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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?

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Abstract: The Kuznetsk Basin (Kuzbass) is one of the largest coal basins in Siberia and a reference area for the ancient Angaraland continent. The proximity of the Kuzbass and Siberian Platform caused their biotic similarities in the Late Palaeozoic. However, due to biota endemism, the Kuzbass Upper Palaeozoic does not correlate directly with the International Chronostratigraphic Chart (ICC). This paper discusses radioisotopic (CA-ID-TIMS) dating of zircons from a volcanic tuff located in the Starokuznetsk Formation (Fm). This level matches the interval of the Balakhonka/Kolchugino (B/K) floral change in Kuzbass, i.e., the gradual replacement of cordaitoid-dominated wet forests (Balakhonka flora) with more arid fern–pteridosperm–cordaitoid assemblages (Kolchugino flora). New age (276.9 ± 0.4 Ma) directly correlates the Starokuznetsk Fm with the Upper Kungurian of the ICC. We compared the Kuzbass data with data of the Western Verkhoyanie, where Middle Permian ammonoids (*Sverdrupites* assemblage) occur in strata recording the B/K floral change. The available (ICC) and new datings indicate the lag between the B/K floral change in low (Kuzbass) and high (Verkhoyanie) latitudes of Angaraland. The B/K floral change in the Kuzbass began in the early Late Kungurian and was completed by the end of this age. In contrast, the B/K floral change in Verkhoyanie began at the end of the Late Kungurian and was completed in the Late Wordian. The delay in the floral changes at different latitudes of Angaraland suggests that existing interregional correlations need further improvement.

Keywords: Kuznetsk Basin; Permian; ash bed; U-PB dating; geochronology; biostratigraphy; Angaraland

1. Introduction

Radioisotopic uranium–lead (U-Pb) dating of individual zircon grains—including thermal ionisation mass spectrometry with isotope dilution and chemical abrasion (CA-ID-TIMS)—has been successfully applied to detailed coal basin stratigraphy for more than two decades. Radioisotopic ages facilitated intra-basin correlation and direct comparison with the International Chronostratigraphic Chart of coal seams in Australia [1,2], China [3], Eastern Europe (Donetsk Basin) [4,5], North America [6], South America [7–10] and Western

Europe [11,12]. This article continues to present the results of radioisotopic dating (CA-ID-TIMS) of coal-bearing sediments of the Kuznetsk Basin, which was started several years ago [13,14].

The Kuznetsk Basin (Kuzbass)—one of the largest coal basins in Siberia—lies in the northern part of the Altai–Sayan Fold Belt (Figure 1A,B). Previously thought to be a relatively small intramountainous depression, the Kuzbass is now recognised as a giant Late Palaeozoic fore-mountain trough, adjacent to the Siberian Platform from the south (Figure 1D). The Kuzbass sedimentary trough is bordered by the Kuznetsk Alatau and Gornaya Shoria Caledonian fold systems from the east and south, respectively; these systems were already consolidated at that time with the Siberian Platform. In the west and north, the trough was in contact with the Hercynian mobile belts of Salair and Kolyvan–Tomsk [15].

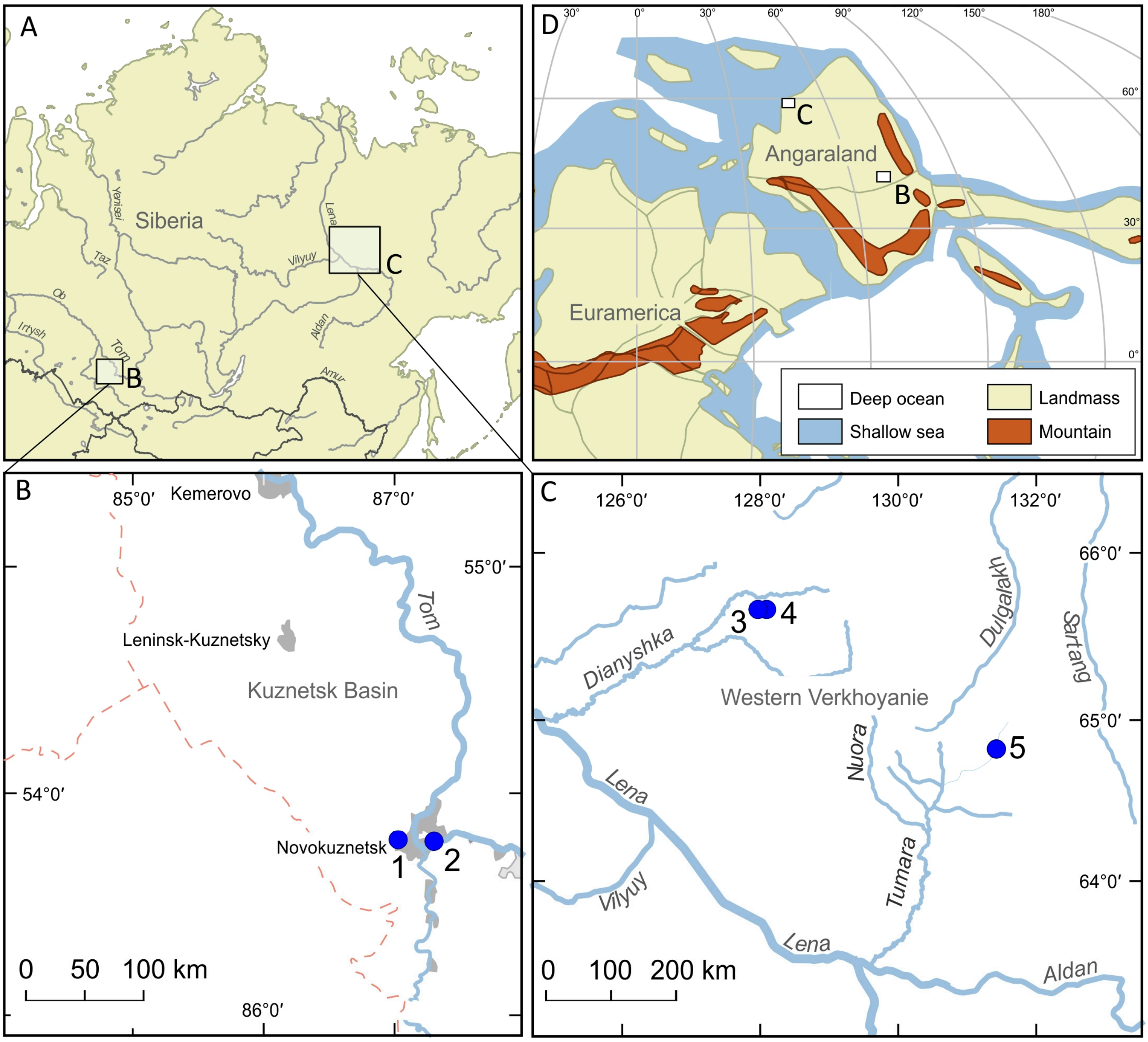

Figure 1. Locations of the studied sections: (**A**) Overview map, (**B**) Kuznetsk Basin, (**C**) Verkhoyanie Basin: (**D**) Late Permian palaeogeographic map. Points with numbers: (1) Starokuznetsk Fm section with dated volcanic tuff located on the Novokuznetsk bypass road; (2) Starokuznetsk Fm reference section within Novokuznetsk city; (3) Malinovyi Creek; (4) Pravaya Galochka Creek; (5) Upper reaches of the Delenzha River. Map D was created using QGIS and Gplates, with datasets available in ref. [16].

The close position of the Kuznetsk Basin and Siberian Platform in the Late Palaeozoic, as shown in Figure 1D, caused floral and faunal similarities between these two areas. The specificity of the largely endemic faunal and floral assemblages of this vast area was used to define a separate Late Palaeozoic phytogeographic and biogeographic province named Angaran, Angarian or Angaraland [17–25]. At the same time, some data on the palaeogeographic distribution of plants, conchostracans, ostracods, bivalves and fishes indicate possible short-term biotic exchanges between Angaraland, Euramerica (Laurussia) and Gondwana [20,24–27].

Kuzbass is considered a reference area for the whole Angaraland [21,25] due to its high level of geological investigation. Detailed studies in Kuzbass began in 1914 and continued for more than a hundred years by numerous scientific groups from various industrial and academic geological organisations [28]. The Upper Palaeozoic stratigraphic framework of the Kuzbass developed during this period was based on data from thousands of prospective and exploration wells, mine excavations and natural outcrops. It was characterised by a high degree of stratification and detailed palaeontological and palaeobotanical validation of the units: groups, formations, regional stages, etc. The Regional Stratigraphic Scheme of the Kuzbass was approved in 1979 [29]. Since its approval, it has undergone only one minor modification [30], which indicates its continuing relevance (Figure 2). The Regional Stratigraphic Scheme is implemented in geological mapping and is used in all geological surveys both in the Kuzbass and in adjacent areas, i.e., it is the basis for interregional correlations within the Angaraland, including the Verkhoyanie [21,22,25,31], etc.

Despite its detail, the Upper Palaeozoic Regional Stratigraphic Scheme of Kuzbass does not correlate directly with the General Stratigraphic Scale of Russia (GSSR) [32] or with the International Chronostratigraphic Chart [33] (Figure 2). The impossibility of direct correlation is related to the absence of marine fauna (e.g., conodonts, ammonoids, fusulinids, etc.) and the endemism of the continental (non-marine and terrestrial) biota of Angaraland due to its isolation from the Euramerican and Tethys regions in the Late Palaeozoic [20–22].

The Permian coal-bearing succession of the Kuzbass is subdivided into two thick units, the Balakhonka and Kolchugino Groups, which are stratified into subgroups, formations and beds (Figure 2). The boundary between the Balakhonka and Kolchugino Groups traditionally corresponds to the upper boundary of the Lower Permian [25] or, more recently, to the Cisuralian–Guadalupian boundary [32,34]. The biostratigraphic evidence for this boundary is based on the replacement of the "Early Permian" Balakhonka Flora with the "Middle Permian" Kolchugino Flora. The Balakhonka/Kolchugino floral change has been traced throughout Angaraland and is considered to mark the boundary between the Early and Middle Permian [34].

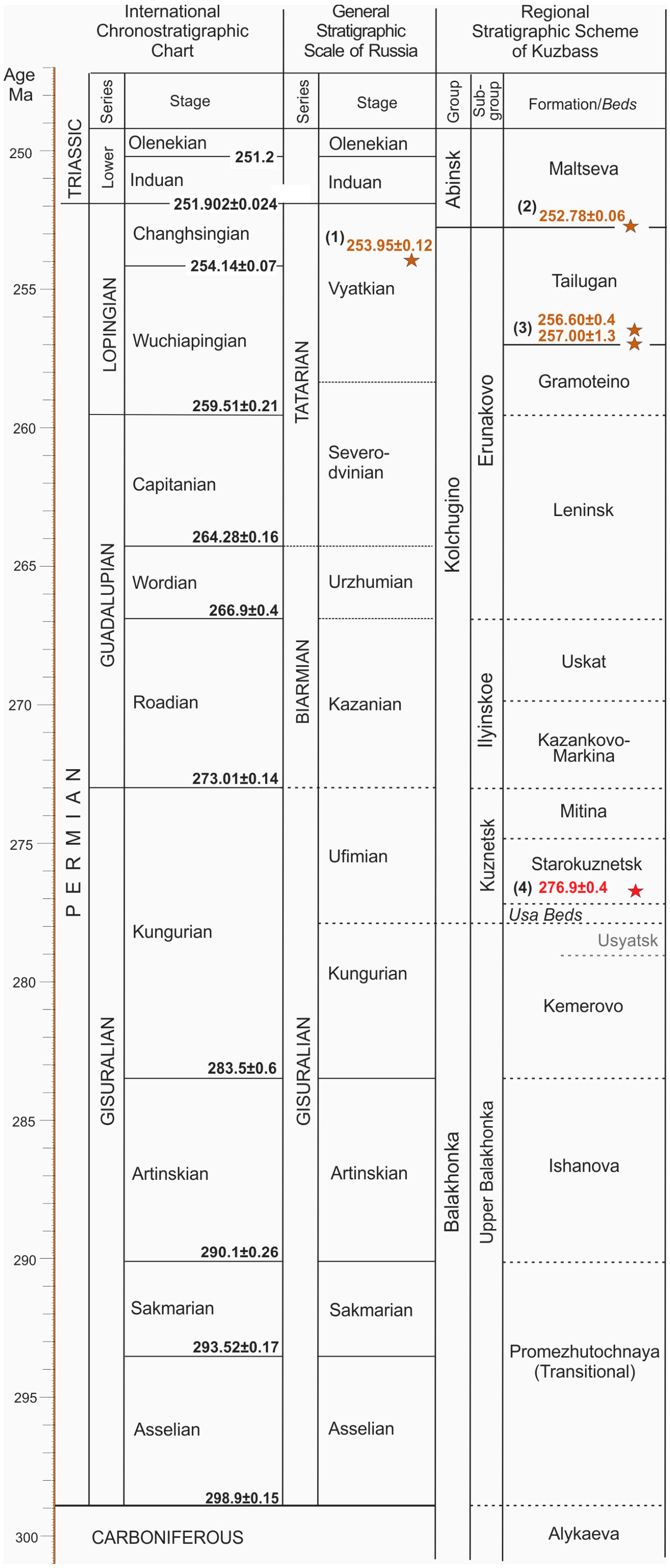

Figure 2. The Regional Stratigraphic Scheme of the Permian coal-bearing sediments of Kuzbass [29,30] and its comparison with the General Stratigraphic Scale of Russia [32] and the International Chronostratigraphic Chart [33]; Radioisotopic datings highlighted with star symbols are based on (1) ref. [35]; (2) ref. [13]; (3) ref. [14]; (4) this article.

