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Tectonic history of the Kolyvan–Tomsk folded zone (KTFZ), Russia: Insight from zircon U/Pb geochronology and Nd isotopes

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The Kolyvan–Tomsk folded zone (KTFZ) represents part of the Central Asian Orogenic Belt (CAOB). The KTFZ is mainly composed of detrital Late Palaeozoic sedimentary deposits, with minor intrusions. Detrital zircon geochronology on the Upper Devonian to Lower Permian sedimentary sequences of the KTFZ and the associated Gorlovo foreland basin yields four age peaks, reflecting the magmatic events in the source terranes. These events consist of (a) a minor Neoproterozoic peak (0.9–0.7 Ga), (b) a significant Early Palaeozoic peak (550–460 Ma), with a maximum at 500 Ma, and two well-defined Late Palaeozoic peaks during (c) the Middle–Late Devonian (385–360 Ma) and (d) the Carboniferous–Early Permian (360–280 Ma), with a maximum at 320 Ma. Older zircons (>1 Ga) are quite rare in the sampled sedimentary sequences. Slightly negative εNd values and associated relatively young Nd model ages were obtained (εNd(T) = −0.78, T (DM) ~1.1 Ga for Upper Devonian sandstones, εNd(T) = −1.1, T (DM) ~1.1 Ga for Lower Permian sandstones), suggesting only minor contribution of ancient continental crust to the main sedimentary units of the KTFZ. All intrusive and volcaniclastic rocks on the contrary are characterized by high positive εNd(T) values in the range of 3.78–6.86 and a Late Precambrian model age (T (DM) = 581–916 Ma), which corroborates its juvenile nature and an important depleted mantle component in their source. The oldest unit of the KTFZ, the Bugotak volcanic complex formed at the Givetian–Early Frasnian transition, at about 380 Ma. Upper Devonian detrital deposits of the KTFZ were formed in the Early Palaeozoic accretion belt of the Siberian continent and specifically in a passive continental margin environment. Deposits of the Gorlovo foreland basin, adjoining the KTFZ, were accumulated as a result of erosion of the Carboniferous–Early Permian volcanic rocks, which are now buried under the Meso–Cenozoic sedimentary cover of the West Siberian Basin. The magmatic events, recorded in the KTFZ zircon data, correspond to the most significant magmatic stages that affected the western part of the CAOB as a whole.

KEYWORDS
Atai–Sayan, Central Asian Orogenic Belt, detrital zircon geochronology, Devonian, magmatism, Nd isotope composition, West Siberia

1 | INTRODUCTION

The Kolyvan–Tomsk folded zone (KTFZ) is located at the junction of the Altai–Sayan fold belt (ASFA; e.g., Buslov et al., 2013; Glorie et al., 2011), and the Ob′–Zaisan fold belt (Matveyevskaya, 1969) in the northern Central Asian Orogenic Belt (CAOB; Wilhem, Windley, & Stampfli, 2012; Windley, Alexeiev, Xiao, Kröner, & Badarch, 2007, Xiao et al., 2009; Xiao, Huang, Han, Sun, & Li, 2010; Figure 1). The CAOB is the largest Phanerozoic accretionary orogen in the world, located between the East–European, Siberian, Tarim, and North China cratons (Figure 1) and consists of a collage of different terranes: fragments of microcontinents, volcanic arcs, and accretionary complexes (Wilhem et al., 2012; Windley et al., 2007; Xiao et al., 2010, 2009). In recent decades, the tectonic structure and evolution of the CAOB have been an important topic for various geological and geochronological studies, due to its importance in terms of metallogeny, geohazards, and fundamental geoscientific issues such as the growth of the continental crust (e.g.,Goldfarb, Taylor, Collins, Goryachev, & Orlandini, 2014 ; Jahn, Wu, & Chen, 2000 ; Kröner et al., 2014 ; Safonova, 2017 ; Sengör, Natal'in, & Burtman, 1993 ; Wang et al., 2009, 2014 ; Windley et al., 2007 ; Xiao et al., 2010). The presumed presence of ancient continental crustal blocks in the basement of the overprinted sedimentary basins, such as Junggar, Ili, Minusa, Kuznetsk, and others, is a hotly debated topic (Zhao et al., 2019). The Ob′–Zaisan folded system runs through eastern Kazakhstan and north-western China, east of the Altai–Sayan (Figure 1). The Ob′–Zaisan system includes the KTFZ with a characteristic NE strike and the NW-striking Rudny Altai folded zone. This difference in orientation can be explained as a result of oroclinal bending (Choulet et al., 2011; Li et al., 2017, 2018; Sengör et al., 1993; Vladimirov et al., 2005; Zonenshain, Kuzmin, & Natapov, 1990). Berzin et al. (1994) suggested that the propagation of the KTFZ to the south is represented by the Rudny Altai folded zone, although this is difficult to ascertain, as the junction between the Rudny Altai and the KTFZ is covered by the thick Meso–Cenozoic sediments of the West Siberian Basin (WSB). Despite numerous studies by Russian geologists, which focused on geological mapping (Babin et al., 2015; Belyaev & Nechaev, 2015; Kotel'nikov, Maksikov, Kotel'nikova, Makarenko, & Subbotin, 2008), palaeontology and biostratigraphy (Izokh & Yazikov, 2015; Yazikov, Izokh, Shirokikh, & Kutolin, 2015), ore resources (Kalinin, Naumov, Borisenko, Kovalev, & Antropova, 2015), petrology (Kungurtsev et al., 1998; Sotnikov, Fedoseev, Ponomarchuk, Borisenko, & Berzina, 2000), and some associated overview monographs published in Russian (Roslyakov et al., 2001; Sotnikov et al., 1999; Sviridov et al., 1999; Vrublevskii, Nagorniy, Rubtsov, & Erv'ye, 1987), the KTFZ remains very poorly constrained in terms of geochronology. Whereas the geochronology of the Chinese and to a lesser extent the Russian Altai has been intensively studied (e.g., Cai et al., 2016; Chen et al., 2016, 2015; Dong et al., 2018; Glorie et al., 2011; Kruk, Kuibida, Shokalsky, Kiselev, & Gusev, 2018; Li et al., 2017; Long et al., 2007), the northern extension of these structures in the Kolyvan–Tomsk and Salair regions remains very poorly characterized concerning its geochronologic framework. Currently, there are no zircon U–Pb ages and for magmatic intrusions or sedimentary sequences in the KTFZ published within the international literature. The tectonic environment of sedimentation and magmatism in this zone thus remains poorly understood, making it difficult to accurately correlate the KTFZ with the Late Palaeozoic folded zones of Eastern Kazakhstan (e.g., Glorie et al., 2012; Vladimirov et al., 2005) and north-western China in the context of CAOB evolution (e.g., Choulet et al., 2011, 2012; Hong et al., 2017; Li et al., 2017, 2018; Liu, Han, Gong, & Chen, 2019; Long et al., 2007; Zhou et al., 2017).

The KTFZ along its entire length is composed of fairly homogeneous along-strike Late Devonian–Carboniferous carbonate–detrital deposits. Volcanic and intrusive rocks are relatively scarce. The tectonic setting in which this sedimentary unit was deposited is not completely defined. Dating of the detrital zircons from these deposits will provide valuable information about the source provenance, basin evolution, sedimentation rates, and the general character of the tectonic events in the region. Volcanic rocks, lying at the base of the sedimentary unit, have been dated in this work, to provide a geochronological constraint on the onset of this particular regional tectonic cycle. Nd isotope composition of the intrusive, volcanic, and sedimentary rocks of the KTFZ was measured to estimate the age of the continental crust and to evaluate a possible contribution of the recycled ancient crustal material. The geochronological results on the KTFZ rocks presented here are an important contribution to our understanding of the tectonic evolution of the less studied north-western part of CAOB during the Late Palaeozoic.

2 | GEOLOGICAL SETTING

The KTFZ is located at the north-western edge of the Altai–Sayan folded area (ASFA; Figure 1), extending to the north-east for a distance of about 450 km, with a width of 60–100 km (Figure 2). The south-eastern boundary of the KTFZ is defined by a north-westerly dipping thrust zone. Devonian sediments, forming the KTFZ allochthonous nappes, are thrusted onto the Early Palaeozoic complexes of the Kuznetsk Alatau and Salair terranes and the Carboniferous–Permian and Jurassic sediments of the Kuznetsk, Gorlovo–Zarubin, and Doronin basins (Zonenshain et al., 1990). The horizontal displacement of the well-studied Tomsk Thrust (Figure 2) exceeds 30 km according to drill-hole data (Vrublevskii et al., 1987; Yuzvitskiy, 1966). To the north-west, and to both sides perpendicular to its strike, the KTFZ is overlain by the Meso–Cenozoic cover of the West Siberian Basin (WSB). Available drill-hole data confirm the wide distribution of Devonian–Carboniferous volcanic and sedimentary units, as well as Carboniferous granites in the WSB folded basement (Isaev, 2009; Ivanov, Erokhin, Ponomarev, Pogromskaya, & Berzin, 2016; Ivanov, Koroteev, Pecherkin, Fedorov, & Erokhin, 2009).

