schaltegger, U.; Ovtcharova, M.; Gaynor, S.; Schoene, B.; Wotzlaw, J.-F.; Davies, J.; Farina, F.; Greber, N.D.; Szymanowski, D.; Chelle-Michou, C. Long-term repeatability and interlaboratory reproducibility of high-precision ID-TIMS U-Pb geochronology. *J. Anal. At. Spectrom.* **2021**, *36*, 1466–1477.
60. Pakh, E.M., Artser, A.S. *Petrographic composition of coals. In Coal Basins and Deposits of Western Siberia (Kuznetsk, Gorlovsky, Zapadno-Sibirsky Basins, Deposits of the Altai Territory and the Republic of Altai)*; Geoinformtsentr: Moscow, Russia, 2003; Volume 2, pp. 46–51. (In Russian)
61. Betekhtina, O.A., Batyayeva, S.K., Dryagina, L.L., Gorelova, S.G. Biochronological scale of the Upper Paleozoic of the Angarida In *Stratigraphy and lithofacies analysis of the Upper Paleozoic of Siberia*; Nauka: Novosibirsk, Russia, 1991; pp. 14–23. (In Russian)
62. Polukonova, N.A. Geological and economic districts: Tom-Usinsk region. In *Coal Basins and Deposits of Western Siberia (Kuznetsk, Gorlovsky, Zapadno-Sibirsky Basins, Deposits of the Altai Territory and the Republic of Altai)*; Geoinformtsentr: Moscow, Russia, 2003; Volume 2, pp. 433–452. (In Russian)
63. Papin, A.A.; Lezhnin, Y.A. Marker Horizons of the Carboniferous–Permian of the Kuznetsk Basin. In *Kuznetsk Basin – Key Region in Stratigraphy of the Angarida Upper Paleozoic*; Budnikov, I.V., Ed.; YuzhSibgeolkom: Novosibirsk, Russia, 1996; Volume 2, pp. 42–49. (In Russian)
64. Davies, C.; Allen, M.B.; Buslov, M.M.; Safonova, I. Deposition in the Kuznetsk Basin, Siberia: Insights into the Permian-Triassic transition and the Mesozoic evolution of Central Asia. *Palaeogeogr. Palaeoclimatol. Palaeoecol*. **2010**, *295*(1–2), 307–22.
65. Buslov, M.M.; Safonova, I.Y.; Fedoseev, G.S.; Reichow, M.K.; Davies, K.; Babin, G.A. Permo-Triassic plume magmatism of the Kuznetsk Basin, Central Asia: Geology, geochronology, and geochemistry. *Russ Geol Geophys.* **2010**, *51*(9), 1021–36.
66. Svetlitskaya, T.V.; Nevolko, P.A. Late Permian–Early Triassic traps of the Kuznetsk Basin, Russia: Geochemistry and petrogenesis in respect to an extension of the Siberian Large Igneous Province. *Gondwana Res.* **2016**, *39*, 57–76.
67. Reichow, M.K.; Pringle, M.S.; Al'Mukhamedov, A.I.; Allen, M.B.; Andreichev, V.L.; Buslov, M.M.; Davies, C.E.; Fedoseev, G.S.; Fitton, J.G.; Inger, S.; Medvedev, A.Ya.; Mitchell, C.; Puchkov, V.N.; Safonova, I.Yu.; Scott, R.A.; Saunder A.D. The timing and extent of the eruption of the Siberian Traps large igneous province: Implications for the end-Permian environmental crisis. *Earth Planet Sci Lett.* **2009**; *277*(1–2), 9–20. Available from: http://dx.doi.org/10.1016/j.epsl.2008.09.030
68. Sadovnikov, G.N. Evolution of the Biome of the Middle Siberian Trappean Plateau. *Paleontological Journal* **2016**, *50*(5), 518–532.
69. Montañez, I.P. Current synthesis of the penultimate icehouse and its imprint on the Upper Devonian through Permian stratigraphic record. *Geol. Soc. Spec. Publ.* **2022**, *512*(1), 213–245.