This paper discusses radioisotopic (CA-ID-TIMS) dating of zircons from a volcanic tuff located in the middle of the Starokuznetsk Formation (Fm) (Figure 2), exactly in the stratigraphic interval where the Balakhonka Flora is gradually replaced with Kolchugino Flora. We provide new evidence for the evolution of vegetation at different latitudes in Angaraland during the Late Palaeozoic. In this context, it is particularly important to correlate the dated Kuzbass level with the reference sections of the Verkhoyanie, where beds with plant remains are intercalated with beds containing Middle Permian ammonoids [36]. The Verkhoyanie, located during the Late Palaeozoic on the northern margin of Angaraland (Figure 1D), contains several well-studied stratigraphic successions in which the Balakhonka/Kolchugino floral change is recorded [13,31]. These stratigraphic successions also contain the Lower Delenzhian ammonoids (*Sverdrupites*, *Daubichites*, etc.), a reliable marker of the Roadian Stage [37,38].

The present study demonstrates the potential of radioisotopic dating (CA-ID-TIMS) of zircons obtained from the basal part of the Kolchugino Group in establishing a direct correlation with the International Chronostratigraphic Chart [33]. In addition, we attempt to answer the challenging question of whether the replacement of Balakhonka ("Lower Permian") Flora with Kolchugino ("Middle Permian") Flora was synchronous at different latitudes of Angaraland.

2. Geological Setting

The sedimentary succession of the Kuzbass was accumulated over a period of about 350 Ma—from the Early Palaeozoic to the Middle Mesozoic. The most significant subsidence, accompanied by marine basin ingression, began in the Devonian and continued into the Mississippian. Several episodes of folding in the early Pennsylvanian changed the pattern of sedimentation from marine to continental clastic and coal-bearing. The uplift of the area resulted in the denudation of previously formed sedimentary structures. The Kuzbass acquired its present geological configuration at the beginning of the Cretaceous [28].

2.1. General Features of the Coal-Bearing Succession of the Kuzbass

The upper Carboniferous and all Permian rocks consist of continental, predominantly clastic and coal-bearing sediments. Their greatest thickness (7000–8000 m) is restricted to the axial and western parts of the basin. The reference sections consist of sandstones, siltstones and mudstones, including thick coal seams and thin coal interbeds. The subordinate lenses of gravels and conglomerates mark the boundaries of sedimentary cycles. The proportion of coal in the total succession averages between 1% and 6% (70–480 m), rising to 20–25% in some stratigraphic units.

The Permian coal-bearing succession in the Kuzbass consists of the Balakhonka and Kolchugino Groups, the boundary between which is controversial despite a long history of geological studies. The boundary is controversial because, in the absence of reliable biostratigraphic markers, it is still based on the lithological criterion, i.e., on the replacement of the coal-bearing interval with thick productive coal seams (uppermost Balakhonka) with clastic rocks without coal beds (lowermost Kolchugino). The last shift in this boundary to the roof of the Aralicheva I coal seam took place in 1993 [30]. This facies-dependent boundary may be located at various stratigraphic levels in different regions of the Kuzbass. Local erosion in the upper part of the Balakhonka Group [39] reduces the completeness of the succession and complicates stratigraphic correlations.

The boundary between the Balakhonka and Kolchugino Groups in the Kuzbass is traditionally accepted as the boundary between the Lower (Cisuralian) and Middle (Guadalupian) Series of the Permian (Figure 3). Accordingly, the level of this boundary in the Kuzbass succession is also controversial and changes depending on the boundary between these groups.

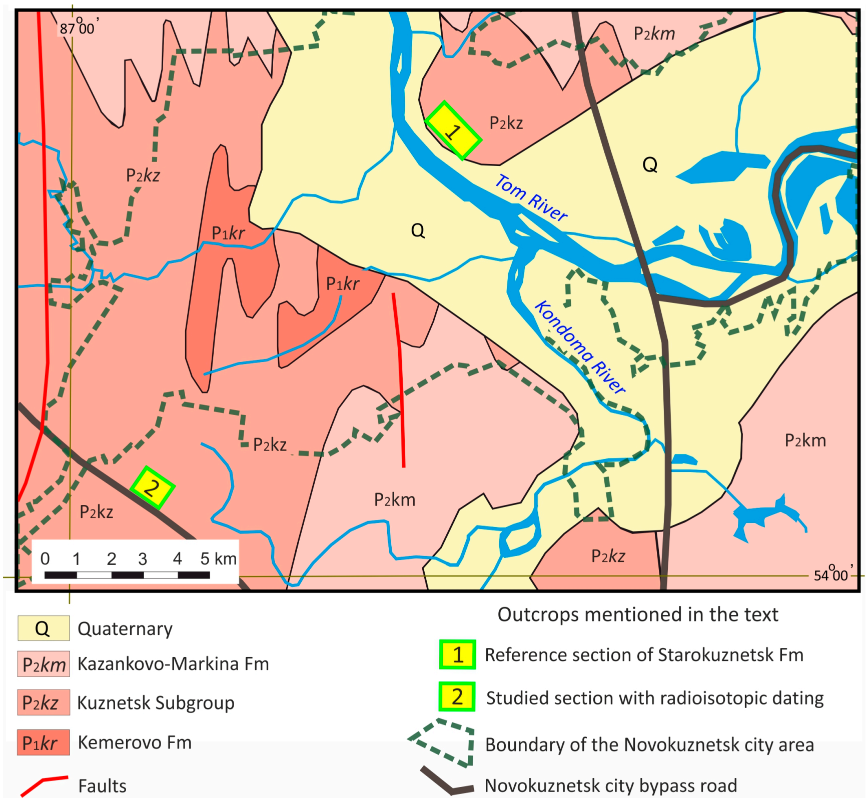

Figure 3. Geological map of the studied area of Kuzbass.

2.2. Sedimentary Succession of the Balakhonka/Kolchugino Boundary Interval

The Balakhonka Group consists of clastic and coal-bearing sediments (1300–3200 m thick) belonging to the Pennsylvanian (the Lower Balakhonka Subgroup) and Cisuralian (the Upper Balakhonka Subgroup) Series. The Upper Balakhonka Subgroup (700–2000 m thick) is composed of three formations (Fm), of which the Kemerovo Fm completes its succession (Figure 2). Below, we briefly summarise the main features of the Balakhonka/Kolchugino boundary interval.

The Kemerovo Fm (175–530 m thick) includes sandstones, siltstones and mudstones with thick productive coal seams. The reference section outcrops on the banks of the Tom River, near the city of Kemerovo (Figure 1B). The formation extends throughout the Kuzbass and in adjacent basins of the Altai–Sayan Fold Belt.

The Kemerovian regional stage corresponds to the Kemerovo Fm and is based on the characteristics of fossil plants (mainly cordaitoids and sphenopsids) and invertebrates (mainly non-marine bivalves).

The plant assemblage includes sphenopsids *Paracalamites decoratus* (Eichwald) Zalessky, *Annulina neuburgiana* (Radczenko) Neuburg, *Annularia* (?) *planifolia* Radczenko, *A.* (?) *tenuifolia* Neuburg and *Phyllotheca deliquescens* (Göppert) Schmalhausen, the fern *Prynadaeopteris maneichensis* (Zalessky) Radczenko and supposed fern *Sphenopteris batschatensis* Zalessky. Cordaitoids are represented by leaves of *Rufloria* with narrow sunken stomata rows, such as *Rufloria derzavinii* (Neuburg) S. Meyen, *R. multipapillata* Gluch., *R. tuberculosa* Gluch. and *R. plana* Gluch., less common leaves of *Cordaites*, scaly leaves of *Nephropsis rhomboidea* Neuburg and *N. integgerima* (Schmalhausen) Zalessky. Numerous seeds include *Samaropsis*, *Carpolithus*, *Sylvella* and *Skokia*.

Non-marine ostracods first appear in the coal-bearing Kuzbass succession only in the Kemerovo Fm, where only one species of the genus *Tomiellina* is reported. This is of some interest because in the neighbouring Minusinsk Coal Basin, non-marine ostracods (suborder Cytherocopina) are known from the Late Carboniferous [24]. The absence of ostracods in most of the Balakhonka Group is explained by the low content of calcium carbonate in the water of peat bogs and adjacent aquatic settings [23].

Non-marine bivalves include the "giant" forms of *Prokopievskia* Ragozin, *Sinomya* Betekhtina and *Ussiella* Betekhtina. Giant bivalve shells are sporadic in the lower part of the Kemerovo Fm and become more abundant in its upper part [25].

The upper part of the Kemerovo Fm (75–280 m thick) consists of interbedded sandstones, siltstones and mudstones, including thick productive coal seams.

The dominant plant remains in this interval are the large-leaved cordaitoids *Rufloria derzavinii* (Neuburg) Meyen, *Cordaites latifolius* (Neuburg) Meyen, *Vojnovskya minima* (Chachl. et Poll.) (Neuburg) and sphenopsids with large whorls *Annularia* (?) *tenuifolia* Neuburg, *A.* (?) *planifolia* Neuburg, *Paracalamites angustus* Such., *P. vicinalis* Radczenko. Associated with the dominant groups are the ferns *Pecopteris abensis* Zal. and *P. martia* Neuburg and bryophytes *Salairia longifolia* Neuburg [25,40].

Non-marine bivalves are still represented by the mass accumulations of "giant" (up to 80–100 mm) shells of *Prokopievskia gigantea* Rag., *Pr. pseudogigantea* Bet, *Pr. sygmoidea* Khalfin, *Ussiella gigantissima* (Khalfin), *Sinomya* sp., occurring together with *Myalina*-like forms, coiled shells of a *Spirorbis* (possibly microconchids?) and cirripede crustaceans [25].

The assemblages of "giant" non-marine bivalves *Prokopievskia*, *Ussiella*, *Sinomya* are widespread in the Upper Kungurian of the Tunguska Basin (Upper Burgukli Sfm) [25], Eastern Taimyr (Sokolinaya Fm) [41,42] and the Timan-Pechora Basin (Lek-Vorkuta Fm) [26]. The marker floral beds with bryophytes *Salairia longifolia*, sphenopsids *Paracalamites angustus*, cordaitoid *Vojnovskya minima* and numerous seeds *Skokia*, specific to the upper part of the Kemerovian regional stage, have been traced throughout the Kuzbass and adjacent areas [25,40].

Based on floral and faunal characteristics, the upper part of the Kemerovo Fm was previously established as a distinct Usyatsk Fm [43,44] and then as the Usyatskian regional stage [25]. However, these stratigraphic units were later questioned and are no longer used due to the "...uncertainty of their stratigraphic extent..." [30] (p. 93).

The Kolchugino Group (up to 6000 m thick) roughly corresponds to the Guadalupian and Lopingian Series of the Permian System (Figure 2). The lower boundary of the group is accepted in the roof of the upper productive coal seam (Aralicheva I coal seam) of the Balakhonka Group; the upper boundary is provisionally determined by the replacement of coal-bearing sediments with tuffogenic and clastic rocks of the Abinsk Group of predominantly Triassic age. Complete sections of the upper part of the Kolchugino Group show gradual replacement of coal-bearing sediments with volcanogenic and clastic rocks with characteristic spheroidal spalling and zeolite mineralisation. As a result, the boundary between the Kolchugino and Abinsk Groups is often not clearly defined.

The Kuznetsk Subgroup, whose radioisotopic dating we discuss in this paper, is the lowest unit of the Kolchugino Group and lacks productive coal seams (Figures 2, 4 and 5). The stratotype of the Kuznetsk Subgroup outcrops on the Tom River within the city of Novokuznetsk (Figure 3). The Kuznetsk Subgroup (700–930 m thick) consists of sandstones and siltstones with interlayers of mudstones and lenses of marls and siderites.

Initially, this stratigraphic interval was separated under the name "Empty Formation" and provisionally assigned to the Upper Permian (in the concept of the two-series division of the system). Since 1935, geologists have referred to this stratigraphic interval as the Kuznetsk Formation. Later, the Kuznetsk Fm was divided into three Subformations (Sfm)—from bottom to top—the Usa, Starokuznetsk and Mitina [45]. The Usa Sfm is now recognised as "beds with fossil plants" [32]; the Starokuznetsk and Mitina Sfm are raised in status to formations, while the Kuznetsk Fm is turned into a subgroup [30] (Figures 2 and 4). In the modern Regional Stratigraphic Scheme, the Kuznetsk Subgroup consists of (from bottom to top) the Usa Beds, the Starokuznetsk Fm and the Mitina Fm.