The internal structure of the KTFZ consists of a package of tectonic nappes, folded and overthrusted in a south-easterly direction. The frontal part of the KTFZ consists of a chain of uplifts, elongated parallel to strike. These uplifts are the cores of large antiformal folds, consisting of tectonic nappes. The Ordyn, Bugotak, and Mitrofanovo

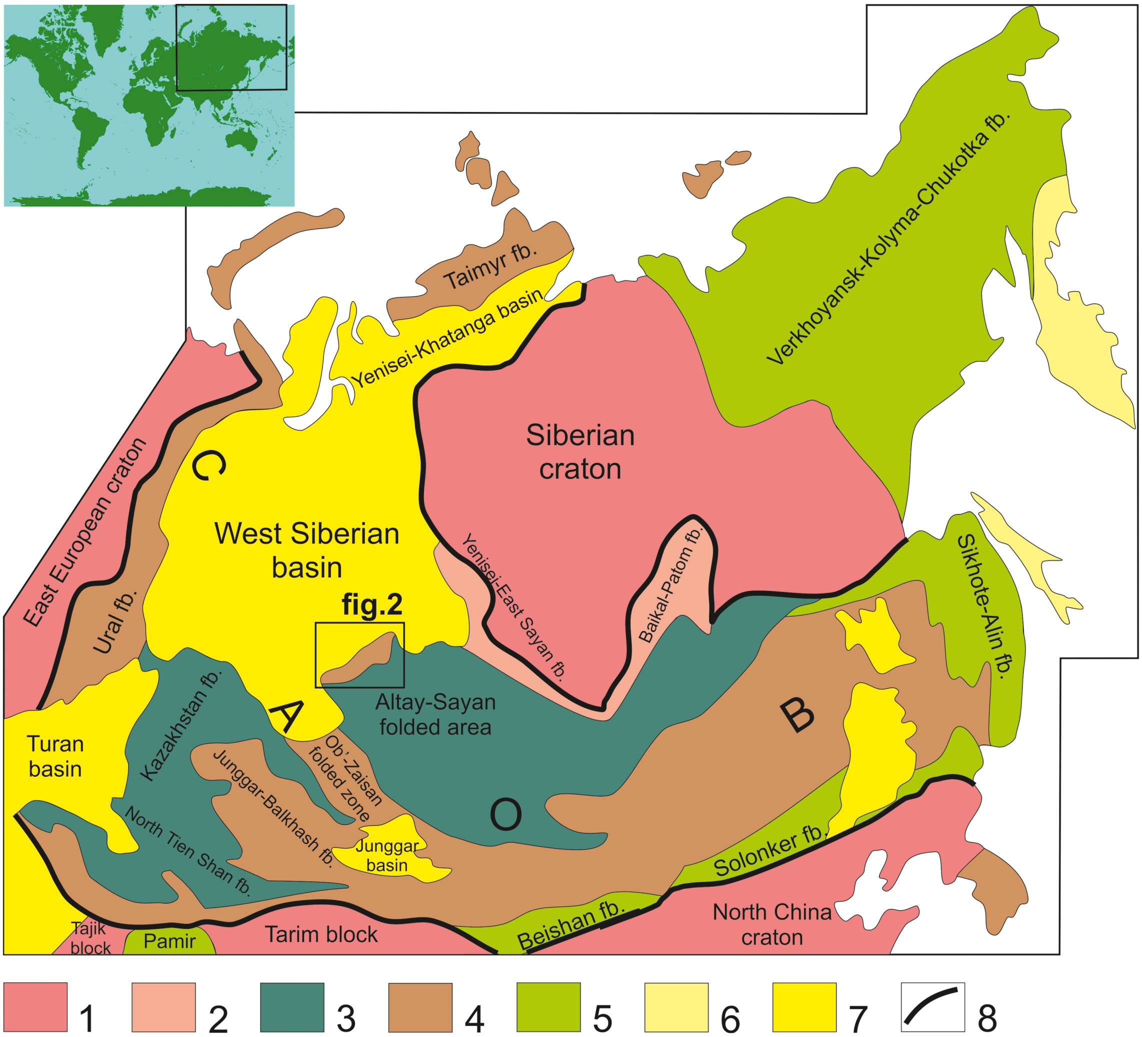

FIGURE 1 Tectonic map of Northern Asia (simplified after Petrov, Leonov, Tingdong, & Tomurtogoo, 2014). Our study area is shown in the box. (1) Early Precambrian cratons; (2–6) gold belts of various age: 2—Neoproterozoic, 3—Early Palaeozoic, 4—Late Palaeozoic, 5—Mesozoic, 6—Cenozoic; (7) Mesozoic–Cenozoic intracontinental basins; (8) boundaries of the Central Asian Orogenic Belt. Fb., fold belt [Colour figure can be viewed at wileyonlinelibrary.com]

uplifts (Figure 2) contain volcanic and sedimentary rocks of the Bugotak Formation of Givetian age. The Bugotak Formation is intruded by numerous small subvolcanic bodies of diabase and sub-alkaline dacites and rhyodacites. This volcanic–sedimentary complex is the oldest unit of the KTFZ (Matveyevskaya, 1969; Sotnikov et al., 1999). The central zone of the KTFZ consists predominantly of detrital Upper Devonian (Frasnian)–Carboniferous units (Figure 2). The main tectonic units are described in detail below. Simplified stratigraphic columns for the KTFZ and the upper part of Gorlovo Basin are shown in Figure 3.

2.1 | Bugotak Uplift

The oldest formations of the KTFZ are situated in the Bugotak uplift. This uplift represents a tectonic nappe of Devonian units overthrusted onto Middle Cambrian carbonate–volcanogenic deposits (Sotnikov et al., 1999). The lower part of the nappe is composed of 400-m-thick limestones of Eifelian age that are overlain by a rhyodacite–basalt unit of Givetian age. This volcanogenic unit is known as the Bugotak Formation (Matveyevskaya, 1969). Volcanic material in the form of lavas and tuffs of basaltic, andesitic, and rhyodacitic composition, comprise up to 75% of the formation. Volcanic rocks are interbedded with sandstones, siltstones, and limestones. The total thickness of the Bugotak Formation is about 1,500–2,000 m (Babin et al., 2015; Matveyevskaya, 1969). The volcanic deposits are intruded by subvolcanic units of diabase, gabbro-diabase, and plagioclase porphyry. A Rb–Sr isochron age of 334 ± 7 Ma was obtained for a sill of pyroxene porphyry, while a K/Ar age of 385 ± 13 Ma for the rhyolites is also reported (Sotnikov et al., 1999). Volcanic rocks are interbedded with clastic deposits and limestones containing fauna. According to biostratigraphic data, the age of the Bugotak Formation is Late Eifelian–Middle Givetian (~395–385 Ma). New conodont data from limestone interbedded with the volcanic rocks suggest that volcanic activity occurred in a

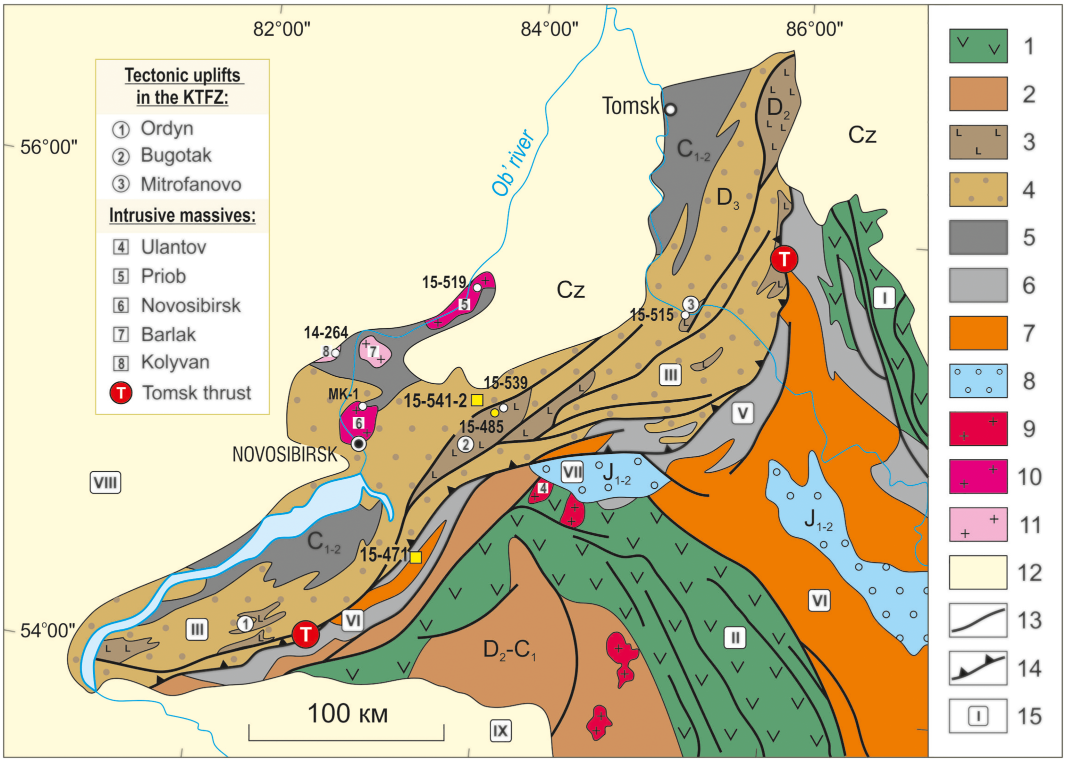

FIGURE 2 Tectonic map of the Kolyvan–Tomsk folded area and sample positions (simplified after Li, Daukeev, Kim, Tomurtogoo, & Petrov, 2008). (1) Early Palaeozoic (Caledonian) Salair and Kuznetsk Alatau terranes. (2) Upper Devonian–Mississippian (Lower Carboniferous) deposits beyond KTFZ, sedimentary cover of the basins, overprinted at the Early Palaeozoic terranes. (3) Middle Devonian volcanics and sediments of the KTFZ (Bugotak Formations and its analogues, Mitrofanovo and Toguchin formations). (4) Upper Devonian detrital and carbonate deposits (Pacha and Yurga formations). (5) Mississippian (Lower Carboniferous) deposits of the KTFZ, shales, and limestones. (6) Detrital Carboniferous deposits of the Gorlovo, Zarubin, and Kuznetsk basins, including coal molasses. (7) Permian continental molasses of the Gorlovo, Zarubin, and Kuznetsk basins. (8) Early–Middle Jurassic coal-bearing detrital deposits. (9) Undivided granite intrusions of the Salair terrane. (10) Late Permian–Early Triassic Priob granite–granodiorite–granosyenite complex. (11) Early–Middle Triassic Barlak leucogranite complex. (12) Cenozoic and Cretaceous deposits, sedimentary cover of the West Siberian Basin. (13) Faults. (14) Tomsk Thrust. (15) Numbers of tectonic units. Tectonic units: I—Kuznetsk Alatau terrane, II—Salair terrane, II—Kuznetsk Basin, III—Kolyvan–Tomsk folded zone, IV—Kuznetsk Basin, V—Zarubin Basin, VI—Gorlovo Basin, VII—Doronin Basin, VIII—West Siberian Basin, IX—Biysk–Barnaul Basin. Squares: detrital zircon U/Pb samples 15-541-2 and 15-471; yellow circle: bedrock zircon U/Pb sample 15-485; white circles samples for Nd isotopes analyses [Colour figure can be viewed at wileyonlinelibrary.com]

narrow window of time from the end of the Givetian to the earliest Frasnian (~383 Ma, Yazikov et al., 2015). The petrogenesis and context of the complex are still debated, and hypotheses vary from island arc to back-arc basin or rift setting (Belyaev & Nechaev, 2015; Kungurtsev et al., 1998; Zonenshain et al., 1990).

