

The age of the North Asian Cratonic basement: An overview

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Abstract

The North Asian Craton is the largest Precambrian continental fragment in the present-day geologic mosaic of Asia. It includes a basement comprising an ancient platform surrounded by orogenic belts and is largely overlain by Late Precambrian, Paleozoic, and Mesozoic sedimentary cover rocks. Recently, a large number (~400) of isotopic dates from metamorphic rocks have been generated and this paper summarizes these data together with new geological information on the composition and age of the metamorphic terranes comprising the basement. An evolutionary model of the North Asian Craton is presented which shows that the basement is composed of Archean (55.0%), undifferentiated Archean and Paleoproterozoic (13.0%), Paleoproterozoic (20.0%) and Mesoproterozoic (12.0%) terranes. A consistent eastward and southward younging of terranes is observed from the Neoproterozoic Tunguska and West Aldan terranes, suggesting that crust-forming processes were most extensive in the Neoproterozoic. The basement of the Verkhoyansk fold-and-thrust Belt is composed of Mesoproterozoic crystalline complexes with a metamorphic age of 1.0 to 0.9 Ga.

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1. Introduction

The North Asian Craton is the largest Precambrian continental fragment comprising the present-day Asia and is largely covered by Late Precambrian, Paleozoic, and Mesozoic sedimentary rocks of the Siberian Platform (Fig. 1). Along its edges are the Verkhoyansk, Baikal-Patom and Southern Taymir fold-and-thrust belts and the Near Sayan, Akitkan and Olenek uplifts (Nokleberg et al., 2003). The fold-and-thrust belts are separated from the platform by frontal thrusts. Windows of the basement underlying the Siberian Platform comprise the Aldan–Stanovoy and Anabar shields.

The basement of the North Asian Craton represents a collage of terranes composed mainly of granulite and amphibolite facies metamorphic rocks (Rosen et al., 1994; Smelov et al., 1998). Although a large body of research has been undertaken, many of the key problems concerning geology and petrology of Precambrian metamorphic and magmatic rocks of the basement have remained unresolved. The main reason for this situation

was that until recently, no reliable geochronological and isotope-geochemical data were available. However, over 400 isotopic age determinations have recently obtained by a variety of methods (Kovach et al., 1995a,b; Smelov et al., 1998; Kovach et al., 2000; Rosen, 2002; etc.). These data have allowed refined tectonic models for the basement evolution to be developed (Rosen et al., 1994; Frost et al., 1998) and models for the position of the North Asian Craton within proposed Precambrian supercontinents can now be tested with better precision. These issues have been addressed within the project “Mineral Resources, Metallogensis, and Tectonics of North-east Asia” (Nokleberg et al., 2003). In this paper the new data from Russia are used to construct an internally consistent model for the geodynamic evolution of the basement to the North Asian Craton.

2. Methods

The authors employ the technique of terrane analysis as proposed by Coney et al. (1980). Terrane analysis requires the following steps: (1) the recognition of terranes, their overlap units (sedimentary and volcanic-sedimentary) and “stitching”