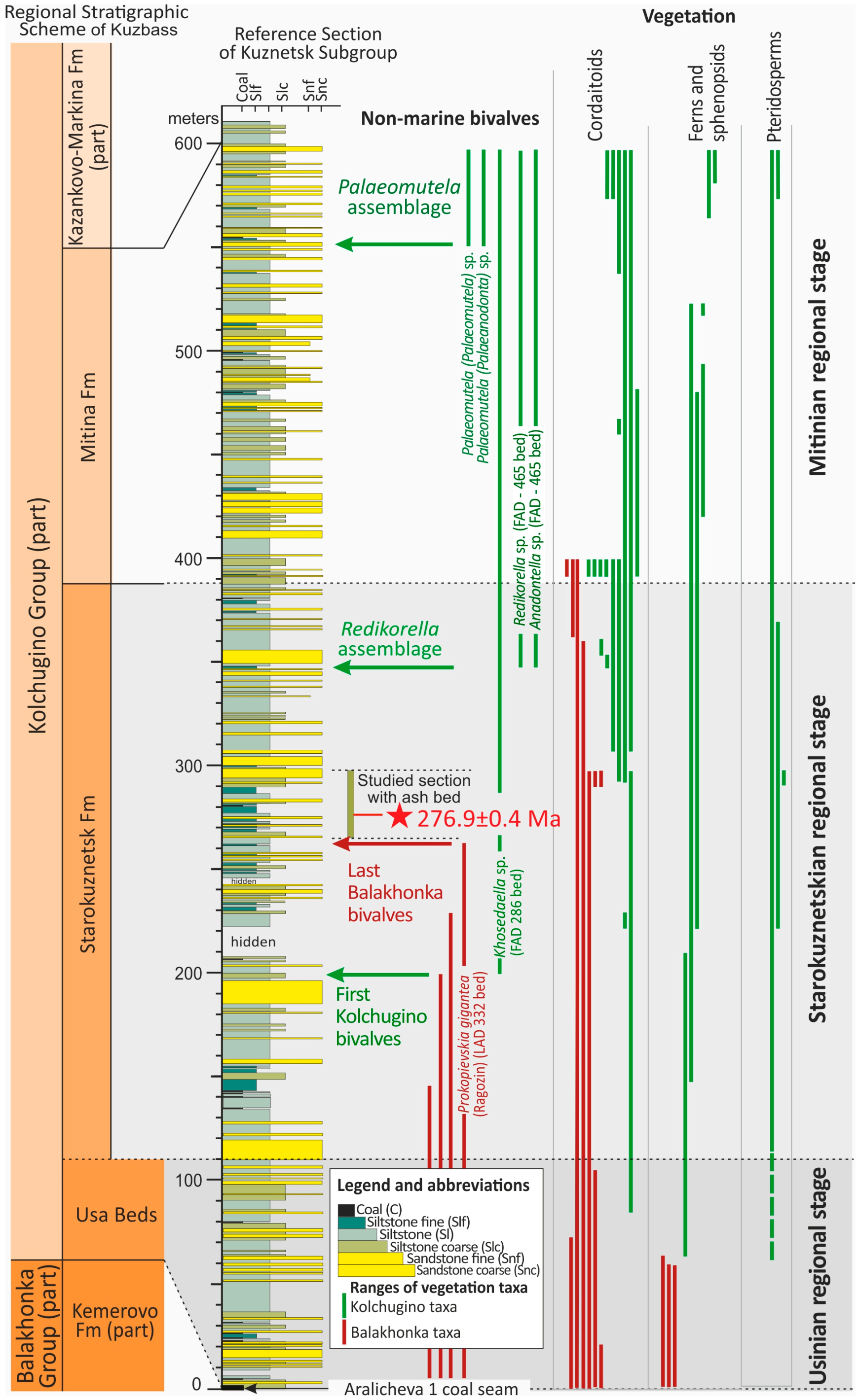

Figure 4. Reference section of the Kuznetsk Subgroup and stratigraphic position of the studied section with the dated ash bed. Generalised major biotic events are shown. The star symbol indicates the radioisotopic dating discussed in this article. The Regional stratigraphic scheme is given according to refs. [29,30].

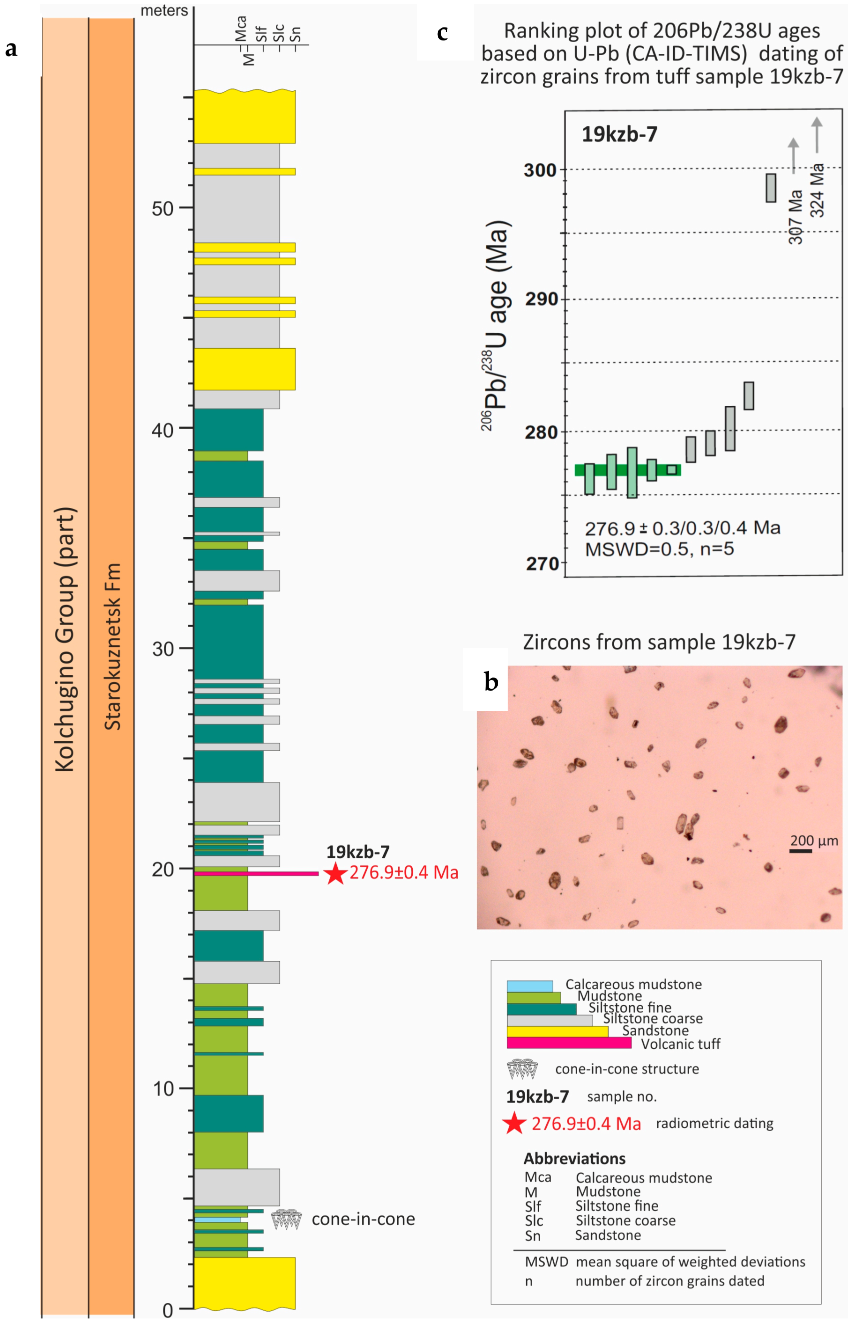

Figure 5. Stratigraphic position of the dated ash layer (sample no. 19 kzb-7) and the results obtained: (**a**) Section of the Starokuznetsk Formation on the Novokuznetsk bypass road; (**b**) Photographs of zircon grains; (**c**) Ranking plot of 206Pb/238U ages (CA-ID-TIMS) for individual zircon grains. The star symbol indicates the radioisotopic dating discussed in this article.

The Usa Beds (70–110 m thick) consist of dominant siltstones interbedded with packages of fine-grained and silty sandstones, rare mudstone interlayers and a few levels with carbonate nodules (Figure 4). The lower boundary is accepted in the roof of the Aralicheva I coal seam [30,46].

The Usa Beds contain one to three lens-shaped interbeds of polymictic boulder conglomerates (up to 11 m in total thickness) occurring at different stratigraphic levels within 0–70 m interval above the Aralicheva I coal seam. Some researchers suggest that the conglomerates are regionally widespread and related to orogenic movements, which caused angular unconformity. A marker package of mottled carbonate-clayey rocks, 5–25 m thick, overlies the conglomerates [39].

The plant assemblage is dominated by sphenopsids and cordaitoids [25,47], which co-occur with poorly preserved leaves' pteridosperms of the genus *Comia* (Figure 4). A characteristic feature of Usa Beds is the co-occurrence of Balakhonka cordaitoids and Kolchugino pteridosperms. This co-occurrence indicates that the late Balakhonka Flora is beginning to be gradually replaced with early Kolchugino Flora.

Non-marine bivalves of the Usa Beds are similar to the Late Balakhonka fauna and include "giant" shells of *Prokopievskia*, *Sinomya* and *Ussiella*.

The Starokuznetsk Fm (280–325 m thick) consists of interbedded packages of grey fine-grained and silty sandstones, siltstones and mudstones, including numerous interlayers and lenses of concretions (siderites, phosphorites) and sporadic thin interlayers of tuffites. The lower boundary of the formation is assumed to be 110 m above the roof of Aralicheva I coal seam. Sandstones and siltstones differ from similar rocks in adjacent intervals by an increasing quartz content [46]. The upper part of the reference section of Starokuznetsk Fm (Figures 1 and 3) contains tuffs and agglomerates consisting of altered vitroclastic material. The newly dated ash bed (sample no. 19kzb-7) is located approximately in the middle part of the Starokuznetsk Fm, in the upper part of one of the mudstone intervals (Figures 4 and 5).

The Starokuznetsk *plant assemblage* contains the co-existing late Balakhonka and early Kolchugino species of cordaitoids. The first distinct occurrence of the genus *Comia*, which is widespread in younger Permian floras of Angaraland, is also characteristic of this assemblage. The cordaitoids consist mainly of *Cordaites* and *Rufloria*, and the former dominate. This dominance distinguishes the Starokuznetsk Fm from the Upper Balakhonka Subgroup, where the proportions of these genera are approximately equal.

The *Cordaites* contain late Balakhonka species, e.g., *Cordaites latifolius* (Neuburg) Meyen, and new early Kolchugino species appearing for the first time: *C. praeincisus* Gorelova, *C. kuznetskianus* (Gorelova) Meyen, *C. gracilentus* (Gorelova) Meyen, *C. candalepensis* (Zalessky) Meyen. A similar picture is characteristic of the genus *Rufloria*, which includes rare large-leaved late Balakhonka species *Rufloria* (*Alaetorufloria*) *derzavinii* (Neuburg) Meyen, *R.* (*A.*) *meyenii* Gluchova and new early Kolchugino species, e.g., *R.* (*A.*) *arta* (Zalessky) Meyen.

In addition to the two genera mentioned above, the cordaitoids of the Starokuznetsk Fm include the scaly leaves of *Crassinervia peltiformis* Gorelova, *C. pentagonata* Gorelova, *Nephropsis lampadiformis* Gorelova, *N. grandis* Gorelova. The sandy sediments of the lower part of the Starokuznetsk Fm contain moderate-sized trunks with leaf cushions and leaf traces of *Lophoderma tersiensis* Radczenko, originally assigned to lycophytes [48] and later to cordaitoids [19,49].

Sphenopsids are the second dominant group. The more characteristic sphenopsids are *Annularia planifolia* Radczenko, *Annulina iljinskiensis* (Radczenko) Meyen and *Phyllopitys* (?) *sessilifolia* Gorelova.

Pteridosperms contain two genera: *Zamiopteris* and *Comia*. *Zamiopteris* includes two Kolchugino species: *Z. kuznetskiana* Gorelova and *Z. crassinervis* Gorelova. The layers with pinnate leaves of the first-appearing Kolchugino species *Comia osinovskiensis* Gorelova are used as a correlation marker and are traced within the Kuzbass and adjacent basins.

Fossil seeds also include a mixture of late Balakhonka and early Kolchugino species. The species known from the Upper Balakhonka, i.e., *Skokia elongata* (Tarasova) Suchov, *Samaropsis prokopievskiensis* Suchov and *S. neuburgii* f. *bungurica* Suchov, occur together with *Samaropsis pseudotriquetra* Neuburg, which first appears in the Starokuznetsk Fm. Ferns and bryophytes are extremely rare.

The Starokuznetsk *non-marine bivalve assemblage* is very similar to that of the Kemerovo Fm and includes relict species of the late Balakhonka fauna: *Ussiella* (=*Mrassiella*) *gigantissima* (Khalf.), *U. ussiensis* (Khalf.), *Prokopievskia gigantea* Rag., *Pr. pseudogigantea* Bet., *Sinomya* sp. New taxa appearing for the first time in the Starokuznetsk Fm are predominantly endemic and phylogenetically related to the Balakhonka fauna, i.e., *Augea elliptica* Khalf., *A. ovata* Khalf., *Zvonarevia convexa* Tok., *Bunguria tetragonalis* Tok., *B. rhomboidea* Tok.

Most interesting are the cosmopolitan *Redikorella* Silantiev, 1994, appearing for the first time in the Starokuznetsk Fm. This genus is abundant in the Solikamskian regional stage of the East European Platform and the Urals, in the Inta Fm of the Timan-Pechora Basin and in the upper part of the Burguklian regional stage of the Tunguska Basin [26], and it has recently been found in the Guncina Fm of the Southern Alps [50]. In the upper part of the Starokuznetsk Fm, non-marine bivalves become smaller in size, and their taxonomic diversity decreases.

Non-marine ostracods are widespread in the Starokuznetsk Fm [23,51] and include representatives of the suborders Cytherocopina and Darwinulocopina. Cytherocopines dominate and contain five genera—*Iniella*, *Kemeroviana*, *Tomiella*, *Tomiellina* and *Suriekovella*—among which the *Tomiellina* are most diverse. The darwinulocopines are represented by a few species of *Darwinula* and *Darwinuloides* [46,52].

The assemblages of non-marine ostracods, comprising mainly the Siberian genera *Tomiella*, *Tomiellina*, *Iniella*, *Kemeroviana* and *Suriekovella*, constitute the so-called Angarian fauna [53]. The generic composition of this fauna distinguishes it from Kazakhstan fauna, which consists mainly of *Darwinula*, and from Euramerican fauna, which mainly unites representatives of the Carbonitacea. The Angarian fauna appears for the first time in the Middle Carboniferous of the Minusinsk Coal Basin [24]. Some elements of Angarian fauna, e.g., the *Iniella* and *Tomiella* species, are described in the Inta Fm (Ufimian) of the Timan-Pechora Basin [54] and in the Degali Fm (Late Permian) of the Tunguska Basin [55].

The fishes of the Starokuznetsk Fm can only be provisionally characterised, as the two taxa known from the Kuznetsk Subgroup—*Holuropsis yavorskyi* and *Paraeurynotus chabakovi*—have no precise stratigraphic and geographic setting. Both genera are known only from the Permian deposits and are endemic in the Kuzbass [56,57]. Initially, these genera were assigned to families from the Lower Carboniferous of Great Britain. At present, we can assume that this assignment was erroneous. The scale morphology of *P. chabakovi* is very similar to that of *Usolia* sp. from the Kazankovo-Markina Fm [27]. The Usolia species have been described in the Ufimian of European Russia [58], where they apparently migrated from Angaraland in the same way as other Angarian fishes [27]. The phylogenetic relationships of *H. yavorskyi* are unclear.