2.2 | Sedimentary deposits of the KTFZ

The volcanogenic–sedimentary complex of the Bugotak uplift is covered by a thick, continuous, predominantly clastic sequence. This sedimentary unit is located to the north-west of the Bugotak Uplift and is composed of sandstones, siltstones, and shales that formed from the Frasnian to the Serpukhovian (Babin et al., 2015; Sotnikov et al., 1999).

This sequence includes three major sedimentary formations: the Pacha Formation, the Yurga Formation, and the Inya Group (Figure 3). The contact between the Pacha Formation and the underlying Bugotak Formation is usually tectonic, although the normal conformable contact is rarely observed. Sediments of the Pacha Formation are typically quite monotonous in terms of lithology. The formation mostly consists of thin-bedded grey to yellow mudstone, chlorite and carbonate schists, interbedded with thin grey siltstones, sandstones, and limestones. In the southern part of the KTFZ, the Pacha Formation contains reef limestone massifs, up to 500 m thick, while the overall thickness of the formation is at least 1,500 m. The age of the Pacha Formation is determined by the fossil record as a whole to be Frasnian to Early Famennian (Matveyevskaya, 1969). Recent conodont findings confirm this Frasnian age (Izokh & Yazikov, 2015). The Pacha Formation is overlain conformably by the Yurga Formation, with a gradual transitional boundary. The Yurga Formation is composed of grey sandstone, dark grey shales, and siltstones, with interlayers of coarse sands. The age of the Yurga Formation is biostratigraphically constrained to the Late Famennian (Babin et al., 2015). The total thickness of the Yurga Formation is 1,500–1,600 m. It is conformably covered by the Inya Group, which includes deposits from Upper Famennian to Lower Visean age. These sediments are

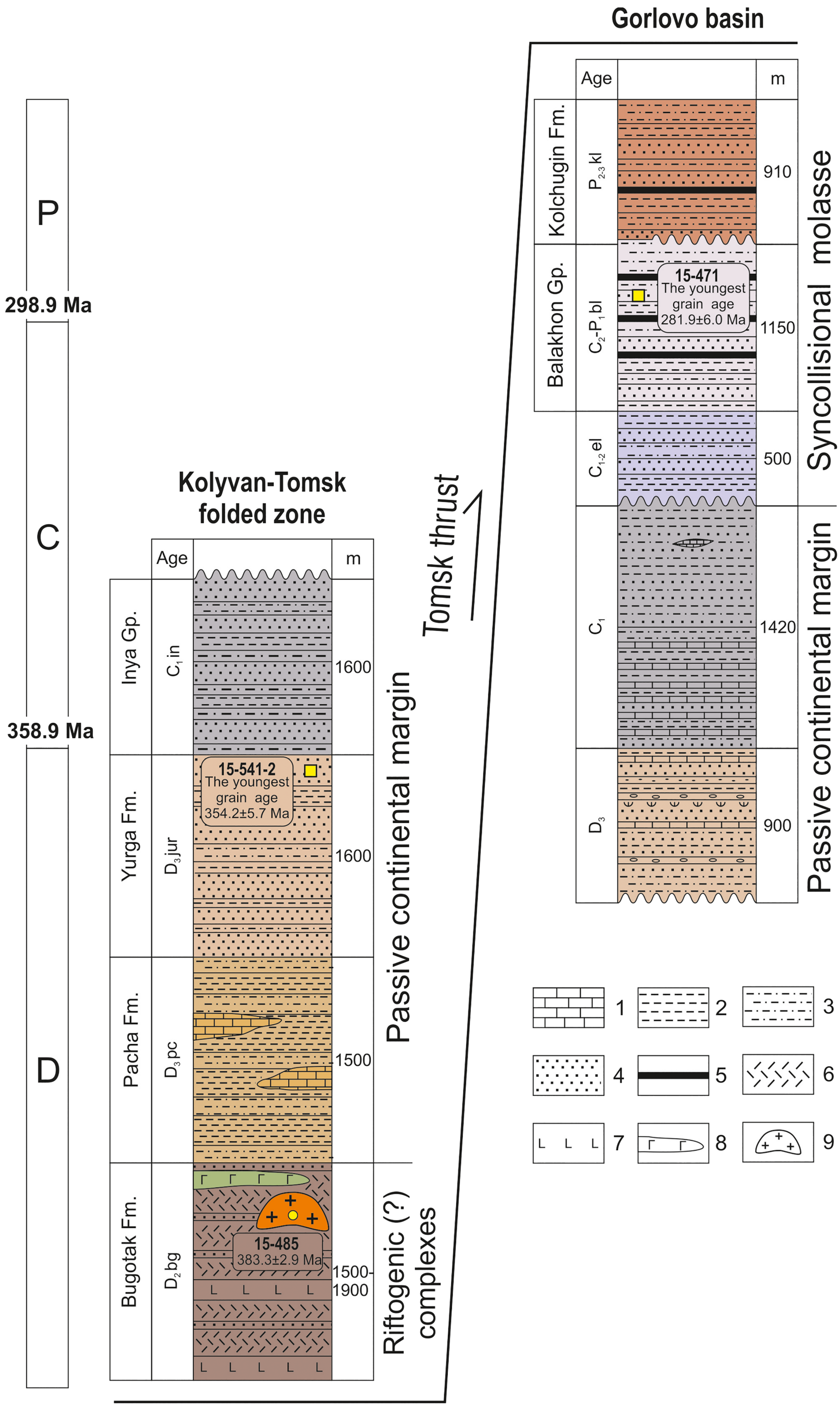

FIGURE 3 Stratigraphic column for the Kolyvan–Tomsk folded area and the upper part of the Gorlovo Basin, with position of igneous and detrital samples. Based on Kotel'nikov et al. (2008), Babin et al. (2015), and Sotnikov et al. (1999). (1) limestones; (2) mudstones; (3) siltstones; (4) sandstones; (5) coals; (6) felsic lavas and tuffs; (7) basalts; (8) dolerite subvolcanic intrusions; (9) (plagio)rhyolite subvolcanic intrusions. Circle: bedrock zircon U/Pb sample; squares: detrital zircon U/Pb samples [Colour figure can be viewed at wileyonlinelibrary.com]

typically dark grey shales and siltstones, with rare interbedding of sandstone and limestone layers. The total thickness of the Inya Group is about 1,600 m (Babin et al., 2015; Belyaev & Nechaev,2015 ; Kotel'nikov et al., 2008).

The deposits of the Pacha and Yurga formations and Inya Group are folded into inclined and overturned folds of south-western vergence. The cleavage of the axial plane is widely developed, and often masks the bedding. Mudstones are foliated and turned into phyllites. Hinge zones and overturned limbs are often dissected and shifted by the reverse faults and thrusts. The fault and hinge zones contain tectonic breccia and quartz veins. There are no traces of high-grade metamorphism in the Late Palaeozoic sedimentary sequences of the KTFZ. All features of the KTFZ interior structure are oriented according to its frontal boundary, and its interpretation as the frontal part of the fold-thrust belt is widely accepted (Sotnikov et al., 1999). This tectonic package is intruded by undeformed intrusions: Late Palaeozoic–Early Mesozoic granitoid massifs and Early Triassic mafic dykes (Babin et al., 2015). A more detailed description of the entire sedimentary sequence is hindered due to very poor outcrops, intense folding, and lack of marker beds.

2.3 | Gorlovo Basin

The Gorlovo Basin is located in front of the Tomsk Thrust, which separates KTFZ, on the NW, from the Salair with superimposed Gorlovo Basin, on the SE (Figure 2). The sediments of the Gorlovo Basin consist of two different units. The lower unit includes fine-grained clastic deposits with cherty and limestone interlayers of Eifelian to Visean age (Figure 3). The total thickness of these deposits is about 1,500 m (Kotel'nikov et al., 2008). This unit is similar to the Upper Devonian–Lower Carboniferous deposits of the KTFZ but is less thick and represents a shallower facies. It can be interpreted as the sedimentary cover of shallow water facies on the Salair continental margin (Babin et al., 2015; Kotel'nikov et al., 2008). From the Serpukhovian onwards, the style of sedimentation changed in the Gorlovo Basin. The upper part of the sedimentary cover is composed of coal-bearing molasse of Middle Carboniferous–Permian age (Figure 3). The coal-bearing formation is called the Balakhon Group. The uppermost sediments of the basin are mudstones, siltstones, and sandstones that contain only sparse and thin coal layers, and which belong to the Middle–Upper Permian Kolchugin Group (Kotel'nikov et al., 2008). In terms of composition and texture, the deposits of the Balakhon and Kolchugin groups in the Gorlovo Basin are similar to the same stratigraphic units in the Kuznetsk Basin (Davies, Allen, Buslov, & Safonova, 2010; De Grave et al., 2011, and references therein). This Serpukhovian–Permian unit has a thickness of about 2,500 m, 1,150 m of which is represented by the Upper Carboniferous–Lower Permian Balakhon Group. The upper unit is interpreted as a syncollisional mollasse deposit (Sotnikov et al., 1999).

