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# *P–T–t* constraints on polymetamorphic complexes of the Yenisey Ridge, East Siberia: Implications for Neoproterozoic paleocontinental reconstructions

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Studies of pelitic gneisses and schists within the Yenisey regional shear zone (Garevka complex) at the western margin of the Siberian craton provide important constraints on the tectonothermal events and geodynamic processes in the Yenisey Ridge. *In situ* U–Th–Pb geochronology of monazite and xenotime from different growth zones of the garnet porphyroblasts coupled with *P–T* path calculations derived from garnet zoning patterns records three superimposed metamorphic event. The first stage occurred as a result of the Grenville-age orogeny during late Meso–early Neoproterozoic (1050–850 Ma) and was marked by low-pressure zoned metamorphism at *c.* 4.8–5.0 kbar and 565–580 °C with a metamorphic field gradient of $dT/dZ = 20–30$ °C/km. At the second stage, the rocks experienced middle Neoproterozoic (801–793 Ma) collision-related medium-pressure metamorphism at *c.* 7.7–7.9 kbar and 630 °C with $dT/dZ < 10$ °C/km. The final stage evolved as a synexhumation retrograde metamorphism (785–776 Ma) at *c.* 4.8–5.4 kbar and 500 °C with $dT/dZ < 14$ °C/km and recorded uplift of the rocks to upper crustal levels in shear zones. The duration of post-collisional thrust exhumation does not exceed 16 Myr, which gives an exhumation rate of the metamorphic rocks of about 500–700 m/Myr. This is in good agreement with the rate of exhumation (400 m/Myr) calculated for coeval collision-related metamorphic events in the Teya complex of the Yenisey Ridge resulted from crustal thickening due to overthrusting and also agrees with the results of thermomechanical numerical modeling (350 m/Myr). Post-Grenville metamorphic episodes of regional crust evolution are correlated with the synchronous succession and similar style of the later tectonometamorphic events within the Valhalla orogen along the Arctic margin of Rodinia and supports the spatial proximity of Siberia and North Atlantic cratons (Laurentia, Baltica, Svalbard) at *c.*800 Ma, as indicated by the Neoproterozoic paleocontinental reconstructions of the Rodinia configuration.



## 1. Introduction

The Yenisey Ridge fold-and-thrust belt at the western margin of the Siberian Craton is one of the most geodynamically interesting regions of Siberia. This belt forms part of the Central Asian Orogenic Belt (CAOB) and is a key to understanding the Precambrian tectonic evolution of the Siberian craton and crustal growth in the CAOB. It is one of the few regions of Siberia where Paleoproterozoic, Mesoproterozoic, and Neoproterozoic magmatic and metamorphic rocks are closely associated. Understanding the tectonic evolution of the Siberian cratonal margins is important for global paleotectonic reconstructions and for decyphering the complicated tectonic structure of Central Asia. Studies of the structure and tectonic history of Meso–Neoproterozoic continental margins of Siberia are crucial for solving the problem of the possible incorporation of the Siberian craton into the Rodinia supercontinent and its subsequent breakup with the opening of the Paleoasian ocean, an issue widely debated for more than 20 years (e.g., Pisarevsky et al., 2008 and references therein).

Most existing reconstructions suggest that the Rodinia supercontinent have been produced by the Grenville orogeny at the Meso–Neoproterozoic boundary and that major collisional events that led to the tectonic stabilization of Rodinia may have occurred between 1000 and 900 Ma (Bogdanova et al., 2009). Coeval events are recognized under different names within different continents

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and the Grenville orogen itself can be considered a tectonotype. Evidence for a *c*. 850 Ma collisional orogenesis reported from separate lithospheric blocks was used to constrain the timing of the Grenvillian orogeny to the range of 1200–850 Ma, which is consistent with the relatively stable existence of the supercontinent Rodinia (Yu et al., 2008). This interval of the Earth's tectonic evolution is characterized by very low endogenic activity induced by changes in mantle convection and plume activity (Maruyama et al., 2007). In many of the previous models that rely on these concepts, the Yenisey Ridge is interpreted to have formed after 0.75 Ga (e.g., Vernikovsky et al., 2009) as a result of the step-wise accretion of terranes to the western margin of the Siberian Craton. On the basis of this assumption, several recent studies suggested the absence of the Mesoproterozoic and, in particular, Grenvillian collisional events within the Yenisey Ridge until 750 Ma (Vernikovsky et al., 2011), and this gave rise to contradictory interpretations of the main geological problems of the region (Likhanov et al., 2014).

Our recent U–Pb SHRIMP II and $^{40}Ar/^{39}Ar$ ages support earlier episodes of endogenic activity within the Transangarian Yenisey Ridge (Popov et al., 2010; Likhanov et al., 2011a,b,c, 2012a,b,c, 2014; Kozlov et al., 2012; Likhanov and Reverdatto, 2014a). These data also provide evidence for a temporal link between metamorphism and granite plutonism in the region and the Grenville orogeny (Nozhkin et al., 2011, 2013) and generally agree with a supposed lull in magmatic activity between 1.7 and 1.1 Ga followed by the major peak during the Late Proterozoic (Dobretsov, 2010). In the context of the Precambrian supercontintent reconstructions, this 1.1–0.7 Ga period of time corresponds to Rodinia's assembly and fragmentation. New evidence for Meso–Neoproterozoic events on the western margins of Siberia may provide a basis for resolving the controversy concerning the geodynamic nature of this orogen and constructing a consistent geodynamic model of the Yenisey Ridge.