The Mitina Fm (280–380 m thick) consists of intercalated fine-grained and silty sandstones with packages of siltstones and mudstones containing interbeds with carbonate concretions and rare tuffite interbeds. In the reference section, the lower boundary of the Mitina Fm is provisionally defined at 390–420 m above the top of Aralicheva I coal seam [46] (Figure 4).

The Mitina plant assemblage comprises a new phase in the evolution of Angaraland fern–pteridosperm–cordaitoid flora and corresponds to the typical Kolchugino Flora lacking late Balakhonka elements. Cordaitoids dominate together with pteridosperms (*Permocallipteris*, *Comia*) and ferns (*Pecopteris*).

The taxonomic composition of cordaitoids is renewed. The first-appearing species include *Cordaites minax* (Gorelova) Meyen, *C. radczenkoi* (Gorelova) Meyen, *C. gorelovae* Meyen, scaly leaves of *Crassinervia tenera* Gorelova and *C. ivancevia* Gorelova. The subgenus *Rufloria* (*Rufloria*) first appears in the Mitina Fm and is represented by *R.* (*R.*) *olzerassica* (Gorelova) Meyen; this subgenus is widespread in subsequent younger Permian floras. In contrast, the *R.* (*Alaetorufloria*) occurs rarely as small-leaved forms of the species *R.* (*A.*) *arta* (Zal.) Meyen.

The *Zamiopteris crassinervis* Gorelova and *Z. lanceolata* (Chachlov et Pollak) Neuburg are still abundant and co-occur with the first-appearing pteridosperms *Permocallipteris ivancevia* (Gorelova) Nauglonykh. The fern *Pecopteris pseudomartia* Radczenko is common. Sphenopsids are numerous and diverse, and they include *Phyllopitys* (?) *sessilifolia* Gorelova, *Phyllotheca turnaensis* Gorelova, *Annulina iljinskiensis* (Radczenko) Meyen, *Paracalamites communis* Gorelova. Several new species of seeds appear for the first time in the Mitina Fm, namely *Tungussocarpus elongatus* (Suchov) Suchov, *Sylvella alata* Zalessky, *Cordaicarpus* *petrikensis* Suchov, *Cord. tagaryschskiensis* Suchov, *Samaropsis uncinata* Neuburg; these species are also widespread in the younger intervals of the Permian.

The Mitina Fm contains a marker (correlative) floristic layer with the characteristic pteridosperm *Permocallipteris ivancevia* (Gorelova) Nauglonykh. This marker layer is traced throughout the Kuzbass (Mitinian regional stage) and the Tunguska Basin (Lower Peliatkian regional substage) [25,59].

Non-marine bivalves of the Mitina Fm comprise both genera widespread throughout Angaraland, including the Tunguska and Timan-Pechora Basins (*Khosedaella*, *Brussiella*), and cosmopolitan genera (*Redikorella*, *Palaeomutela*).

Non-marine ostracods are more diverse than the older assemblage of the Starokuznetsk Fm. The suborders Cytherocopina and Darwinulocopina are equally dominant. Within the Cytherocopina, a new genus *Sinusuella* appears; the genus *Tomiella* contains only new species; the genus *Iniella* is characterised by the first appearance of several species [23,52,60]. Within Darwinulocopina, the genera *Darwinula* and *Darwinuloides* mainly consist of new species, many of which are cosmopolitan, widespread in the Ufimian Stage of the East European Platform, in the Cis-Ural and Timan-Pechora Basins [54].

2.3. Volcanogenic Rocks in the Kuzbass Coal-Bearing Succession

Volcanogenic rocks are widespread in the coal-bearing succession of the Kuzbass. This is apparently due to the volcanic activity of the mobile fold belts on the periphery of the Kuznetsk sedimentary basin. At least 12 volcanogenic interbeds (few centimetres to ten metres thick) of tuffs, tuffites and montmorillonite clays are described in the Kuzbass coal-bearing succession [61–63] and subsequently traced in the adjacent Minusinsk and Tunguska Basins [64]. The mineralogy and geochemistry of volcanogenic rocks, e.g., the content of rare and radioactive elements, were studied in detail [65–67].

In coal seams, volcanic ash is usually transformed into tonsteins, representing cemented hard pelitic interbeds. In clastic rocks, volcanic ash is altered into plastic clays. In both cases, the interbeds of volcanic material are thin (usually a few centimetres), predominantly kaolinitic in composition and different from the host rocks in colour (light grey, grey, brownish, almost black), mineral composition and lack of lamination. Most tonsteins and volcanic ashes contain idiomorphic zircon grains. The origin of these grains is related to the precipitation of ash cloud material produced by volcanic eruptions synchronous with the accumulation of clastic or peat sediments.

The search and study of volcanic ash interbeds enables the development of a chronostratigraphic framework for the Kuzbass coal-bearing succession based on radioisotopic dating of zircons. At present, the following radioisotopic datings of Permian sediments in the Kuzbass are available:

(a) Abinsk Group. Maltseva Fm. Radioisotopic dating of zircons from volcanic ash interbeds in the lower part of the formation indicates an $^{206}Pb/^{238}U$ age of 252.78 ± 0.06 (0.14) [0.30] Ma, 252.65 ± 0.08 (0.18) [0.11] Ma and 252.33 ± 0.08 (0.20) [0.33] Ma [13], which is slightly older than the accepted dating (251.902 Ma) of the Permian–Triassic boundary [33] (Figure 2). Thus, the lowermost strata (10–40 m) of the Maltseva Fm—traditionally attributed to the Triassic [29,30]—are in fact of the Late Changhsingian.

(b) Erunakovo Subgroup. Tailugan Fm. Radioisotopic dating of zircons extracted from the tonsteins of coal seam 78 at the base of the Tailugan Fm indicates an $^{206}Pb/^{238}U$ age of 257.0 ± 1.3 and 256.6 ± 0.4 Ma (Middle Wuchiapingian) [14].

(c) Kuznetsk Subgroup. Starokuznetsk Fm. Radioisotopic dating of zircons from a volcanic ash interbed in the middle part of Starokuznetsk Fm indicates an $^{206}Pb/^{238}U$ age of 276.9 ± 0.4 Ma (MSWD = 0.5) (this paper).

3. Materials

The section from which we sampled volcanic ash—which served as the material for separation of zircon grains and their radioisotopic dating (sample no. 19kzb-7)—is located near the southern boundary of the city of Novokuznetsk in the incision of the bypass road (53.711694 N, 86.957161 E) (Figure 3, loc. 2). The beds dip northwards at an angle of 60 degrees (Figure 6A). The subtle cyclicity of the section is a result of regularly recurring mudstones, fine- and coarse-grained siltstones and sandstones. The lenses and interbeds of carbonate concretions emphasise the cyclic pattern of the section (Figure 6B). The volcanic ash layer is lighter in colour than the host rocks and is clearly visible on the outcrop wall (Figure 6C).

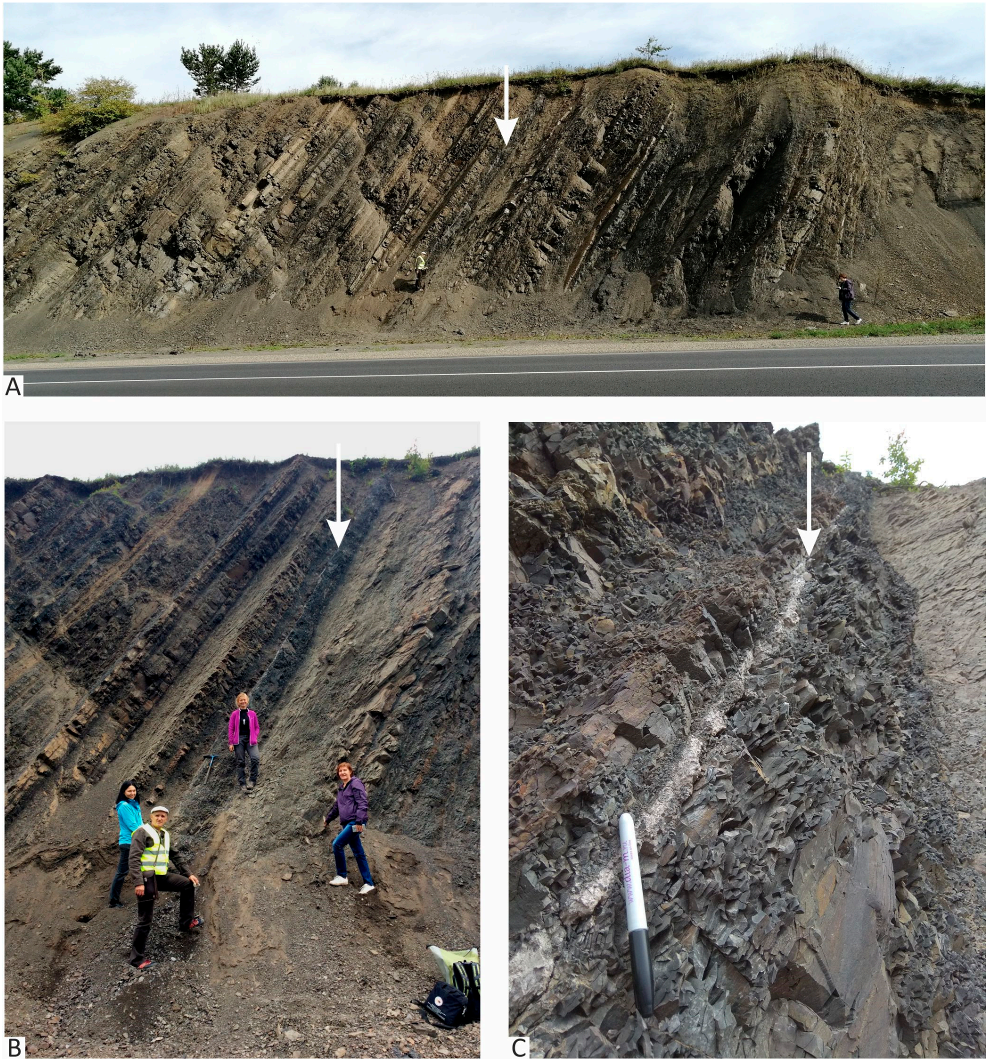

Figure 6. Location of volcanic ash bed (sample no. 19kzb-7; white arrow) in the middle part of the Starokuznetsk Fm in the outcrop on the bypass road near the southern border of the city of Novokuznetsk: (**A**) General view of the outcrop; (**B**) Fine cyclicity of the succession; (**C**) Volcanic ash bed (sample no. 19kzb-7).

The stratigraphic position of volcanic ash in the Starokuznetsk Fm is shown in Figures 4 and 5. The weight of the sample was approximately 3 kg. The entire sample was processed for subsequent zircon grain separation.

Zircon characterisation. The zircon grains from sample no. 19kzb-7 were very small (ca. 100 µm). Many of them had rounded surfaces, indicating inheritance (Figure 7). We selected zircon grains with even surfaces and sharp crystallographic edges (most idiomorphic zircon grains) to avoid xenocrystic older cores.

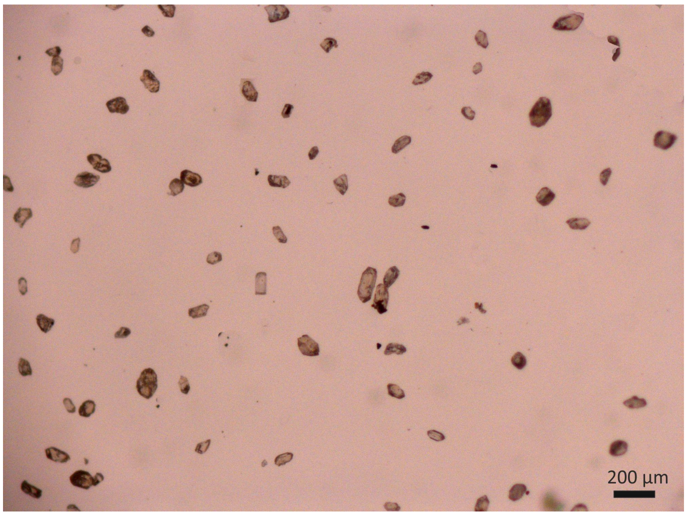

Figure 7. Zircon grains from sample no. 19kzb-7.

4. Methods

The tuff sample was processed at Kazan Federal University. The most prospective zircon grains were subsequently sent to the Isotopic Laboratory, Institute of Mineralogy, Technische Universität Bergakademie Freiberg (Germany), for precise dating using chemical abrasion–isotope dilution–thermal ionisation mass spectrometry (CA-ID-TIMS).

4.1. Sample Preparation

Zircons were separated from the tuff using three standard procedures. Initially, the tuff samples were crushed to a fraction of 0.5–1.5 cm and treated with dimethyl sulfoxide ($(CH_3)_2SO$) for 48 h at 50 °C. As a result, the entire tuff material turned into a clay-like pulp. The next procedure involved ultrasonic dispersion (emission frequency of 25 kHz) of the clay-like pulp with constant stirring and gradual washing of the clay fraction in a system of communicating vessels. This procedure took from 72 to 96 h per sample. The mineral fraction with a size of 30–250 µm, obtained after washing the clay, was about 0.01% of the weight of the clay-like pulp. It was further treated in the heavy liquid GPS-V (a concentrated aqueous solution of sodium heteropolytungstate) with a maximum density of 3.00 ± 0.05 g/mL. Individual zircon grains were extracted from the heavy fraction using a ZEISS Stemi DV4 binocular microscope (ZEISS, Jena, Germany).

4.2. Zircon Dating Using Chemical Abrasion–Isotope Dilution–Thermal Ionisation Mass Spectrometry

Selected zircon grains (ca. 50 grains with most idiomorphic forms) were annealed for 96 h at 900 °C and subsequently chemically abraded for 2 h at 210 °C with concentrated HF and HNO_3 in a pressurised Parr dissolution vessel. We applied this short leaching time in order not to dissolve the small zircon grains before dating. This procedure dissolves crystal domains—which are suspected to have experienced post-crystallisation lead loss—by inflicting strong radiation damage [68].