Sediments of the Gorlovo Basin are deformed into linear folds, and the coals are composed of different grades up to anthracite. In terms of its structure, the Gorlovo–Zarubin Basin is a graben–syncline that extends for more than 100 km and with a width of 12–15 km (Figure 2). The basin is separated from the KTFZ by a series of faults that are thought to be NW-dipping thrusts on the basis of geological and geophysical data (Kotel'nikov et al., 2008; Sotnikov et al., 1999). The Gorlovo Basin can be considered as a foreland basin that developed during a stage of thrusting of the KTFZ onto the Salair block, at the margin of the Siberian continent (Sotnikov et al., 1999). Upper Devonian rocks of the KTFZ are thrust upon the Permian deposits of the Kuznetsk and Gorlovo basins, and therefore, the timing of thrusting appears to be Late Permian (Babin et al., 2015; Yuzvitskiy, 1966).

2.4 | Granites of KTFZ

The granitoids of the region form two distinct magmatic complexes, which differ in composition and age. These complexes are known as the Priob granite–granodiorite–granosyenite complex and the Barlak leucogranite complex (Figure 2; Sotnikov et al., 2000). The Priob complex includes the Ob′ and Novosibirsk massifs and consists of three phases of magmatism: (a) monzonite and diorite, (b) monzogranite, and (c) monzo–leucogranites. The zircon U/Pb age (SHRIMP-II) of the granites from the main, second, phase of the Ob and Novosibirsk massifs lies in the range of 260.7 ± 3.2–49 ± 1 Ma (Babin, Fedoseev, Borisenko, Zhigalov, & Vetrov, 2014). The third phase of the Novosibirsk monzogranite intrusion was dated at 249 ± 1 Ma (Babin et al., 2014). Biotite Ar–Ar ages for the granitoids of the second and third phases of the Novosibirsk and Ob plutons range from 251.2 ± 2.4 to 243.7 ± 1.8 Ma, while Rb–Sr analysis of the Novosibirsk granitoids produced an isochron age of 245.5 ± 3.1 Ma (Sotnikov et al., 2000). Therefore, the age of the Priob complex is interpreted to be Late Permian–Early Triassic. The Barlak leucogranite complex consists of the Barlak and Kolyvan massifs and associated minor massifs that are completely covered by Cenozoic deposits. Two intrusion phases can be distinguished in the complex. The first and major phase is composed of voluminous monzo–leucogranites. The second phase consists of the intrusion of small bodies and dikes of fine-grained monzo–leucogranites. The zircon U–Pb age (SHRIMP-II) from the granites of the main phase of the Barlak massif is 242 ± 2 Ma, while monzo–leucogranites from the second phase produce an age of 249.1 ± 0.7 Ma. Similar ages (249–247 Ma) were obtained for the Kolyvan′ massif for example (Babin et al., 2014). Ar/Ar ages for feldspar and biotite from the Kolyvan′ massifs are 233.0 ± 1.8 Ma and 235.5 ± 2.6 Ma, respectively (Sotnikov et al., 1999). The Rb–Sr isochron age of the granites from the Barlak Complex is 232.0 ± 6.9 Ma, that is, Early–Middle Triassic (Sotnikov et al., 1999). The granitic outcrops are intersected by the nappe-fold structures of the KTFZ. The Priob Complex corresponds to the collisional stage of the orogen, while the Barlak Complex is related to the post-collisional extension stage (Sotnikov et al., 2000).

3 | SAMPLING

Representative samples of some of the magmatic complexes and sedimentary sequences of the KTFZ were collected for zircon U–Pb geochronologic and Nd isotopic composition analysis (Figures 2-4).

Sample 15-541-2 was collected from the Famennian Yurga Formation, at the open pit quarry on the right bank of the Bugotak River (Figure 2). This sample is composed of yellowish–grey sandstones (greywackes) with a clay matrix (Figure 4a). The sandstones form lenses in the predominantly siltstone and mudstone facies of a distal turbidite sequence. There are no idiomorphic crystals of plagioclase

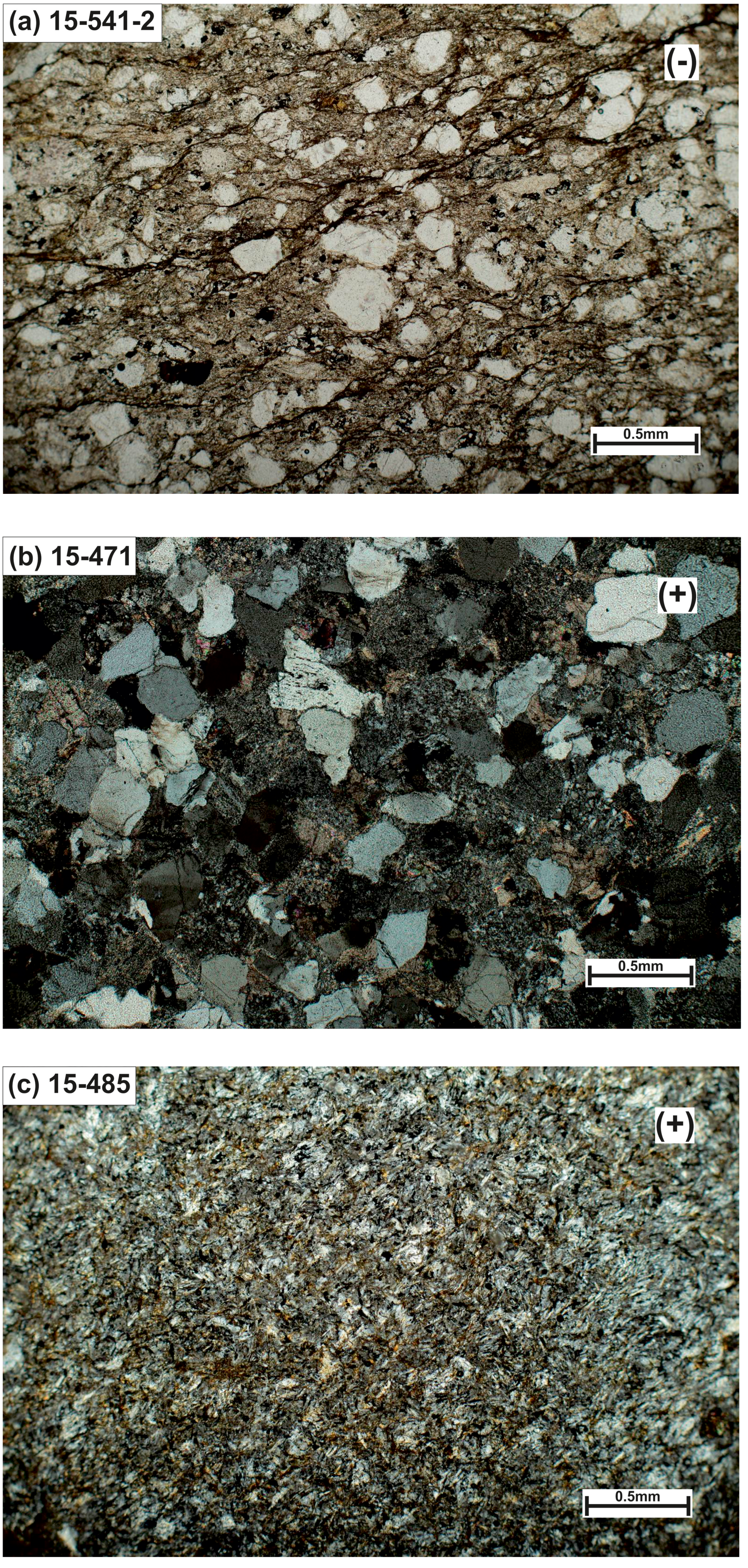

FIGURE 4 Thin section photographs of the dated rocks. (a) Greywacke of the Famennian Yurga Formation (15-541-2). Sub-rounded to sub-angular quartz grains are immersed in the clay matrix. (b) Coarse-grained sandstones of the Late Carboniferous–Early Permian Balakhon Group, Gorlovo open pit (15-471). Quartz grains are clearly prevalent, indicating the mature character of the sediments. Grains are cemented by secondary carbonate; (c) rhyolites of the Bugotak subvolcanic intrusive massif (15-485). Rock fabric is composed dominantly of fine-grained elongated plagioclase, quartz, and a minor amount of magnetite. The symbols "(−)" and "(+)" in the upper right corners of each diagram represents plane-polarized light and cross-polarized light, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

or other evidence to suggest volcanic activity (tuffs) in the vicinity of the sedimentation area. The sample of the Upper Devonian Yurga Formation (15-541-2) is characteristic of the marine accumulation of clastic sediments at the continental margin (Sotnikov et al., 1999).

Sample 15-471 was taken from the Gorlovo open pit coal mine, from the Upper Carboniferous to the Lower Permian deposits of the Balakhon Group. The sample was taken from a 4-m-thick sandstone layer in the coal-bearing siltstones and is composed of grey, rounded coarse-grained, poorly sorted, cross-bedded sandstone and can be described as a lithic arenite (Figure 4b). This layer also contains numerous fragments of underlying black siltstones. These sandstone beds appear to be alluvial channel deposits and are typical features of the Balakhon Group. The Late Mississippian–Cisuralian (Middle Carboniferous–Lower Permian in Russian stratigraphy) Balakhon Group (sample 15-471) was formed in a continental environment as an orogenic molasse deposit, during the collision stage of the Kolyvan–Tomsk orogeny (Sotnikov et al., 1999; Vladimirov et al., 2005).