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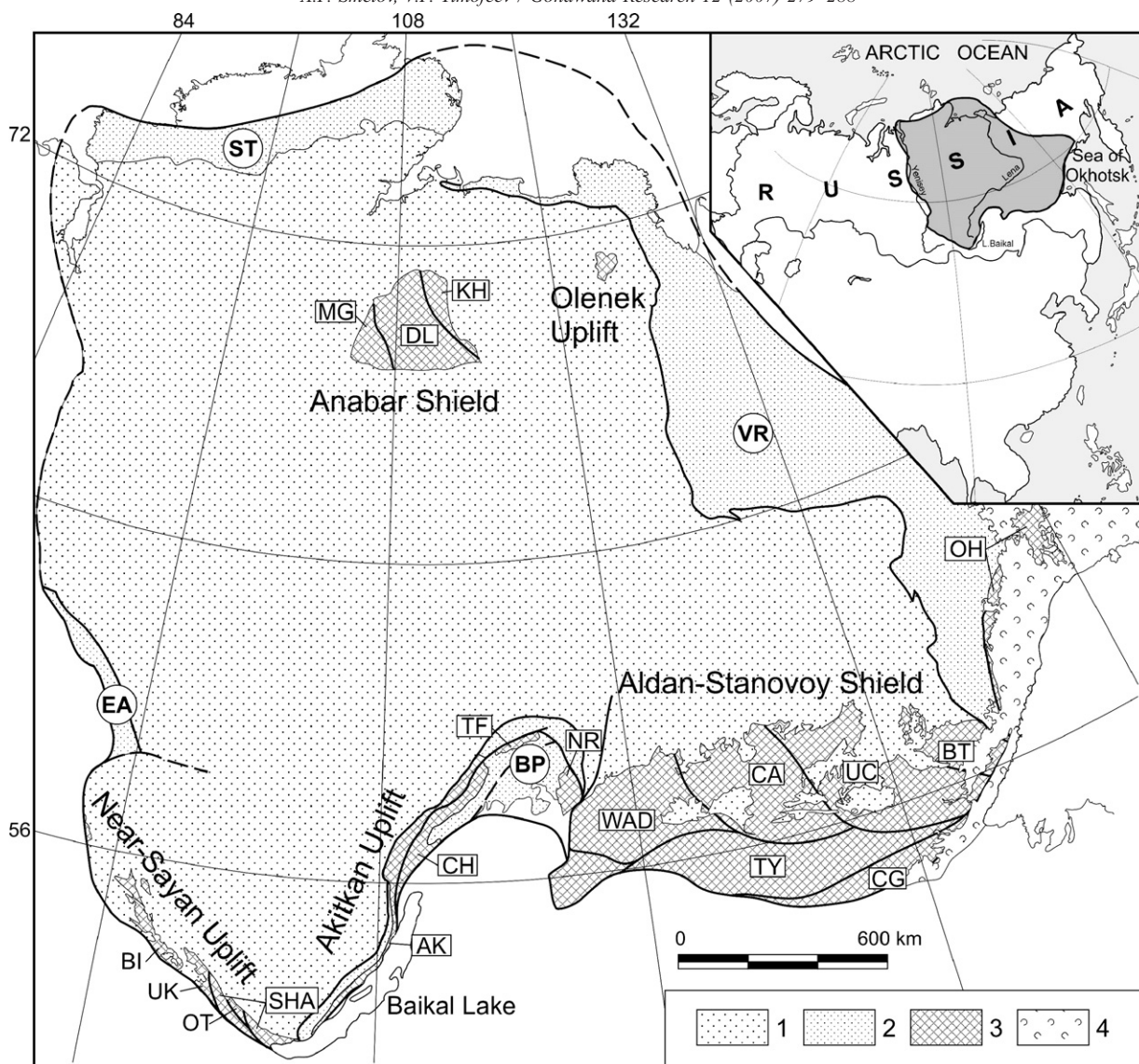


Fig. 1. Tectonic scheme of the North Asian Craton. 1 — ancient platform, 2 — subsided craton margin-fold-and-thrust belt (ST=South Taimyr, EA=East Angara, BP=Baikal-Patom, VR=Verkhoyansk), 3 — shields and uplifts (Precambrian terranes are coded: West Aldan (WAD), Central Aldan (CA), Uchur (UC), Batomga (BT), Chogar (CG), Tynda (TY), Daldyn (DL), Khapchan (KH), Magan (MG), Akitkan (AK), Chuja (CH), Nechera (NR), Tonod (TF), Sharizhlgay (SHA), Onot (OT), Urik-Lay (UK), Biryusa (BI)), 4 — Mesozoic volcano-plutonic belt. Inset shows location of the region.

assemblages (magmatic and metamorphic); (2) the definition of terrane boundaries and types (thrust, strike-slip, or normal fault); (3) the genetic classification of terranes and their overlap and “stitching” assemblages on an actualistic basis (e.g. island-arc formations, accretionary wedge complexes, active and passive continental margin sequences, fragments of oceanic crust, etc., and magmatic formations related to rifting, collision, subduction, and other processes); (4) the recognition and classification of post-accretionary faults formed after accretion of the terranes to a continental margin and of tectonic displacements responsible for dismembering and dispersion of terranes; and (5) the analysis of paleobiogeographic and paleomagnetic data that clarify the signature of the terranes and help to identify their origin (Parfenov et al., 1998).