Afterwards, the acid, together with dissolved zircon material, was completely pipetted out, and 3.5N HNO_3 was added to the remaining zircon grains and fragments and left for 30 min at 50 °C to remove surface lead. Several cleaning cycles with water combined with repeated ultrasonic treatment were conducted before single zircon fragments were selected for further processing. Single zircon grains/fragments were washed with 3.5 N HNO_3 and transferred into clean microcapsules with a small drop of this fluid and four drops of concentrated HF. Samples were spiked with a ^{205}Pb-^{233}U-^{235}U- tracer solution (ET535 at TU Bergakademie Freiberg) [69]. For final dissolution, the microcapsules were placed in pressurised Parr dissolution vessels and heated to 200 °C for 48 h, followed by drying at 130 °C and then re-dissolution in 6N HCl for 24 h at 200 °C to transfer them into chlorides. After repeated drying, the samples were dissolved in ten drops of 3.1 N HNO_3

and transferred into micro-columns for column chemistry. U and Pb were separated from the rest of the sample by anion exchange chromatography using HCl and H_2O. The U and Pb containing fraction was loaded on pre-degassed rhenium filaments with a drop of silica gel [70] and measured on an IsotopX Phoenix Mass Spectrometer using a SEM Daly ion counter. The accuracy of dating results was checked by repeated measurement of zircon standards 91500 [71] and Temora 2 [72]. The published ages of Temora 2 were determined as 416.8 ± 0.3 Ma [72]. Our date of 417.3 ± 0.6 Ma [73] perfectly matches these values. Zircon standard 91500 was determined to be 1062.4 ± 0.4 Ma [71] or 1063.6 ± 0.3 Ma [74]. Our weighted mean $^{206}Pb/^{238}U$-age of 1064.6 ± 1.3 Ma was within 0.1% of the accepted values. Based on the results of standard dating, we presume the present CA-ID-TIMS ages to be accurate at the 0.1% level.

5. Results of CA-ID-TIMS Zircon Dating

Zircon U-Pb CA-ID-TIMS isotopic results are presented in Table S1 and are shown as $^{206}Pb/^{238}U$ ranked age plots in Figure 8. Mean sample ages representing crystallisation were calculated from established age clusters with the software ET Redux [75]. The error of weighted mean ages is given as ±x/y/z, where x is the internal 2σ measurement error; y is the internal 2σ error plus tracer calibration uncertainty; and z additionally includes the uncertainty of the decay constant. For discussion, we use the z-error, which includes the internal 2σ measurement error, the tracer calibration uncertainty and the uncertainty of the decay constant and enables comparison with other dating methods.

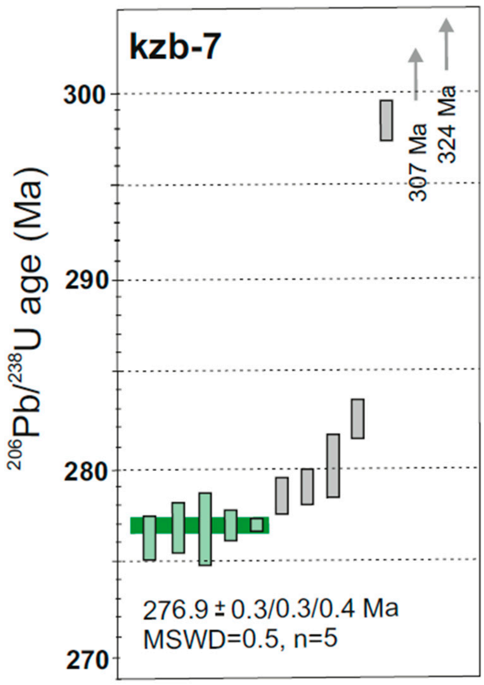

Figure 8. Ranking plot of $^{206}Pb/^{238}U$ dates from single grains of zircon analysed using CA-ID-TIMS; volcanic tuff, sample no. 19kzb-7; Starokuznetsk Fm. A weighted mean date is shown and represented by the grey boxes behind the error bars. Abbreviations: MSWD—mean square of weighted deviations; n—number of zircon grains dated.

For sample no. 19kzb-7, even short (2 h) chemical abrasion (CA) removed more than 50% of the selected zircon grains, so that only very small zircon fragments remained. We were able to date 12 such zircon fragments. The single zircon ages vary from 276 to 324 Ma and have a high measurement error due to the small size of remaining zircon fragments. Five measurements (fractions 1, 8, 9, 11, 13) form a cluster with identical ages between 276.2 and 277.0 Ma (Figure 8).

These five measurements were used to calculate a weighted mean age of 276.9 ± 0.4 Ma (MSWD = 0.5). All other zircon fragments show older ages, which represent inherited components (e.g., xenocrystic cores).

6. Discussion

The newly dated ash bed from the middle part of the Starokuznetsk Fm indicates a late Kungurian age of 276.9 ± 0.4 Ma of the interval where the late Balakhonka (cordaitoid) Flora is replaced with Kolchugino (fern–pteridosperm–cordaitoid) Flora (Figures 4 and 5). The Balakhonka/Kolchugino floral change is confidently traced throughout Angaraland and is widely used in stratigraphic correlations [34,76]. First of all, it is important to compare the newly dated Kuzbass succession with other plant-bearing sequences in Western Verkhoyanie (Figure 1A,C,D), where beds with fossil plants are intercalated with beds containing ammonoids [36].

6.1. The Balakhonka/Kolchugino Floral Change in Western Verkhoyanie

Western Verkhoyanie is a key region for resolving questions regarding the chronological relationship of Late Palaeozoic terrestrial flora and marine invertebrates. The Balakhonka/Kolchugino floral change in Western Verkhoyanie is presented in the sequences of Tumarian and Delenzhian regional stages of Kuranakh and Kobycha Basins (or structural facies zones in Russian terminology) (Figure 9).

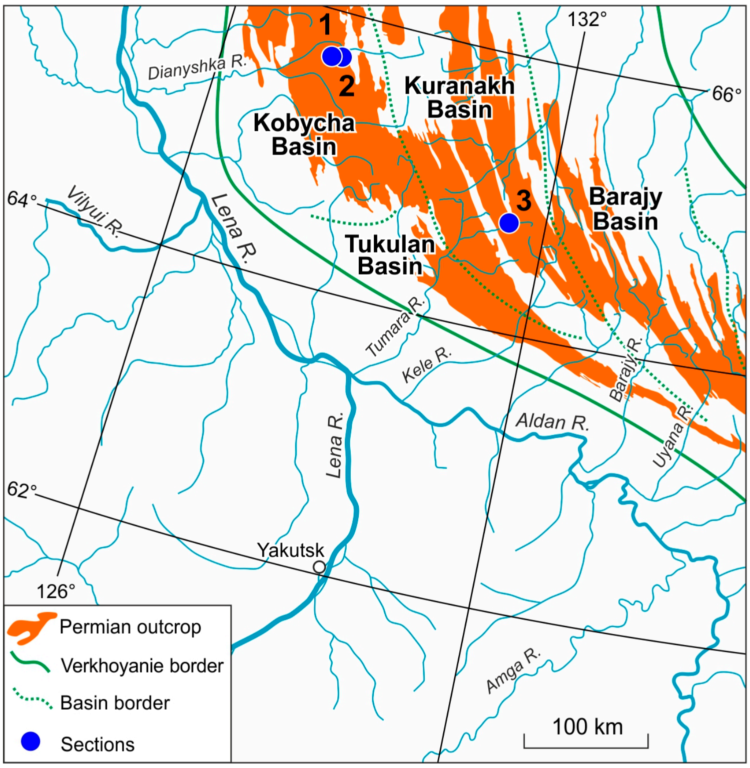

Figure 9. Geographical location of reference sections containing plant remains of the Balakhonka and Kolchugino Floras in Western Verkhoyanie: (1) Malinovyi Creek section; (2) Pravaya Galochka Creek section; (3) Section in the upper reaches of Delenzha River.

6.1.1. Kuranakh Basin

In the second half of the last century, A.N. Tolstykh [77] studied the first collections of plant remains from the Tumarian and Delenzhian regional stages (Figure 10) from Kuranakh Basin. She compared the Upper Tumarian plant assemblage with the floras from the Kemerovo and Usyatsk Fms (Upper Balakhonka Subgroup), and the Upper Delenzhian plant assemblage with the flora from the Ilyinskoe Subgroup (Kolchugino Group) in the Kuzbass (Figure 2). Subsequently, the Lower Delenzhian regional substage containing

Roadian ammonoids [37,78] was correlated with the Kuznetsk Subgroup (Kolchugino Group) from the Kuzbass [76].

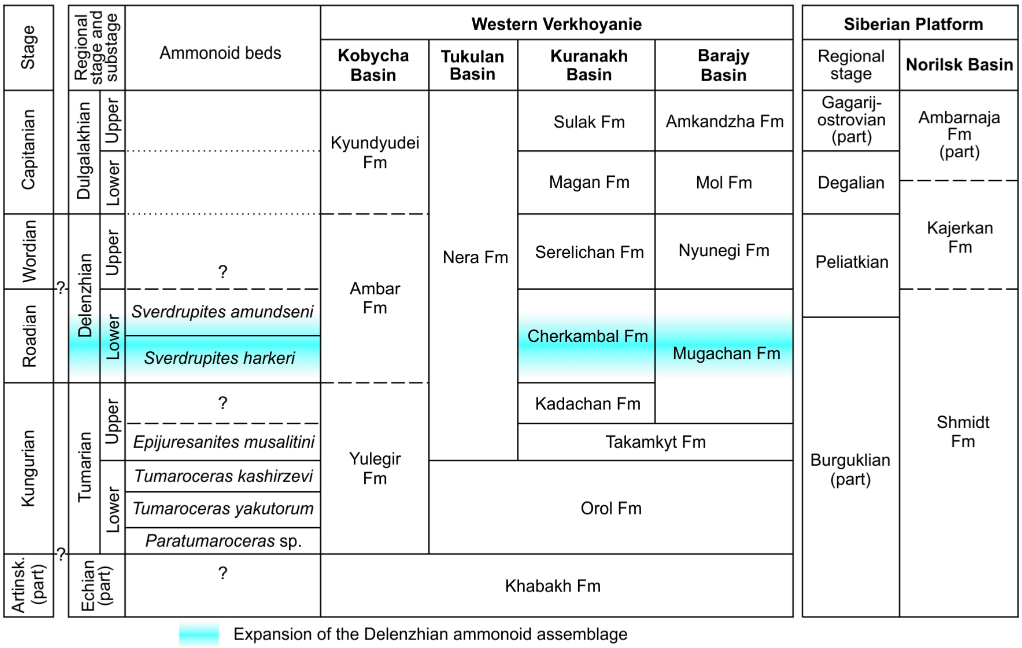

Figure 10. Correlation diagram showing the relationship between the upper Artinskian–Capitanian formations in Western Verkhoyanie and northwest of Siberian Platform. Ammonoid beds are given according to Budnikov et al., 2020 [31].

Later, I.V. Budnikov performed detailed stratigraphic and sedimentological studies of the Upper Palaeozoic of Western Verkhoyanie and sampled rich plant remains from the Serelichan Fm (Upper Delenzhian, Wordian) (Figure 10). This collection was studied in detail in 1992 by participants of the Palaeobotanical Colloquium on the correlation of Late Palaeozoic floras in Western Verkhoyanie, Tunguska and Kuzbass. The Colloquium decision confidently matched the Upper Delenzhian plant remains with the flora in the Kuznetsk Subgroup (Kolchugino Group) of the Kuzbass [21] (Volume 2, pp. 95–99). At the same time, the decision of the Colloquium stated that the Balakhonka/Kolchugino floral change occurs in Western Verkhoyanie at the boundary interval of the Lower and Upper Delenzhian regional substages immediately above the *Sverdrupites* Beds of the Lower Delenzhian (Roadian) (Figure 10).

6.1.2. Kobycha Basin

The Balakhonka/Kolchugino floral change was best documented in the Kobycha Basin, which was further inland than the Kuranakh Basin and therefore had a more continental environment. According to the Regional Stratigraphic Scheme [36,79], the Kungurian–Capitanian interval of the Kobycha Basin consists of the Yulegir, Ambar and Kyundyudei Fms (Figure 10). These formations lack ammonoids but contain rich assemblages of plant remains and rare marine bivalves.

A rich collection of fossil plants from the strata yielding the Balakhonka/Kolchugino floral change was collected by I.V. Budnikov in the outcrop of the Malinovyi Creek on the left bank of the Dianyshka River (Figures 9 and 11).