Sample 15-485 was taken from a rhyolite subvolcanic intrusion of the Bugotak Complex (Sopka Bolshaya hill, near the town of Gorniy). It is an aphyric, grey, fine-grained rock with a strong felsic (acidic) composition (Figure 4d). Samples 15-515 and 15-539 are also collected from the Bugotak Complex. Sample 15-515 is the fine-grained volcanoclastic breccia at the top of volcanic sequence, just below the base layers of the Pacha Formation. Sample 15-539 is dolerite from the subvolcanic intrusion of the Bugotak Complex.

Samples 15-519, MK-1, and 14-264 were taken from the granite intrusions of the KTFZ. Sample 15-519 is granite of the Priob Complex, taken from the outcrop near the Novobibeevo village, MK-1 is granite of the Mochishe stock, and 14-264 is leucogranite of the Barlak complex, taken from the Kolyvan open pit mine.

Sample locations are summarized in Table 1. Whole-rock major and trace element composition of the dated rocks are presented in Data S1.

4 | METHODOLOGY

4.1 | Zircon U/Pb geochronology

Sample preparation including rock crushing and zircon separation were performed at Novosibirsk State University. Zircon separates were hand-picked and mounted in epoxy resin, then polished to expose the grains. Cathodoluminescence images of the zircon grains (Figure 5) were produced using a FEI Quanta600 Scanning Electron Microscope at Adelaide Microscopy to identify the internal structure. U–Pb geochronology was conducted via LA–ICP–MS at the University of Adelaide using an Agilent 7900 mass spectrometer coupled to a New Wave UP-213 ablation system. Zircons were ablated using a spot size of 30 μm and a frequency of 5 Hz, with 30 s of background acquisition and 30 s of sample ablation. The GJ zircon standard ($^{206}Pb/^{238}U$ = 608.5 ± 0.4 Ma, Jackson, Pearson, Griffin, & Belousova, 2004) was used to correct for U–Pb fractionation, while Plešovice ($^{206}Pb/^{238}U$ = 337.13 ± 0.37 Ma, Sláma et al., 2008) was used as a secondary standard. Nineteen analyses of this standard over the course of the analytical session yielded a weighted mean $^{206}Pb/^{238}U$ age of 340.3 ± 1.6 Ma (MSWD = 1.8). U–Pb data reduction was conducted using the Iolite software package (Paton, Hellstrom, Paul, Woodhead, & Hergt, 2011). The complete isotopic dataset and single-spot age results can be found in Data S2.

4.2 | Nd isotope geochemistry

The Sm and Nd concentrations were measured at the Analytical Center for Multi-elemental and Isotope Research SB-RAS (Novosibirsk) using the ICP–MS method. Isotopic compositions were determined at the Geological Institute of the Kola Scientific Center of the Russian Academy of Sciences (Apatity, Russia) using the methods described by Bayanova (2004).

The average ratio of $^{143}Nd/^{144}Nd$ in the JNdi-1 standard over the measurement period was 0.512090 ± 13 (N = 9). The error on the $^{147}Sm/^{144}Nd$ ratio was evaluated at 0.3% (2σ), that is, an average over seven measurements of the BCR-2 standard (Raczek, Jochum, & Hofmann, 2003). The error calculated for the Nd isotopic ratio for an individual analysis is as low as up to 0.005%. In the calculation of the Nd–isochron, these effective errors were used, but not below the level of reproducibility of the measurement (0.003%). The accuracy of the determination of Sm and Nd concentrations is ±0.5%, for minerals with low contents (ppm levels)—up to ±10%. Isotopic ratios were normalized relatively to $^{146}Nd/^{144}Nd$ = 0.7219 and then recalculated to the ratio of $^{143}Nd/^{144}Nd$ in the standard JNdi-1 = 0.512115 (Tanaka

TABLE 1 Summary of sample localities, rock types, and geological setting for the Kolyvan–Tomsk folded zone

Sample	N latitude	E longitude	Rock type	Sample localities	Complex/Formation
15-541-2	55° 8′5.44″	83°47′17.05″	Sandstone	Open pit near the Bugotak railway station	Yurga Formation
15-471	54°34′22.80″	83°35′20.31″	Sandstone	Gorlovo coal open pit	Balakhon Group
15-485	55° 7′18.79″	83°56′36.23″	Rhyolite	Sopka Bolshaya hill	Bugotak Complex
15-539	55° 7′37.97″	83°55′16.13″	Dolerite	Open pit near the Gorniy town	Bugotak Complex
15-515	55°39′6.65″	85°16′28.79″	Volcanoclastic breccia	Bank of the Tom′ river	Bugotak Complex
15-519	55°41′19.26″	83°44′32.30″	Granite	Outcrop near the Novobibeevo village	Priob Complex
MK-1	55° 7′41.36″	82°54′25.59″	Granite	Open pit in the Novosibirsk	Priob Complex
14-264	55°21′18.27″	82°45′45.97″	Leucogranite	Open pit near the Kolyvan′ town	Barlak Complex

FIGURE 5 Cathodoluminescence images of representative zircons from samples 15-541-2—Upper Devonian sandstone and Yurga Formation; 15-471—Lower Permian sandstone and Balakhon Group; 15-485—plagiorhyolites and Givetian–Early Frasnian Bugotak Formation [Colour figure can be viewed at wileyonlinelibrary.com]

et al., 2000). For the calculation of εNd(T) values and model ages T (DM), we used the conventional present-day CHUR values of $^{143}Nd/^{144}Nd$ = 0.512630, $^{147}Sm/^{144}Nd$ = 0.1960 (Bouvier, Vervoort, & Patchett, 2008) and DM $^{143}Nd/^{144}Nd$ = 0.513151, $^{147}Sm/^{144}Nd$ = 0.2136 (Goldstein & Jacobsen, 1988). In order to account for possible Sm–Nd fractionation during intracrustal processes, the two-stage Nd model ages (Keto & Jacobsen, 1987) were calculated for the studied rock samples using the average crustal ratio of $^{147}Sm/^{144}Nd$ = 0.12 (Taylor & McLennan, 1985).

5 | RESULTS

5.1 | Zircon U/Pb dating

The CL images show that most detrital zircons from the samples are euhedral to subhedral crystals with sharp edges and have concentric oscillatory zoning (Figure 5). The Th/U ratio for the zircons from sample 15-541-2 lies in the range of 0.15–1.30, and sample 15-471 shows similar values (0.20–1.50). These features are hence typical of magmatic zircons. A few detrital zircons exhibit low luminescent characteristics and homogeneous internal structure, but their high Th/U ratios nevertheless also suggest an igneous origin (Hoskin & Black, 2000; Hoskin & Schaltegger, 2003). Zircon grains from the rhyolite sample 15-485 are clearly euhedral crystals showing obvious oscillatory magmatic zoning and have a Th/U ratio of 0.20–0.80 with an average of 0.37.

The concordia plots in Figure 6 show that most analysed zircons are concordant. Age peaks are based on Kernel Density Estimation (KDE) plots (Vermeesch, 2012) that were constructed based on the analyses for each sample that were no more than 10% discordant.

The diagram of the relative probability of ages, constructed based on 80 concordant values, for sample 15-541-2 (Yurga Fm) yields three distinct age populations: Palaeoproterozoic, 2,020–1,800 Ma—5% of all concordant values; Neoproterozoic, 919–767 Ma—8.7%;

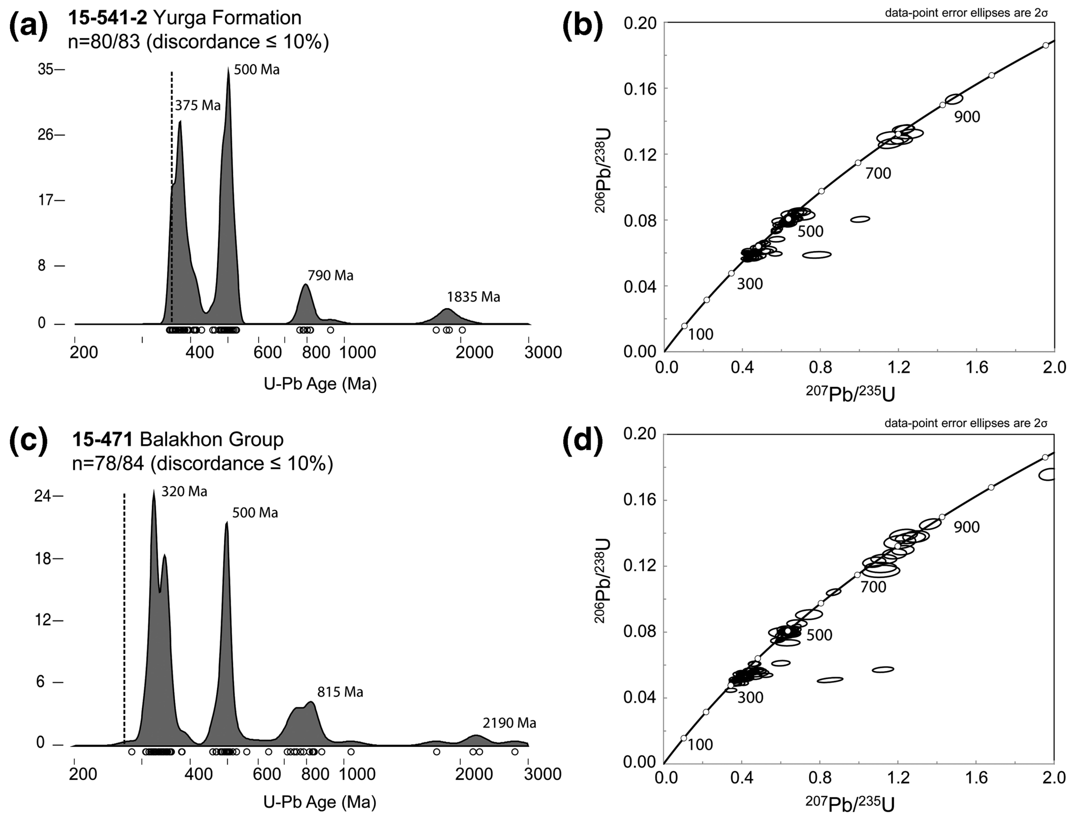

FIGURE 6 Zircon U–Pb age–frequency diagrams and concordia plots for the zircons from the sedimentary samples (a, b: sample 15-541-2; c, d: sample 15-471). The age (in Ma) on the *x*-axis represents the $^{206}Pb/^{238}U$ age when this age is lower than 1 Ga and the $^{207}Pb/^{206}Pb$ age in the other case. The dotted line at the age–frequency diagrams shows the depositional age

Cambrian–Ordovician, 525–455 Ma—42.5%, with a peak at 500 Ma; and Late Devonian, 395–352 Ma—39%, with a peak at 375 Ma, in addition 5% of the grains have a Silurian–Early Devonian age of 425–406 Ma (Figure 6a,b).