The aim of this study is to unravel *P–T–t* constraints on the development of the polymetamorphic complexes to obtain information on tectonic processes operating within the Yenisey Ridge during the late Proterozoic and correlate them to a succession of global events that played an important role in the evolution of Rodinia.

## 2. Geological background

### *2.1. Overview of regional setting*

The Yenisey Ridge is a complex Precambrian fold-and-thrust belt situated at the western margin of the Siberian craton, where it strikes for 700 km northwestwards along the Yenisey River (Fig. 1a). Geophysical data indicate transpression and vertical crustal thickening while the width of the folded area of the Yenisey Ridge is halved at a depth of >10 km. The Moho deepens to 40–50 km beneath the ridge compared to the adjacent regions. Therefore, this orogeny is characterized by structurally thickened crust preserved for a long period of time (Vernikovsky et al., 2011). The regional structural framework of the Yenisey Ridge has traditionally been interpreted as a system of NW–SE oriented crustal tectonic units characterized by large-scale isoclinal folds dipping to the NE and accompanied by regionally developed schistosities. The thrusts follow the general structural trend of the Yenisey Ridge. According to structural and seismic data (Sal'nikov, 2009), the thrust systems generally are W-vergent thrusts dipping 40–60° to the NE. The NW-trending structures of the Yenisey Ridge are divided into two segments, separated by the ENE-trending strike-slip Nizhneangara Fault. Two allochthonous units have been recognized south of the Nizhneangara Fault (Fig. 1), the Paleoproterozoic granulite–amphibolite facies Angara-Kan craton block and the Neoproterozoic, mainly island arc Predivinsk terrane, which lies along the eastern bank of the Yenisey River. North of the Nizhneangara Fault, the Yenisey Ridge is composed mainly of west-verging thrust sheets that contain Meso–Neoproterozoic rocks, including the East and Central continental margin blocks, and the Isakov island arc terrane. All the tectonic blocks and terranes represent crustal segments 300–500 km long and 50–80 km wide (Fig. 1), which are separated by the largest known thrust faults in the region (Kheraskova et al., 2009). A series of higher-order splay faults suggest a dip slip displacement forming thrust faults (Egorov, 2004). These processes brought about a regionally heterogeneous pressure field of metamorphism and, consequently, a combination of two facies series: andalusite–sillimanite (low-pressure) and kyanite–sillimanite (medium-pressure) (Likhanov et al., 2001a, 2006, 2008b; Likhanov and Reverdatto, 2014b). Collision-related medium-pressure metamorphism that locally overprints the low-pressure metamorphic rocks is thought to be younger (Likhanov and Reverdatto, 2011b, 2013).

The study area includes the Garevka (GC) and the Teya (TC) metamorphic complexes. The GC comprises the oldest rocks in the Transangarian Yenisey Ridge and is located within the Yenisey regional shear zone (YRSZ), a large lineament represented by deformation and metamorphic structures, which separates the Central cratonic block and the Isakov island arc terrane (Fig. 1). This shear zone forms an extension of the Baikal-Yenisey fault within the right bank of the Yeniey River and is be traced for about 200 km along the western flank of the Yenisey Ridge. In the western part of the Central block, the GC is succeeded by the TC, so that the Garevka Sequence is overlain by the lower Proterozoic Teya Group. Tectonically, the TC is located within the axial part of the Central block, which is bound by a set of extensive faults along the Tatarka-Ishimba suture zone. These rocks display prominent blastomylonitic fabrics produced by brittle and ductile deformation along faults (Kozlov et al., 2012).

### *2.2. Geology of the study area: petrography and textural observations*

#### *2.2.1. Garevka complex*

The GC comprises plagiogneiss, granite-gneiss, schist as well as widespread migmatites and subordinate amphibolite and metaterrigenous-carbonate rocks (quartzite, calciphyre, marble) (Kozlov et al., 2012). Metapelite samples used in this study were collected within the GC in the lower course of the Tis (sample 58–59° 36′ 21.9 N, 91° 09′ 42.99 E) and Garevka rivers (sample 27–59° 51′ 10.5 N, 90° 49′ 36 E) and from outcrops on the right bank of the Yenisey River (sample 56–59° 16′ 48.5 N, 91° 20′ 29.2 E) (Fig. 2). The metapelitic rocks of the study area are intensely deformed, migmatitic Grt + Bt + Ms + Pl + Qz ± St ± Ilm ± Ky ± Chl ± Ep gneisses and schists crosscut by steeply-dipping, sheeted, coarse-grained felsic dykes (Likhanov et al., 2013a,c). Mineral abbreviations through the text, including those in the figures and tables, are after Whitney and Evans (2010).

The characteristic features of blastomylonites from the GC are linear gneissosity, ordered structures of cataclastic and ductile flow, extension and en-echelon flow folding and faulting, kink bands in mica, strain shadows in recrystallized quartz, S-shaped fabric in garnets with snowball textures, disruption of mineral grains by cracks with the development of ribbon structure, parallelism in the distribution of fine-grained lenticularmineral aggregates, as well as foliation, cataclastic deformation and boudinage. The blastomylonite zones are dominated by dextral shear, although sinistral shear displacement is also present (60% and 40%, respectively). Blastomylonites are bounded laterally by detachment and shear planes and the scalloped fringe patterns are seen along strike. All these structures of the YRSZ blastomylonite complexes are generally typical of tectonites from regional