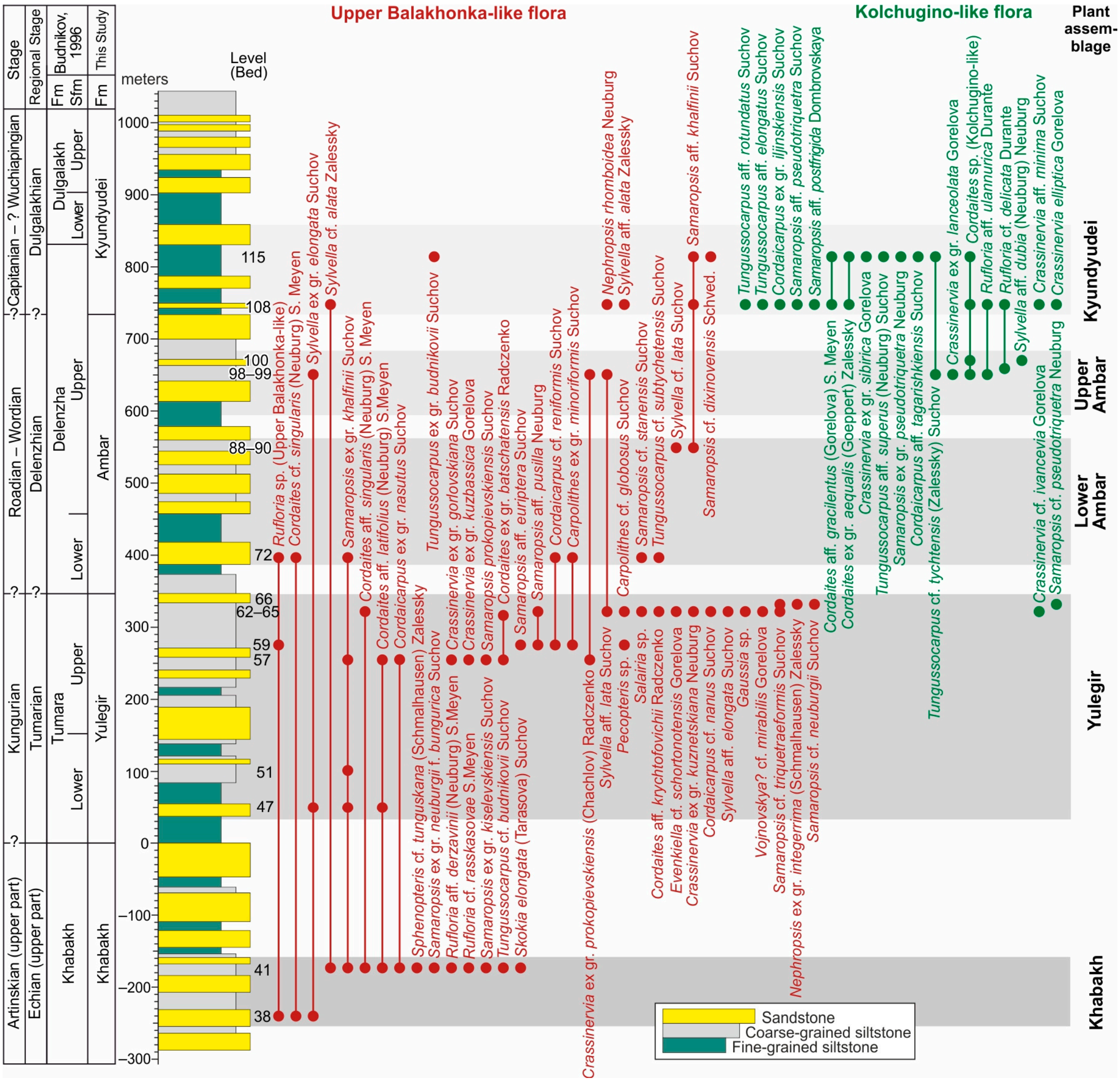

Figure 11. Distribution of plant remains in the Malinovyi Creek section of Western Verkhoyanie. The section was compiled by I.V. Budnikov in 1980 [21] (Volume 2, pp. 95–99). The plant remains were identified by M.V. Durante (pers. comm., 2007).

The abundance and diversity of plant remains and seeds make it possible to consider the outcrop of the Malinovyi Creek as a reference section of the Balakhonka/Kolchugino floral change in Western Verkhoyanie [21] (Volume 2, pp. 95–99). Later, I.V. Budnikov and R.V. Kutygin documented in detail another reference section located in the Pravaya Galochka Creek, 5 km east of the Malinovyi Creek section (Figures 9 and 12). Plant remains from both sections were studied at different times by M.V. Durante, V.E. Sivtchikov and L.G. Porokhovnichenko [80]. Below, we briefly summarise plant diversity, including data on the associated marine fauna, in the Kungurian–Wordian sequences of these reference sections.

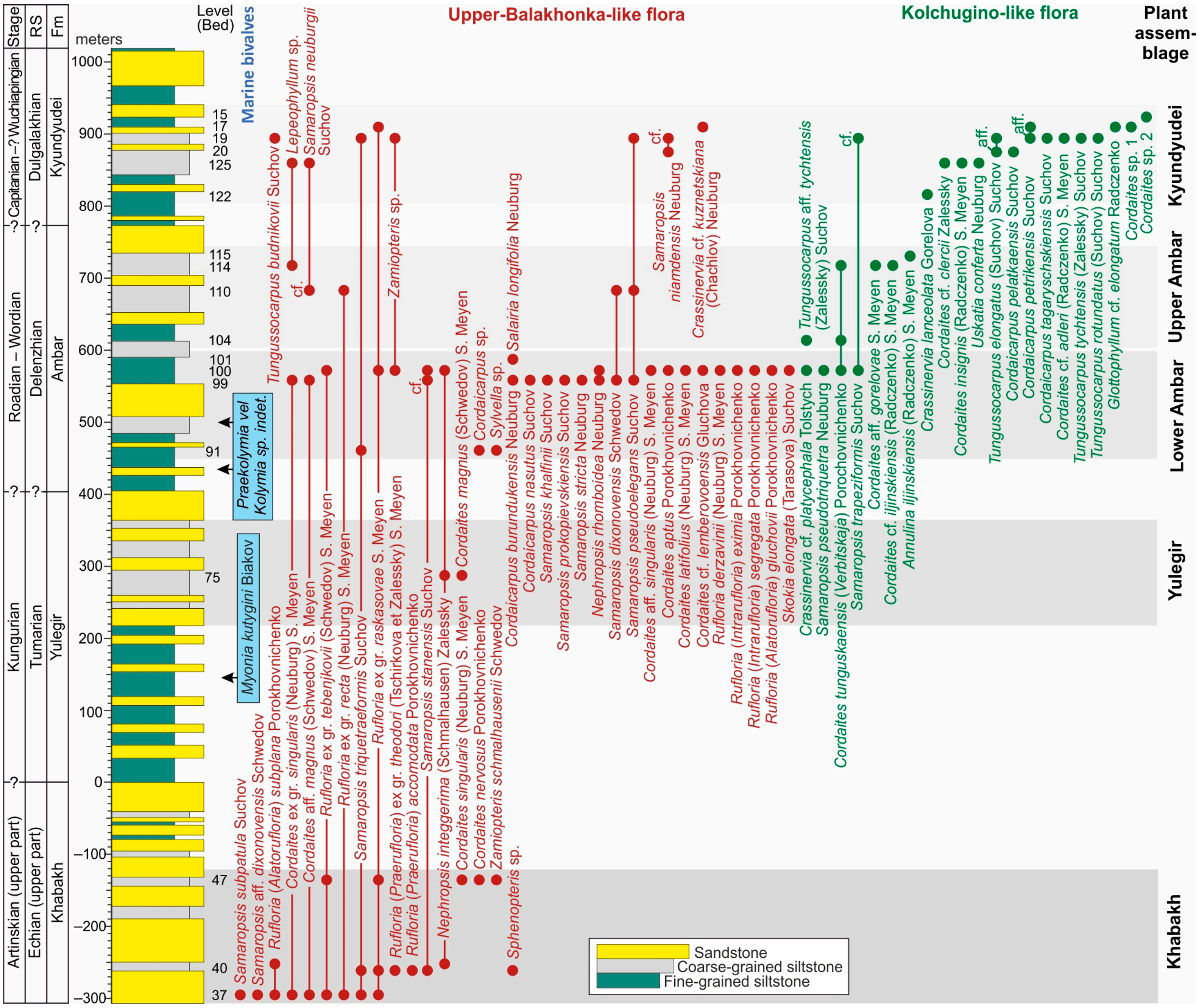

Figure 12. Distribution of plant remains and bivalves in the Pravaya Galochka Creek section of Western Verkhoyanie. The section was documented by I.V. Budnikov and R.V. Kutygin in 2006. The plant remains were identified by L.G. Porokhovnichenko [80], and the bivalves were identified by A.S. Biakov (pers. comm.).

The lower part of the Yulegir Fm in the Malinovyi Creek section (Figure 11) contains plant remains identified by M.V. Durante (pers. comm., 2007) as the Balakhonka species *Cordaites* aff. *latifolius* (Neuburg) S. Meyen, *Samaropsis* ex gr. *khalfinii* Suchov, *Sylvella* ex gr. *elongata* Suchov and as *Paracalamites* sp. This plant assemblage resembles the assemblage of the Khabakh Fm (Artinskian) in the same section (Figure 11). The upper part of the Yulegir Fm (upper Kungurian) (Figure 11) includes rare shoots of small-stemmed lycophytes and single megaspores. There are also single shoots of the leaf-stemmed moss *Salairia* sp. and possibly the first rare specimens of the Kolchugino plants *Crassinervia* cf. *ivancevia* Gorelova and *Samaropsis* cf. *pseudotriquetra* Neuburg.

The lower part of the Yulegir Fm in the Pravaya Galochka Creek (Figure 12) contains bivalves *Myonia kutygini* Biakov, the type specimens of which occur with the ammonoids *Tumarioceras kashirzevi* Andrianov in the Orol Fm of adjacent basins (Figure 10) [81]. This confirms that the lower part of Yulegir Fm belongs to the Lower Tumarian (lower Kungurian) regional substage (Figure 10), characterised by a rich assemblage of Kungurian ammonoids in the nearby Kuranakh Basin [82].

The plant remains in the Ambar Fm reveal a clear division into Lower Ambar and Upper Ambar assemblages, differentiated by the ratio of Balakhonka and Kolchugino cordaitoids and by the diversity of Balakhonka-like and Kolchugino-like plants, which are widespread in the Siberian Platform but do not occur in the Kuzbass [80].

The lower part of the Ambar Fm (Figure 12) contains numerous *Inoceramus*-like bivalves *Aphanaia*? sp. and *Praekolymia* vel *Kolymia*? sp. This interval belongs to the Lower Delenzhian regional substage (Roadian) (Figure 10) [31,36].

The Lower Ambar plant assemblage. The taxonomic composition of this assemblage was significantly renewed in comparison with the older Yulegir (Kungurian) floras, but Balakhonka and Balakhonka-like cordaitoids and seeds still dominated. The most representative collection of the Lower Ambar plant assemblage is found in bed 100 of the Pravaya Galochka Creek section (Figure 12).

The cordaitoids are dominated by two subgenera of *Rufloria*: *R.* (*Alatorufloria*) [83] and *R.* (*Intrarufloria*). The dominance and diverse composition of *R.* (*Alatorufloria*) are characteristic. This subgenus includes three groups of taxa. The first group contains the Balakhonka species *R.* (*Alatorufloria*) *deržavinii* (Neuburg) S. Meyen and the closely related Balakhonka-like species with specific epidermal characteristics [84]. In particular, we also include in this group the abundant fragments of large and medium-sized Balakhonka-like leaves of *R.* (*Alatorufloria*) *recta* (Neuburg) S. Meyen, known to occur in the Khabakh (Artinskian) flora. The second group consists of the Balakhonka-like species *R.* (*Alatorufloria*) ex gr. *tebenjkovii* (Schwedov) S. Meyen and the closely related cordaitoids. The main element of the third group is represented by the Balakhonka-like *R.* (*Alatorufloria*) *gluchovii* Porokhovnichenko [80].

The subgenus *R.* (*Intrarufloria*) is represented by numerous plant remains, most of which are identified as the Balakhonka species *R.* (*I.*) ex gr. *rasskasovae* S. Meyen, a cordaitoid known to occur in the Upper Balakhonka Subgroup of Kuzbass and the upper part of the Burguklian regional stage of the Tunguska Basin. The Balakhonka-like species *R.* (*I.*) *segregata* Porokhovnichenko and *R.* (*I.*) *eximia* Porokhovnichenko occurring at this level are also of interest for correlation because they are widespread in the upper part of the Shmidt Fm in the Norilsk region of Angaraland [80].

The genus *Cordaites* mainly contains the transient, large-leaved Balakhonka species *C.* aff. *singularis* (Neuburg) S. Meyen, *C. latifolius* (Neuburg) S. Meyen and Balakhonka-like species *C.* cf. *lemberovoensis* Gluchova described for the first time in Taymyr. The large and relatively short leaves of Kolchugino-like species *C. tunguskaensis* (Verbitskaja) Porokhovnichenko are less common.

Leaf-stemmed mosses are represented by the widespread Balakhonka species *Salairia longifolia* Neuburg. The taxonomic composition of seeds is considerably renewed. Several new species appear, in particular the Balakhonka species *Skokia elongata* (Tarasova) Suchov and the Kolchugino species *Samaropsis pseudotriquetra* Neuburg, *S. trapeziformis* Suchov. The latter two species are typical in the lower part of the Kuznetsk Subgroup of Kuzbass [85].

The first appearance of Kolchugino and Kolchugino-like species occurs in bed 100 of the Pravaya Galochka Creek section (Figure 12). The most characteristic species are Kolchugino-like *Cordaites tunguskaensis* (Verbitskaya) Porokhovnichenko, known in the Peliatkian regional stage of the Siberian Platform, and Kolchugino seeds *Samaropsis pseudotriquetra* Neuburg and *S. trapeziformis* Suchov, which are widespread in Kuzbass. Nevertheless, Balakhonka and Balakhonka-like taxa significantly dominate the Lower Ambar plant assemblage, which can be confidently compared with the Upper Shmidt Sfm assemblage (Norilsk region), which corresponds to the upper part of the Burguklian regional stage (probably lower Roadian) of the Siberian Platform (Figure 10) [86].

The Upper Ambar plant assemblage. A characteristic feature of this assemblage is the mixing of Balakhonka-like and Kolchugino-like plants, with Kolchugino-like plants predominating. These changes in taxonomic composition are recorded in layers 98–99 of the Malinovyi Creek section (Figure 11) and layer 104 of the Pravaya Galochka Creek section (Figure 12).

Cordaitoids include the Kolchugino-like species *Cordaites tunguskaensis* (Verbitskaja) Porokhovnichenko and the characteristic Kolchugino species *C.* aff. *gorelovae* S. Meyen and *C.* cf. *iljinskiensis* (Radczenko) S. Meyen. Associated with these cordaitoids is the first appearance of the seeds *Tungussocarpus* aff. *tychtensis* (Zalessky) Suchov, characteristic of the Kolchugino Flora.

The Upper Ambar assemblage contains scale leaves of the Kolchugino species *Crassinervia lanceolata* Gorelova and large leaves of *Lepeophyllum* sp., remains of horsetails *Annulina iljinskiensis* (Radczenko) S. Meyen, *Phyllotheca* aff. *turganensis* Gorelova and *Paracalamites* sp. Numerous seeds include Balakhonka species *Skokia* sp., *Samaropsis* cf. *neuburgii* Suchov, *S.* cf. *pseudoelegans* Suchov and *S.* cf. *dixonovensis* Schwedov.