The age spectrum of sample 15-471 (Balakhon Gp), constructed from 78 concordant values, also includes three significant age populations: Archean–Palaeoproterozoic, 2,700 to 1,800 Ga—5% of all values; Neoproterozoic (880–710 Ma, and two grains with slightly deviant ages of 1,215 and 638 Ma)—16.5%; Cambrian–Early Ordovician (560–460 Ma with a peak at 500 Ma)—28%; and Carboniferous–Permian (380–280 Ma with a peak at 320 Ma)—50% (Figure 6c,d). Therefore, sample 15-471 shows a similar pattern to that of 15-541-2. However, the Neoproterozoic (~830–750 Ma) age peak is more pronounced, and the youngest age peak is centred around Carboniferous–Permian ages of 360–280 Ma.

Sample 15-485 produced a weighted mean age of 383.3 ± 2.9 Ma (MSWD = 3.9) based on the 27 analyses that were no more than 10% discordant (Figure 7).

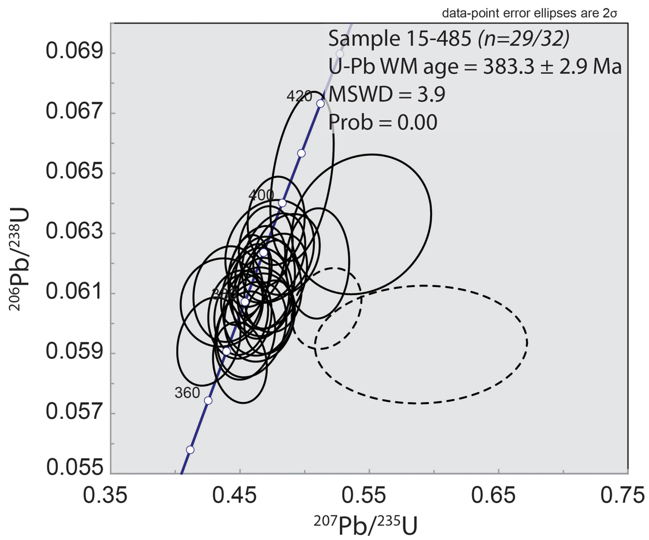

FIGURE 7 Concordia plot for the zircons from the igneous sample 15-485 [Colour figure can be viewed at wileyonlinelibrary.com]

5.2 | Nd isotopic data

The Late Devonian sandstones of the Yurga Formation and the Carboniferous–Permian Balakhon Group have similar Nd isotopic compositions. The value of εNd for the rocks of the Yurga Formation is −0.78, with a T (DM) of ~1.1 Ga, and for the sandstones of the Balakhon Group, εNd(T) is −1.1 and T (DM) is ~1.1 Ga.

All intrusive and volcaniclastic rocks are characterized by high positive values of the εNd(T) in the range of 3.78–6.86 and a Late Precambrian model age (T (DM) = 581–916 Ma). The values for the Devonian volcanic formations of the Bugotak Complex are all within a narrow range of one another (εNd(T) = 6.67–6.86, T (DM) = 581–649 Ma). Late Permian and Triassic granitoids are characterized by lower values of εNd(T) and higher model ages (εNd(T) = 3.78–6.06, T (DM) = 609–916 Ma).

All results of the Nd isotopic analyses are presented in Table 2 and Figure 8.

6 | DISCUSSION

6.1 | Depositional age

Detrital zircon U–Pb geochronology is a widely applied method that is used to determine the maximum depositional age of a sedimentary rock. Various criteria including youngest single grain and youngest cluster ($n \geq 3$) can be applied to provide an estimate of the maximum deposition age, although the success of this approach depends on the age and availability of detrital zircons in the sediment. The detrital zircon method has been found to faithfully record useful information about the timing of deposition of strata (Dickinson & Gehrels, 2009).

The youngest grain in the sample of the Yurga Formation (15-541-2) has a $^{238}U/^{206}Pb$ age of 351.8 ± 7.4 Ma, and the mean age of the youngest three grains is 354 Ma. The stratigraphic age of the Yurga Formation is estimated as Late Famennian, based on its brachiopod fauna (e.g.,Babin et al., 2015 ; Matveyevskaya, 1969). Famenian–Tournaisian stratigraphic boundary lies slightly older, at 358.9 Ma, but our data overlap it within analytical error. The Yurga Formation is associated with the Mississippian Inya Group by a gradual transition, and it cannot be ruled out that in some locations the Yurga Formation includes Lower Mississippian (i.e., Tournasian) deposits. In the Balakhon Group (15-471), the youngest measured $^{238}U/^{206}Pb$ age is 281.9 ± 6.0 Ma. According to stratigraphic data (Sviridov et al., 1999), the Balakhon Group was deposited from the Moscovian epoch of the Pennsylvanian (315.2 ± 0.2 Ma) to the Kungurian epoch of the Permian period (272.9 ± 0.1 Ma), so the youngest single grain age for the sample from the Balakhon Group lies inside the stratigraphic frames of the Balakhon Group. These detrital chronological data are in agreement with stratigraphy constraints for both sedimentary units, and our results now constrain the deposition in an absolute time frame.

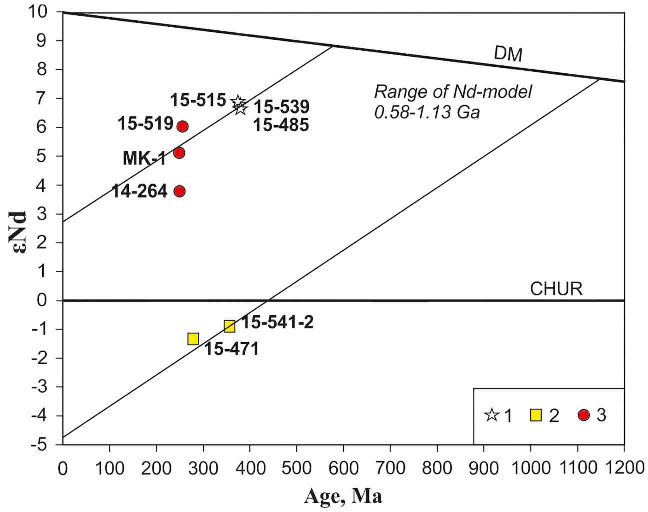

FIGURE 8 Nd evolution diagram for the magmatic and sedimentary rocks of the KTFZ. (1) magmatic rocks of the Bugotak Complex, (2) sediments of the Pacha Formation and Balakhon Group, (3) granites of the Priob and Barlak complexes Evolutionary trends of isotope reservoirs from Bouvier et al. (2008) and Goldstein and Jacobsen (1988) [Colour figure can be viewed at wileyonlinelibrary.com]

6.2 | Provenance for the sedimentary rocks

6.2.1 | Precambrian zircons

A peculiarity of both these zircon age spectra is the low abundance of zircons older than 1 Ga, in particular the rarity of zircons belonging to the characteristic Siberian craton population with ages of 1.9–1.7 Ga (Gladkochub et al., 2013; Letnikova et al., 2013; Safonova, Maruyama, Hirata, Kon, & Rino, 2010). This population is extremely widespread throughout north-eastern Eurasia, and the low abundance of this population in sedimentary rocks on the periphery of the craton is unusual.

A minor Neoproterozoic population with ages of ~0.9–0.7 Ga is observed in both detrital samples. There are three possibilities that could explain the source of the Neoproterozoic zircons. The first potential source area could be the Neoproterozoic fold belts framing the Siberian Craton, such as the Sayan-Yenisei orogen (Turkina, Nozhkin,

TABLE 2 The Sm–Nd isotope data of the rocks from KTFZ.