70. Schneider, J.W.; Werneburg, R.; Voigt, S.; Rößler, R. Karbon und Perm im Thüringer-Wald-Becken – ein euramerisches Referenzprofil für regionale und globale Prozesse. In *Rotliegend-Fauna des Thüringer Waldes*; Werneburg, R., Schneider, J.W., Eds..; Semana, Sonderveröffentlichung, 2024; Kap. 19, 257–268. (In German)

71. Travin, A.B.; Senderzon, E.M.; Shorin, V.P.; Gromova, T.A.; Ivankova, E.E.; Permitina, K.S.; Popova, M.E.; Shugurov, V.F.; Yusupov, T.S. *Atlas of Coals of the Kuznetsk basin*; Nauka, Siberian Publishing House: Novosibirsk, USSR, 1966; 367 p.
72. Lepekhina, V.G. *Paleoxylological characterization of the Upper Palaeozoic coalbearing deposits of the Kuznetsk Basin*; Transactions of VSEGEI: Moscow, USSR, 1969; Volume 130, pp. 126–153.
73. Rodendorf, B.B.; Becker-Migdisova, E.E.; Martynova, O.M.; Sharov, A.G. *Paleozoic insects of the Kuznetsk basin*; Publishing House of the USSR Academy of Sciences: Moscow, USSR, 1961; 746 p.
74. Wright, I.J.; Dong, N.; Maire, V.; Prentice, I.C.; Westoby, M.; Díaz, S.; Gallagher, R.V.; Jacobs, B.F.; Kooyman, R.; Law, E.A.; Leishman, M.R.; Niinemets, Ü.; Reich, P.B.; Sack, L.; Villar, R.; Wang, H.; Wilf, P. Global climatic drivers of leaf size. *Science* **2017**, *357*, № 6354.
75. Sun, Y.-Z.; Püttmann, W.; Kalkreuth, W.; Horsfield, B. Petrologic and geochemical characteristics of Seam 9–3 and Seam 2, Xingtai Coalfield, Northern China. *International Journal of Coal Geology* **2002**, *49*, 251–262.
76. Durante, M.V. Reconstruction of Late Paleozoic climatic changes in Angaraland according to phytogeographic data. *Stratigraphy and Geological Correlation* **1995**, *3*(2), 123–133. (In Russian)
77. Shcherbakov, D.E. Permian Faunas of Homoptera (Hemiptera) in Relation to Phytogeography and the Permo-Triassic Crisis. *Paleontological Journal* **2000**, *34*(3), 251–267.
78. Shcherbakov, D.E. A peculiar new genus of Scytinopteridae (Hemiptera, Cicadomorpha) from the Permian-Triassic boundary beds of Mongolia. *Palaeoentomology* **2022**, *5*(3), 218–221.
79. Ponomarenko, A.G. Beetles (Insecta, Coleoptera) of the late Permian and early Triassic. *Paleontological Journal* **2004**, *38*, 185–196.
80. Glukhova, L.V.; Menshikova, L.V. Microstructure of cordaites from the Upper Permian deposits of the Kuznetsk basin. *Paleontological Journal* **1980**, *3*, 107–117.
81. Zalessky, M.D.; Tchirkova, E.F. Sur la constitution de la substance mère des charbons du bassin de Kuznetzk. *Bull. Acad. Sci. de l'URSS.* **1931**, *2*, 269–276. (In French)
82. Krassilov, V.A. *Evolution and Biostratigraphy*; Nauka: Moscow, USSR, 1977; 256 p. (In Russian)
83. Hudspith, V.; Scott, A.C.; Collinson, M.E.; Pronina, N.; Beeley, T. Evaluating the extent to which wildfire history can be interpreted from inertinite distribution in coal pillars: An example from the Late Permian, Kuznetsk Basin, Russia. International *Journal of Coal Geology* **2012**, *89*(1), 13–25.
84. Radczenko, G.P. Some plant remains from the region of the Ostashkiny Gory in the Kuznetsk basin. *Materialy po geologii Zapadno-Sibirskogo kraya* **1936**, *1–3*(35), 1–24. (in Russian)
85. Mogutcheva, N.K. The change of the flora at the Permian-Triassic boundary in Angarida. In *Upper Paleozoic and Triassic of Siberia*; Dagys, A.S., Dubatolov, V., Eds.; Novosibirsk: Nauka, USSR, 1989; pp. 4–12. (in Russian)
86. Bakaev, A.S. Actinopterygians from the continental Permian–Triassic boundary section at Babiy Kamen (Kuznetsk Basin, Siberia, Russia). *Palaeoworld* **2025**, *34*(2), 100861.