The mixed taxonomic composition of the Upper Ambar assemblage dominated by Kolchugino and Kolchugino-like species is broadly compatible with the "transitional flora" known in the uppermost part of the Shmidt Fm in the Norilsk region. This enables us to synchronise the Upper Ambar plant assemblage with the floras of the uppermost Burguklian and lower Peliatkian (probably upper Roadian–Wordian) regional stages of the Siberian Platform (Figure 10) [86].

The Kyundyudei Fm terminates the Permian succession of the Kobycha Basin [31] and contains the so-called Kyundyudei plant assemblage, which differs from older ones (Figures 11 and 12) by the co-existence of Kolchugino cordaitoids, pteridosperms and mosses with "mixed" seeds represented by both Balakhonka and Kolchugino species. This assemblage includes large-leaved cordaitoids *Cordaites* cf. *clercii* Zalessky, *C. insignis* (Radczenko) S. Meyen, *Cordaites* cf. *adleri* (Radczenko) S. Meyen, pteridosperms *Glottophyllum* cf. *elongatum* Radczenko, mosses *Uskatia conferta* Neuburg, known in the middle and upper part of the Kolchugino Group of Kuzbass, i.e., definitely representing species of the Kolchugino Flora. Numerous seeds associated with cordaitoids are represented by the Balakhonka species *Samaropsis pseudoelegans* Suchov, *S.* aff. *khalfinii* Suchov, *S.* cf. *dixinovensis* Schwedov and the Kolchugino species *Tungussocarpus tychtensis* (Zalessky) Suchov, *T. elongatus* (Suchov) Suchov, *Cordaicarpus* aff. *tagarishkiensis* Suchov, *C.* aff. *petrikensis* Suchov, etc.

This unusual taxonomic composition makes it difficult to compare the Kyundyudei assemblage with other Permian floras of the Siberian Platform and Kuzbass. Broadly, it can be compared with plant assemblages from the Kajerkan and lower Ambarnaja Fms (probably Capitanian) in the Norilsk region (Figure 10).

All of the facts mentioned above show that the change in the Balakhonka and Kolchugino Floras in Western Verkhoyanie occurred relatively gradually throughout the entire Guadalupian (Middle Permian). At the same time, the Kolchugino Flora became clearly dominant at the boundary between the Roadian and Wordian, immediately after the appearance of the *Sverdrupites* ammonoid assemblage.

Recently, a high-precision U-Pb CA-IDTIMS radioisotopic age of 274.0 $\pm$ 0.12 Ma [87] was obtained for beds containing *Sverdrupites harkeri* (Ruzhencev) in the Plastovy Creek section located on the eastern periphery of the Okhotsk Region.

If the assumption is correct that the dominance of the Kolchugino Flora in Western Verkhoyanie begins only at the base of the Upper Delenzhian regional substage (Wordian), i.e., above the *Sverdrupites* beds, then the available U-Pb ages in the Okhotsk Region and the Kuzbass indicate some "lag" in the Balakhonka/Kolchugino floral change in Western Verkhoyanie compared to the Kuzbass.

Previously, we noted a possible diachronism in the disappearance of the genus *Rufloria* in the Kuzbass and Verkhoyanie [88]. This event in the Kuzbass occurred approximately at the beginning of the Wordian and was related to the elimination of large freshwater basins during the sedimentation of the Leninsk Fm. At the same time, Western Verkhoyanie retained similar sedimentological settings until the end of the Permian [31], and *Rufloria* successfully inhabited these environments until the end of the Changhsingian.

Comparison of the geographically distant vegetation in the Tunguska Basin, Western Verkhoyanie and Kuzbass is a difficult task for the Kolchugino time because, although these areas were part of Angaraland, they were at significantly different latitudes and had diverse climates [19]. The climatic differences caused disparities in the taxonomic composition of the vegetation. For instance, callipterids, ferns and pteridosperms were widespread in the Kuzbass, while they were very scarce in Western Verkhoyanie and the Tunguska Basin (Figure 13).

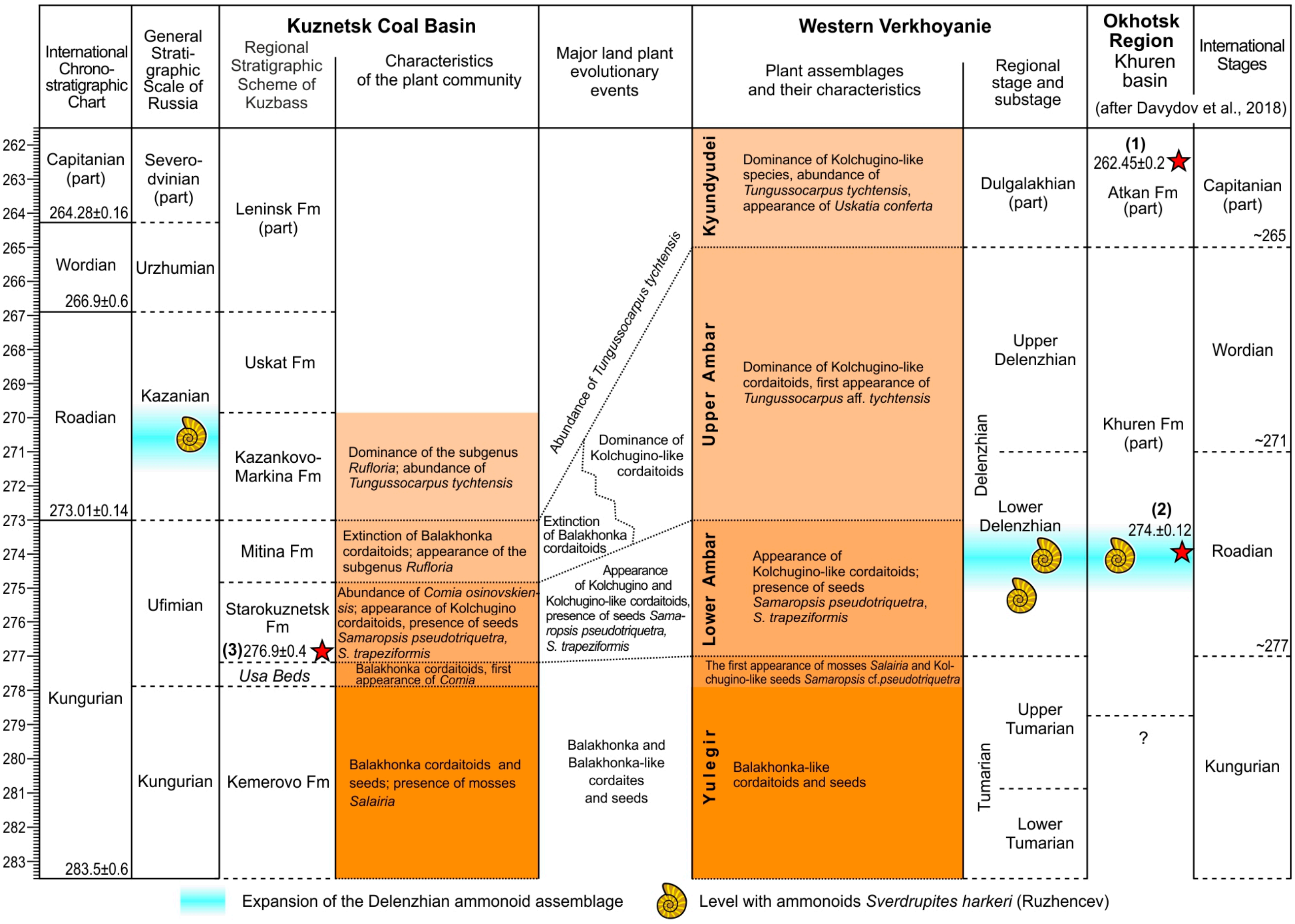

Figure 13. Comparison of the Kungurian–Middle Permian successions of Kuzbass, Western Verkhoyanie and Okhotsk Region in terms of International Chronostratigraphic Chart [33], General Stratigraphic Scale of Russia [32], and proposals of Davydov et al., 2018 [87]. Radioisotopic datings highlighted with star symbols are based on (1), (2) ref. [87]; (3) this article.

The first occurrence of callipterids at the base of the Kolchugino Group (Usa Beds) serves as a peculiar marker for the appearance of a new fern–pteridosperm–cordaitoid Kolchugino Flora in the Kuzbass. This stratigraphic interval still contains Balakhonka species of cordaitoids and seeds. In the Starokuznetsk Fm, the role of Kolchugino cordaitoids and callipterids gradually increases, and in the Mitina Fm, the main dominants of cordaitoids and seeds (*Tungussocarpus*) are represented entirely by Kolchugino species.

We observe a similar pattern of floral changes in the Ambar Fm of Western Verkhoyanie. The first species of Kolchugino-like cordaitoids appear in the Lower Ambar assemblage and begin to dominate and replace the Balakhonka-like species in the Upper Ambar assemblage (Figure 13). Seeds *Tungussocarpus tychtensis* (Zalessky) Suchov, the typical species of the Kolchugino Flora, can serve as a marker in correlating long-distance floras. This species is widespread in the Ilyinskoe Subgroup of the Kuzbass, in the Kyundyudei Fm of Western Verkhoyanie and in the Peliatkian regional stage of the Tunguska Basin.

6.2. The Lower Boundary of the Kolchugino Group in the International Chronostratigraphic Scale

The new high-precision radioisotopic data (276.9 ± 0.4 Ma) determine the age of the middle part of the Starokuznetsk Fm and for the first time directly indicate that this stratigraphic level belongs to the Upper Kungurian of the International Chronostratigraphic Chart (Figures 2 and 14). The Starokuznetsk Fm is located above the base of the Kolchugino Group; therefore, the lower boundary of the Kolchugino Group, which coincides with the basement of the Usa Beds, is slightly older than our new radioisotopic data, but it is also located in the Upper Kungurian.

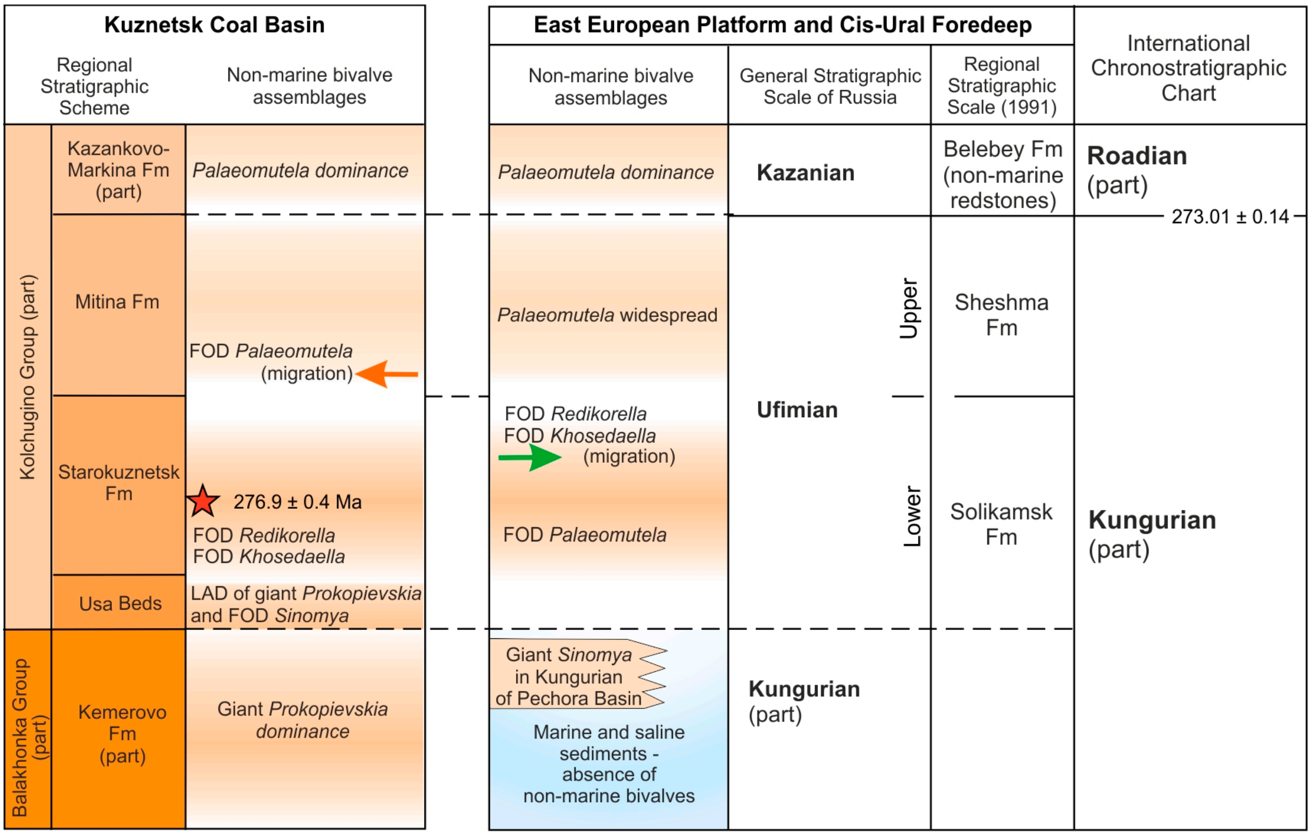

Figure 14. Comparison of the Kungurian–Roadian sediments in the Kuzbass and Eastern Europe in terms of International Chronostratigraphic Chart [33] and General Stratigraphic Scale of Russia [29]. LAD—last appearance datum; FOD—first occurrence datum; orange arrow—migration of East European non-marine bivalves into Angaraland; green arrow—migration of Angarian non-marine bivalves into Eastern Europe. The star symbol indicates the radioisotopic dating discussed in this article. Non-marine bivalve assemblages are given according to ref. [26].