Sample	Rock	Sm, ppm	Nd, ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	εNd(0)	Age, Ma	εNd(T)	T (DM)	T (DM-2)	T (CHUR)
15-541-2	Sandstone	5.099	27.448	0.112285	0.512399 ± 13	-4.67	360	-0.78	1131	1194	433
15-471	Sandstone	4.305	24.291	0.107113	0.512406 ± 13	-4.53	280	-1.10	1066	1174	396
14-264	Leucogranite	11.235	46.223	0.146912	0.512750 ± 4	2.19	250	3.78	916	725	
MK-1	Granite	4.368	22.243	0.118701	0.512772 ± 6	2.62	250	5.11	609	614	
15-519	Granite	4.036	16.502	0.147820	0.512867 ± 16	4.47	255	6.06	658	539	
15-539	Dolerite	7.632	32.128	0.143585	0.512853 ± 10	4.20	380	6.78	649	581	
15-485	Rhyolite	3.917	20.461	0.115711	0.512778 ± 11	2.73	380	6.67	581	591	
15-515	Volcanoclastic breccia	8.263	37.116	0.134568	0.512837 ± 17	3.88	375	6.86	607	571	

Bayanova, Dmitrieva, & Travin, 2007; Vernikovsky, Vernikovskaya, Kotov, Sal'nikova, & Kovach, 2003). The second possibility is represented by the microcontinental blocks of the Altai–Sayan belt, such as the Tuva–Mongolia or Altai–Mongolia microcontinents that are known to host rocks of that age (Chen et al., 2016, 2015; Kuzmichev, Bibikova, & Zhuravlev, 2001; Kuzmichev & Larionov, 2013). A third alternative could be that of the known but poorly described similar buried microcontinents in the basement of the West Siberian Basin is the source. The aforementioned age population is widespread in the Precambrian microcontinental blocks of Central and South Kazakhstan, and this chain of continental blocks might indeed also extend through the West Siberian Basin basement. The first hypothesis is less likely due to the very rare occurrence of "Siberian" zircons with ages of 2.0–1.8 Ga in the samples (four grains in the each detrital sample). The third possibility is also unlikely, because in the most proximal part of the West Siberian Basin, its folded basement mainly consists of Late Palaeozoic sediments and magmatic rocks, and there is little or no evidence for the existence of Precambrian massifs in this location (Cherepanova, Artemieva, Thybo, & Chemia, 2013; Isaev, 2009; Ivanov et al., 2009; Ivanov et al., 2016; Ivanov, Fedorov, Ronkin, & Erokhin, 2005; Kungurtsev et al., 1998; Yolkin et al., 2007). Hence, the most probable sources of the Neoproterozoic zircons are the Tuva–Mongolia and/or Atai–Mongolia microcontinents. Ediacaran (~650–600 Ma) zircons were found in the Palaeozoic sediments at the southern margin of the Siberian Craton (Glorie, De Grave, Buslov, Zhimulev, & Safonova, 2014). The absence of a 650–600 Ma peak in the sediments of the KTFZ suggests that for the latter a different provenance area must be attributed (Nozhkin, Turkina, Sovetov, & Travin, 2007) .

6.2.2 | Early Palaeozoic zircons

An Early Palaeozoic magmatic event is clearly expressed in both samples, suggesting that magmatic activity in the source regions occurred at ~550–460 Ma, with a maximum intensity at 500 Ma. Considering the geological position of the KTFZ, it can be concluded that the source rocks were the volcanic and intrusive rocks of the Salair terrane, the Kuznetsk Alatau, and the northern Altai region. These regions include widespread volcanic and intrusive rocks of the Cambrian–Early Ordovician, which are considered to be Early Cambrian juvenile, and Middle Cambrian–Early Ordovician mature island arc systems (Berzin et al., 1994; Berzin & Kungurtsev, 1996; Glorie et al., 2011; Zonenshain et al., 1990). Furthermore, our data confirm that the basement of the Salair and Kuznetsk Alatau terranes and the KTFZ is composed of Neoproterozoic–Early Palaeozoic juvenile crust and does not contain blocks of Early Precambrian continental crust.

A minor zircon population of igneous affinity of Late Silurian–Early Devonian age (425–409 Ma) is present in the Upper Devonian sandstones. A most likely source for these zircons would be the granite intrusions of the Ulantov Complex, which is situated in the northern part of the Salair terrane (Figure 2).

From the age spectra of both samples, it is clear that, except for this small group, the Silurian–Early Devonian period seems to represent a distinct gap between the two discrete peaks of Cambrian–Ordovician

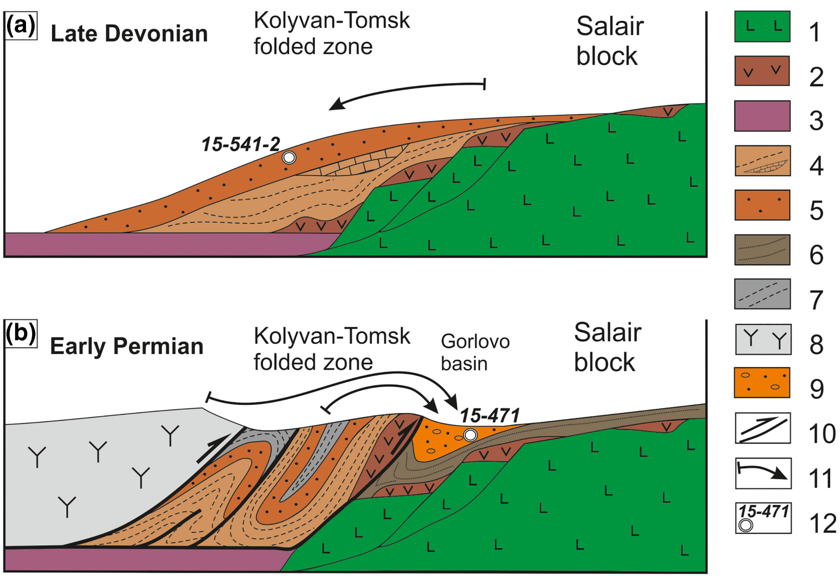

FIGURE 9 Simplified out-of-scale geological cross-section through the Kolyvan–Tomsk folded zone (KTFZ), showing the source provinces and direction of sedimentary pathways in the Late Devonian (a) and Early Permian (b). (1) Early Palaeozoic (Caledonian) Salair and Kuznetsk Alatau terranes, (2) Middle and Upper Devonian volcanics and sediments including the Bugotak Formation and its analogues beyond the KTFZ, (3) Upper Devonian–Carboniferous oceanic crust, (4) Upper Devonian (Frasnian) mudstones, siltstones, and carbonate deposits, Pacha Formation, (5) Upper Devonian (Famennian) sandstones and siltstones Yurga Formation, (6) Upper Devonian to Mississippian carbonate–detrital sedimentary cover of the Salair block, (7) Mississippian black shales, mudstones, marls, Inya Group, (8) Carboniferous island arc volcanic complexes, inferred under the Meso–Cenozoic sedimentary cover of the West Siberian Basin, (9) Pennsylvanian to Permian coal-bearing molasse of the Gorlovo foreland basin, (10) thrusts of the Kolyvan–Tomsk folded zone onto Caledonian basement, (11) direction of the sediment transport, (12) our sample sites [Colour figure can be viewed at wileyonlinelibrary.com]

and Carboniferous magmatic activity. This gap also corresponds to a large break or hiatus in the sedimentation on a regional scale in the area. The lack of magmatism and sedimentation can be explained as reflecting a contemporaneous episode of tectonic stability. We therefore suggest that the depositional environment for the Upper Devonian sediments on the Early Palaeozoic basement is in a passive margin tectonic setting, without contribution from other sources (Figure 9a).

6.2.3 | Late Palaeozoic zircons

A very significant Late Palaeozoic peak at 395–358 Ma in the Upper Devonian sample and at 380–280 Ma (with a maximum at 320 Ma) in the Permian sample can be observed. In the Permian sandstone, this peak is the most significant one in the entire distribution and includes 50% of the all analysed grains. In the Upper Devonian, sample Early Palaeozoic zircons are more prevalent (42.5%).

Detrital zircon ages of 395–380 Ma probably indicate the onset of Devonian volcanic activity in the Northern Salair and KTFZ regions. In the Salair, Middle Devonian volcanic rocks make up the lower parts of the overprinted Late Palaeozoic basins, and in the KTFZ, very similar volcanic rocks are known as the Bugotak Complex (Figure 2). We propose that the Middle Devonian volcanics of Salair and KTFZ are fragments of a single volcanic belt, which was dismembered and juxtaposed in different structural units after a collision in the Pennsylvanian.

The Early Frasnian age of the plagiorhyolites (382 Ma; sample 15-485) that form subvolcanic bodies intruding the volcanics of the Bugotak block, correspond well with biostratigraphical data and K/Ar dating (Sotnikov et al., 1999), as well as with our detrital zircons data. This combined evidence allows us to clearly date the volcanic activity in the KTFZ to the Givetian–Early Frasnian. Moreover, this result is in good agreement with new biostratigraphical data that indicate a very narrow time range for the deposition of the Bugotak Formation, from the latest Givetian to the earliest Frasnian (Yazikov et al., 2015).

Late Palaeozoic detrital zircon age peaks are present in both detrital samples and have an asymmetric shape with a very sharp restraint towards the age of deposition and a gentle skew towards more ancient values. This pattern can be explained by the deposition of zircons from volcanic strata that were emplaced immediately before and during deposition of the sampled sedimentary formations. The similarity between the obtained zircon ages and biostratigraphical data constraining the age of sedimentation for the Yurga Formation and the Balakhon Group further confirms this conclusion. Upper Devonian and Carboniferous volcanic rocks are absent in the KTFZ, Salair, and Kuznetsk Alatau but are widespread in the interior part of the Ob′–Zaisan fold system. Complexes of these rocks are well exposed in East Kazakhstan and Rudny Altai (Glorie et al., 2012; Vladimirov et al., 2001) and form the basement of the West Siberian plate to the west and north-west of the KTFZ (Isaev, 2009; Ivanov et al., 2005; Ivanov et al., 2016; Kungurtsev et al., 1998). Carboniferous volcanic rocks of East Kazakhstan are considered to be a part of the Rudny Altai island arc system (Berzin & Kungurtsev, 1996; Zonenshain et al., 1990). Thus, in the Early Permian, the sediment transport to the Gorlovo Basin occurred mainly from the north-west, that is, from the northern-east part of the growing Ob′–Zaisan orogen, composed mainly of magmatic complexes of the Carboniferous island arc system. The similarity of the zircon age spectra and Nd isotopic composition between the Devonian rocks of the continental margin and the Permian–Carboniferous foreland can be explained by the erosion of Devonian sedimentary rocks composing thrust nappes in the KTFZ and recycling of debris in the syncollisional foreland basin. Therefore, at least part of the “Salair” zircon age signature in the Gorlovo foreland was not sourced directly from the Salair but recycled during nappe formation in the KTFZ and associated erosion (Figure 9b). The abundance of Carboniferous zircons in the deposits of the Gorlovo Basin in comparison with Cambrian–Ordovician and Devonian zircons is an indicator that in the Early Permian, tectonic sheets of Carboniferous volcanics were already included in the collisional fold-and-thrust belt (Figure 9b).

6.3 | Comparison with adjoining regions

The magmatic events identified in this study correspond well with the episodes of juvenile mantle-derived magmatic input into the crust defined in the West Junggar region (Choulet et al., 2012), providing evidence that these events represent periods of relatively rapid growth of the continental crust of the CAOB. Narrow age population peaks, rare occurrence of Early Precambrian zircons, and consistent short lag times between maximum depositional age and main isotopic peak age population are similar features of the detrital zircons from both the sediments of the KTFZ and the West Junggar region. We consider this to be evidence of similar processes acting in the junction zone of the “Caledonian” Altai–Sayan structures and the “Hercynian” structures of the Ob′–Zaisan folded system.

Our results are in a good agreement with the age of populations of detrital zircons in the Chinese Altai (Long et al., 2007). The main population of zircons from the Upper Ordovician and Silurian metasedimentary rocks of the Chinese Altai lies in the range of 460 to 540 Ma, while subordinate population contain Neoproterozoic ages, and Early Precambrian grains are very rare. Long et al. (2007) hence suggested that the complexes of the Chinese Altai were formed in an active continental margin during the Cambrian–Ordovician.

As shown in the sandstones from the Upper Ordovician–Silurian Terekta Formation in the Russian Altai, detrital zircons have similar age distributions as our samples (Cai et al., 2016). The most prominent peak is at 520 Ma, a subordinate peak is found at 800 Ma, and a minor Palaeoproterozoic peak. These data suggest that Precambrian basement blocks may not exist in the Altai–Mongolian terrane after all, and this terrane probably represents a large subduction–accretion complex built on the margin of the Tuva–Mongolian microcontinent in the Early Palaeozoic.

Extremely minor amounts of Precambrian detrital zircons in the sediments are typical for a wide zone, including Russian and Chinese Altai, East Kazakhstan, and Junggar (Cai et al., 2016; Chen et al., 2017; Dong et al., 2018; Kruk et al., 2018; Liu et al., 2019; Long et al., 2007). These data together with our results enable us to conclude that juvenile Early Palaeozoic active marginal sequences or island arc systems can be traced from the Chinese Altai through the Russian Altai to the Salair and Kuznetsk region under investigation here. North and south of this zone, the content of ancient zircons in the sedimentary series increases. At the same time, north of this zone, Precambrian zircons show Siberian affinity—the main peak at 1.8–2.0 and the complete absence of grains with ages of 2.7–2.5, 2.0–1.75, and 0.95–0.57 Ga (Priyatkina, Collins, Khudoley, Letnikova, & Huang, 2018). To the south of this zone, zircons with Tarim affinity with age peaks at 2.0 and 0.8 Ga or Kazakhstan affinity, peaks 1.6–1.3 and 0.9–0.7 Ga (Huang et al., 2016; Liu, Wang, Shu, Jahn, & Lizuka, 2014) prevail in the detrital sediments.

6.4 | Nd isotopic analyses

Neodymium isotopic geochemistry indicates that the source for the all studied magmatic bodies was the Late Precambrian juvenile continental crust, which is typical of granitic intrusions and sedimentary deposits of eastern and some parts of central Kazakhstan (Degtyarev, Shatagin, & Kovach, 2015; Kröner et al., 2008), Russian and Chinese Altai (Kruk, 2015; Tong et al., 2014), Xinjiang (Yin et al., 2013), and other CAOB areas (Jahn et al., 2000; Safonova, 2017).

The highest εNd value is obtained for the Middle Devonian volcanic rocks of the Bugotak Complex. This represents the oldest volcanic complex of the KTFZ, and its composition is inherited from the KTFZ basement through which it intruded.

The KTFZ detrital sediments have a more ancient mean crustal residence age and lower εNd values which indicate some contribution from a more ancient continental crustal material that could be delivered from the fold belts adjacent to the Siberian Craton, or from the microcontinents of the Altai–Sayan region. Individual grains of ancient zircons in the sediments support this assumption. T (DM) model ages of the Upper Devonian Yurga Formation and the Pennsylvanian–Lower Permian Balakhon Group are relatively juvenile and are about 1.1–1.0 Ga. Similar Nd whole-rock model ages are typical for the sedimentary, igneous, and metamorphic Early Palaeozoic rocks of the western part of the broader Altai–Sayan region and Kazakhstan (Jahn et al., 2000; Kruk, 2015; Plotnikov et al., 2003). Nd model ages of ~1.2 Ga were obtained for the Upper Devonian sandstones and shales of the Takyr Formation in the Rudny Altai folded system for example (Plotnikov et al., 2003). The Takyr Formation is therefore considered as an analogue facies for the Upper Devonian clastic sediments in the KTFZ. The Neoproterozoic whole-rock model age of the Early Palaeozoic magmatic source rocks is inherited by their associated Upper Palaeozoic sediments within the KTFZ. This also holds true for the Early Palaeozoic detrital zircons from these units. The obtained Nd isotope compositions confirm that their source province consists of the typical and widespread Early Palaeozoic "Caledonian" complexes. High values of the εNd (slightly negative) also show that the source regions were mainly composed of juvenile Palaeozoic magmatic complexes, rather than ancient blocks of continental crust. Late Palaeozoic granites intruded the Devonian–Carboniferous detrital deposits and the Nd isotopic composition apparently reflects a mixed composition between the signature of the lower crust of this block (similar to the volcanics of the Bugotak complex), and its overlying sedimentary sequence with the more ancient crustal residence ages.

6.5 | Tectonic implication for the geological history of the north-western part of the CAOB

Using the published data cited above regarding the geology of the region, the zircon U–Pb data and the Nd whole-rock geochronology data presented in this work, we propose the following model for the formation of the KTFZ.

1. KTFZ formation as a result of riftogenic processes on the margin of the Early Palaeozoic accretion belt framing the Siberian continent at the end of the Middle Devonian. Indicators of this process are volcanics of the Bugotak Complex.
2. The development KTFZ as a passive continental margin in the Late Devonian–Mississippian. Accumulation of detrital deposits (Pacha and Yurga formations and Inya Group) as a result of erosion of the Early Palaeozoic accretion belt, including Salair, Kuznetsk Alatau, and Altai (Figure 9a).
3. The collision stage in the Late Pennsylvanian–Permian. Carboniferous island arc, now covered by sediments of the West Siberian Basin, was accreted to the Siberian continent. This process led to the formation of the folded and thrust belt structure in the KTFZ, the appearance of the Gorlovo foreland basin (Figure 9b), and emplacement of the collision granitoids of the Priob Complex in the Late Permian.

Low content of ancient detrital zircons in the KTFZ sedimentary deposits as well as the high values εNd in the sedimentary and igneous rocks of the region indicate an insignificant role of the ancient continental crust material in the region as a whole. Individual ancient zircons in the sedimentary deposits of the KTFZ require additional investigation to determine their source.

7 | CONCLUSIONS

(1) Detrital zircon geochronology on the Upper Devonian to Lower Permian sedimentary sequences of the Kolyvan′–Tomsk folded zone and the Gorlovo foreland basin yields four ages peaks, reflecting the magmatic events in the source regions. There is a minor Neoproterozoic peak (0.9–0.7 Ga), a very significant Early Palaeozoic peak (550–460 Ma), and two well-expressed Late Palaeozoic peaks: that is, the Middle–Late Devonian 385–360 Ma and the Carboniferous–Early Permian 360–280 Ma. Zircon grains with ancient ages (>1 Ga) are quite rare in the studied sedimentary sequences. The main magmatic events that provided the source rocks for the KTFZ sediments correspond to the most significant magmatic stages in the development of the western part of the CAOB.

(2) The source province for the Upper Devonian deposits of the KTFZ was an Early Palaeozoic fold belt, which includes the Salair, and the Kuznetsk Alatau terranes and also seems to include some blocks from the basements of the Kuznetsk and south-western part of the West Siberian basins, now covered by thick Late Palaeozoic to Cenozoic deposits. This fold belt is composed mainly of Cambrian–earliest Ordovician juvenile island arc magmatic complexes and does not contain any significant Early Precambrian blocks. This Early Palaeozoic fold belt can be traced from the Kuznetsk Alatau and Salair area through the Russian Altai, all the way to the Chinese Gobi–Altai.

(3) The Bugotak volcanic complex in our study area was formed at the Givetian–Early Frasnian transition, at about 380 Ma. Middle–Late Devonian volcanic activity eventually led to the riftogenic opening of a marine basin.

(4) Deposits of the Gorlovo foreland basin accumulated as a result of erosion of the Carboniferous–Early Permian volcanic rocks that composed collisional fold-and-thrust belts and are now covered by the Meso–Cenozoic sedimentary units of the West Siberian Basin.

(5) Relatively young Nd model ages and high εNd (εNd(T) = −0.78, T (DM) ~1.1 Ga for Late Devonian sandstones, εNd(T) = −1.1, T (DM) ~1.1 Ga for Early Permian sandstones) suggest only a minor contribution of ancient continental crust in the main sedimentary units of the KTFZ. Devonian volcanics and Permain–Triassic granites show positive εNd and Late Precambrian model age: εNd(T) = 6.67–6.86, T (DM) = 581–649 Ma is measured for the Devonian volcanics and εNd(T) = 3.78–6.06, T (DM) = 609–916 Ma for the Late Palaeozoic granites. The continental crust of the KTFZ is juvenile and apparently was formed during the accretion of arc complexes to the growing Siberian continent.

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SUPPORTING INFORMATION

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