According to the available biostratigraphic record, the lower boundary of the Kolchugino Group approximately corresponds to the lower boundary of the Ufimian Stage of the General Stratigraphic Scale of Russia (Figure 14). The Permian subdivisions of this scale are based on the succession of European Russia [32]. In addition to the East European Platform, this area includes the Timan-Pechora Basin, which was part of the Late Palaeozoic Angaraland. The faunal connections between Eastern Europe and the Timan-Pechora Basin through the Cis-Uralian Foredeep are reflected in similar features of the biostratigraphic record, at least for non-marine bivalves. The similar temporal succession of non-marine bivalve assemblages enables the correlation of the Ufimian stage of European Russia with the lower part of the Kolchugino Group (Figure 14).

Before 2004, i.e., before a decision on the three-member division of the Permian System, the Ufimian Stage of the East European Platform and Cis-Uralian Foredeep had an international status, and its lower boundary was considered as the global boundary between the Lower and Upper Permian. Both before 2004 and at present, within the Kuzbass, the boundary between the Lower Permian and the overlying Series (Upper Permian—before 2004; Middle Permian—after 2004) is accepted in the basement of the Kuznetsk Subgroup. The Balakhonka/Kolchugino floral change is considered as the main biotic marker of this boundary. The similar age of the Kuznetsk Subgroup and the Ufimian Stage is supported by biostratigraphic data of non-marine ostracods and bivalves [25,26,54].

6.2.1. Floral Change at the Balakhonka/Kolchugino Boundary

The replacement of the Late Balakhonka (cordaite) Flora with the Kolchugino (fern–pteridosperm–cordaite) Flora occurs in the stratigraphic interval comprising the Usa Beds and the Starokuznetsk Fm. This floral change is traced throughout Angaraland [76,89].

The Kolchugino Flora is more taxonomically diverse than the late Balakhonka Flora. It is characterised by further diversification of pteridosperms (*Comia*, *Compsopteris*, *Permocallipteris*, *Glottophyllum*) and ferns (*Pecopteris*), the appearance of new species of seeds (*Tungussocarpus*, *Sylvella*, etc.) and changes in the morphology of cordaite leaves. The leaves of Kolchugino cordaitoids are small, possessing denser and thicker veins, specific structures of stomatal grooves, epidermal ornamentation, etc. These characteristics are the basis for the establishment of new taxa in Kolchugino *Cordaites* and *Rufloria* [84,90,91].

The increase in taxonomic diversity of Kolchugino Flora and the appearance of callipterids are associated with general climate warming [92]. Changes in the leaf morphology of Kolchugino cordaitoids and a decrease in sphenopsid size are consistent with climate aridification [93].

Analysis of the species distribution in the Kuznetsk Subgroup (Figure 4) indicates that the change in Balakhonka/Kolchugino Floras occurred gradually. The rise of a new Kolchugino Flora in the Kuzbass is fixed by "transitional" plant assemblages of the Usa Beds and Starokuznetsk Fm, which contain a mixture of the late Balakhonka and early Kolchugino species. The dominating plants in the Mitina Fm predominantly consist of the first-appearing species of Kolchugino ferns, pteridosperms and cordaitoids, while the Balakhonka species are no longer present.

Thus, the rise in Kolchugino Flora involves several events: (1) the first appearance of early Kolchugino elements, (2) the pronounced diversification of Kolchugino taxa and (3) the complete replacement of late Balakhonka taxa with Kolchugino species.

6.2.2. Non-Marine Bivalve Change at the Balakhonka/Kolchugino Boundary

The obtained radioisotopic data (276.9 $\pm$ 0.4 Ma) indicate that, in the territory of the Kuzbass, the Balakhonka/Kolchugino floral change occurred in the Late Kungurian. This conclusion is supported by data on non-marine bivalves (Figure 14). In particular, the giant bivalve *Sinomya*, which is morphologically similar to the Kuzbass giant *Prokopievskia*, is widespread in the sediments underlying the Ufimian Stage in the Timan-Pechora Basin [26]. The non-marine bivalves *Khosedaella*, *Redikorella*, *Palaeomutela*—whose first occurrence in the Kuzbass is restricted to the Kuznetsk Subgroup—are widespread in the Ufimian Stage of East European Russia and Cis-Ural. The reverse order of appearance of these genera in the Kuzbass and Eastern Europe is remarkable (Figure 14). In the Kuzbass, *Khosedaella* and *Redikorella* appear first in the succession, followed by the appearance of *Palaeomutela*. In Eastern Europe, *Palaeomutela* first appears in the lower part of the succession, followed by *Khosedaella* and *Redikorella*. Migration processes probably caused the reverse order of appearance: the genus *Palaeomutela* migrated from Eastern Europe to Angaraland, whereas the genera *Khosedaella* and *Redikorella* migrated from Angaraland to Eastern Europe.

For a long time, it was thought that the centre of origin of *Redikorella* and *Palaeomutela* (the latter comprising two subgenera: *P*. (*Palaeomutela*) and *P*. (*Palaeoanodonta*)) was located in the Cis-Uralian Foredeep, from where these bivalves dispersed to Angaraland, Cathaysia and Gondwana [26]. Recent discoveries have broadened the understanding of the geographic radiation of *Redikorella* and *Palaeomutela*. These taxa are found in the Late Kungurian in the continental basins of the western Tethyan sector of the Variscides, suggesting that other areas may be the centre of origin for both genera [50].

6.2.3. Regional and Global Implications of Results

The setting of the lower boundary of the Kolchugino Group in the Upper Kungurian of the ICC raises the question of establishing a distinct unit (possibly of substage rank) in the Upper Kungurian—a unit corresponding to the Ufimian Stage of European Russia. The lower boundary of this unit approximately coincides with the onset of the Balakhonka/Kolchugino floral change in the low latitudes of Angaraland. The biostratigraphic validity of a separate Ufimian Stage in the marine successions of northern Eurasia (Timan-Pechora Basin, Kanin Peninsula, Verkhoyanie) has been discussed in several publications [94,95].

The radioisotopic datings accepted in the ICC (2023) and new radioisotopic data from the Kuzbass indicate a temporal difference in the Balakhonka/Kolchugino floral change in the low (Kuzbass) and high (Verkhoyanie) latitudes of Angaraland (compare Figures 13 and 14). The Balakhonka/Kolchugino floral change in Kuzbass was initiated in the early Late Kungurian (before 277 Ma) and completed by the end of this age (Mitina Fm; Figures 2 and 14). The Balakhonka/Kolchugino floral change in Verkhoyanie began at the end of Late Kungurian, continued throughout the Middle Permian and was completed in the Late Wordian (Figure 13). The conclusion regarding the significant delay (millions of years) in the onset of the Balakhonka/Kolchugino floral change in different latitudes of Angaraland contradicts the data available in numerous palaeobotanical publications by Russian specialists. This suggests that interregional correlations based on fossil plants require further improvement.

The terrestrial biotic events in the Kuzbass at the end of the Kungurian fit well with regional sedimentary history and global climatic changes (Figure 15). The lower half of the Kuznetsk Subgroup, coinciding with the Balakhonka/Kolchugino floral change, is characterised by the absence of coal. This absence is probably related to aridification of the regional climate [92,93] and global warming in the Late Kungurian [96–98].

A global sea-level rise at this time [99] is indirectly supported by (1) modifications in the low-latitude continental landscapes of Angaraland, which have caused differentiation in vegetation, and (2) by the migration (exchange) of non-marine bivalves and ostracods between Angaraland and Eastern Europe (Euramerica).

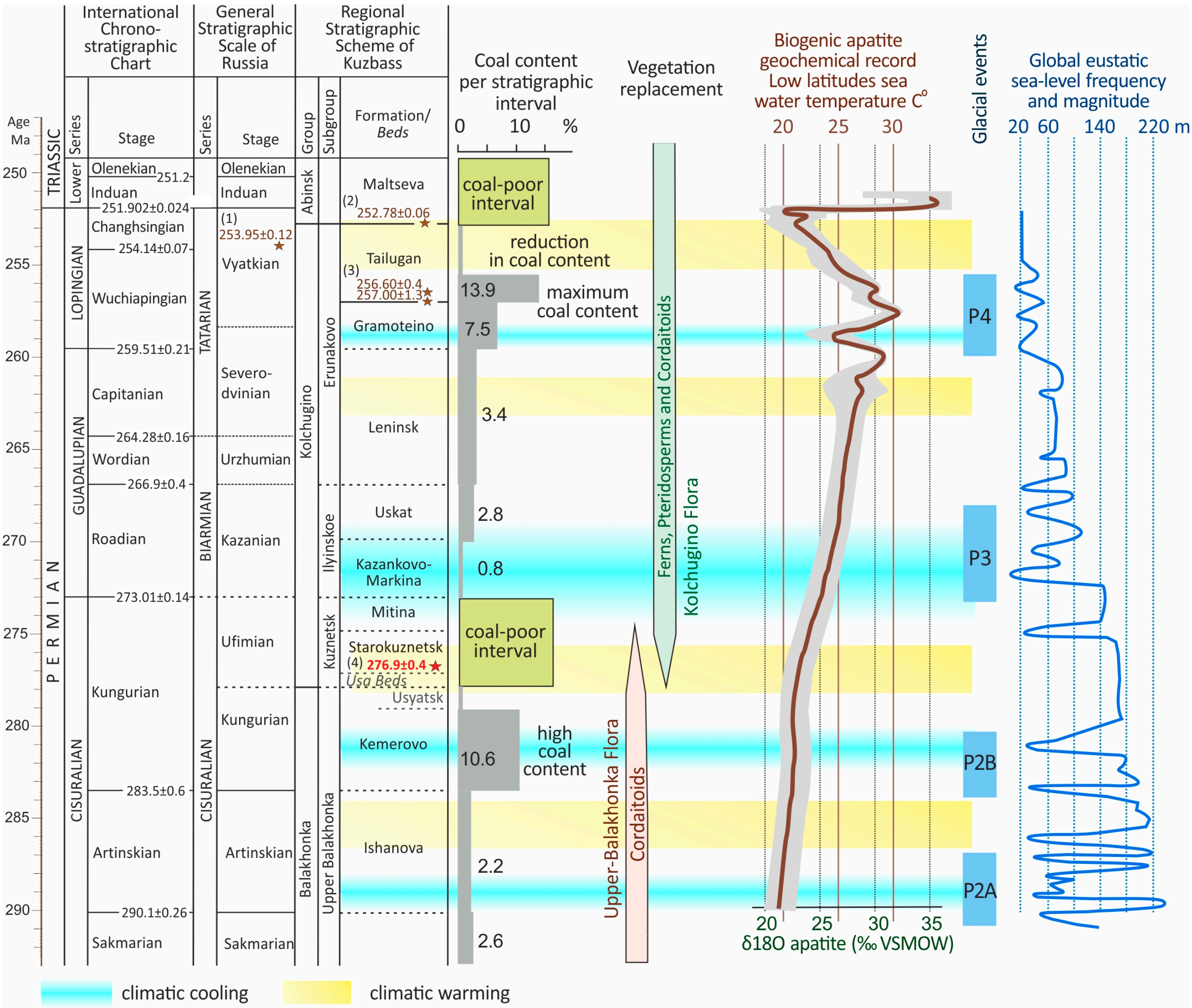

Figure 15. Gradual replacement of late Balakhonka Flora with Kolchugino Flora in the context of coal content, global climatic and eustatic variations. The floral change coincides with climatic warming reflected by a coal-free interval. Coal content in the Kuzbass according to ref. [28]; the biogenic apatite geochemical record and low-latitude seawater temperatures according to ref. [96]; P2A, P2B, P3, P4—the cooling events along the Western Pangea tropical shelves according to refs. [97,98]; the global eustatic sea-level variations according to ref. [99]. Radioisotopic datings highlighted with star symbols are based on (1) ref. [35]; (2) ref. [13]; (3) ref. [14]; (4) this article.

7. Conclusions

1. For the first time, the new radioisotopic data (276.9 ± 0.4 Ma) directly correlate the middle part of the Starokuznetsk Fm with the Upper Kungurian of the International Chronostratigraphic Chart.
2. The radioisotopic age (276.9 ± 0.4 Ma) indicates that the change in Balakhonka (cordaite) and Kolchugino (fern–pteridosperm–cordaite) Floras in the Kuzbass (low latitudes of Angaraland) occurred in the Late Kungurian.
3. Within Western Verkhoyanie (high latitudes of Angaraland), the Balakhonka/Kolchugino floral change could have occurred several million years later; this is evidenced by the fact that, in this area, the layers with transitional Balakhonka–Kolchugino plant assemblages are interbedded with layers containing the Lower Delenzhian ammonoids (*Sverdrupites*, *Daubichites*, etc.), a reliable marker of the Roadian Stage.

4. The morphological changes and increased diversity of the Kolchugino vegetation in the lower latitudes of Angaraland (Kuzbass and adjacent areas) are associated with global climatic warming and aridification in the Late Kungurian, which fits well with the available data on global glacial events of the Permian period and corresponds to the minimum coal content in the Kuzbass coal-bearing succession.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/geosciences14010021/s1, Table S1: Results of U-Pb (CA-ID-TIMS) radioisotopic dating of zircon grains from sample no. 19kzb-7, Starokuznetsk Formation, Kolchugino Group, Kuznetsk Basin.

Author Contributions: Conceptualisation, methodology, V.V.S.; field work (Kuzbass), Y.M.G., A.S.F., E.V.K. and V.V.S.; field work (Verkhoyanie), R.V.K.; radioisotopic CA-ID-TIMS dating, M.T. and A.K.; biostratigraphic investigation, L.G.P., E.V.K., R.V.K., V.V.S., A.S.B., M.A.N., M.N.U. and V.V.Z.; writing—original draft preparation, V.V.S., Y.M.G., L.G.P., E.V.K. and R.V.K.; visualisation, V.V.S., E.V.K., R.V.K. and A.S.F.; writing—review and editing, V.V.S., M.T., A.S.F. and V.V.Z.; project administration, M.N.U.; funding acquisition, M.N.U. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data are contained within the article and Supplementary Materials.

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