Early Precambrian structures preserved in the basement of cratons and exposed in windows or shield nuclei (Fig. 1),

represent a mosaic of blocks up to hundreds of kilometers across that are separated and surrounded by linear folded belts metamorphosed to varying degrees, in some cases up to granulite facies. For the purposes of this analysis we consider that the terranes comprising Early Precambrian cratons should be defined and described in the same way as is in Phanerozoic orogenic belts. They are typically linear fault-bounded tectonic units, tens to a few hundreds of kilometers across with contrasting geologic histories that can be classified on the basis of their rock composition, such as granite–greenstone, granulite–orthogneiss, tonalite–trondhjemite gneiss, granulite–paragneiss, paragneiss, etc. The terranes are separated by faults zones or tectonic mélange zones (collisional sutures). Within these mélange zones slivers of rocks from adjacent terranes and high-pressure granulites from the lower crust levels may be tectonically juxtaposed. All these rocks may have undergone

repeated tectonism and metamorphism and when anorthosites are present they are normally restricted to these mélange zones (Rosen et al., 1994; Smelov et al., 1998).

The main stages in the formation of the Precambrian continental crust and specific isotopic features of the North Asian Craton have been determined from U–Pb zircon ages from critical intrusive magmatic complexes and from Sm–Nd isotope systematics of calc-alkaline granitoid, metasedimentary and metavolcanic rocks (Kovach et al., 2000). The U–Pb zircon ages not only provide information about the time of intrusion but also, in many cases, about the duration of endogenic processes including metamorphism. Nd isotopic compositions may also provide information about the age and composition of the continental crust from which the calc-alkaline granitoid and metavolcanic rocks were ultimately derived from depleted mantle (DM) sources. The percentage of rocks of different ages in some terranes have been determined on the basis of geological maps and sections, and the temporal growth of the crust was estimated from the total area of terranes of different ages with coeval terranes combined into domains.

3. Composition and age of the basement

The metamorphic basement of the North Asian Craton is exposed in the Aldan–Stanovoy and Anabar shields and the Near Sayan, Akitkan and Olenek uplifts, where there are several terranes composed of Early Precambrian crystalline rocks of varying composition and structural style.

3.1. Aldan–Stanovoy Shield

Within the Aldan–Stanovoy Shield, five large terranes are recognized with each, composed of a series of smaller terranes and separated from one another by tectonic mélange zones and faults: they comprise the West Aldan granite–greenstone composite terrane, the Central Aldan and the East Aldan superterrane, the Tynda Tonalite–trondhjemite gneiss Composite Terrane and the Chogar Granulite–orthogneiss Terrane (Fig. 1).

The *West Aldan Composite Terrane (WAD)* consists of several terranes composed of Archean greenstones and orthogneisses of tonalite–trondhjemite composition. The orthogneisses predominate and can be combined into the Olekma Complex. The gneisses form several large linear blocks and are separated by four longitudinal belts each about 300 km long and 30 km wide containing tectonic greenstone slabs known as the Subgan Complex. The protolith age of the tonalite–trondhjemite gneisses is ~3.0 to ~2.7 Ga (Nutman et al., 1992; Dobretsov et al., 1997) whilst orthogneisses older than ~3.0 Ga are also found. Prograde metamorphism of the rocks reaches high-temperature amphibolite facies at moderate pressure, while rocks of low-grade amphibolite facies are less common (Smelov, 1989). Various greenstone belts of the Subgan Complex contain different rock assemblages and differ in metamorphic grade. The time spans for the formation of sedimentary and volcanogenic rocks of the greenstone belts are ~3.2 to ~3.0 and ~3.0 to ~2.7 Ga respectively (Nutman et al., 1992; Smelov and Beryozkin, 1997). The granulites form

relatively thin tectonic slabs thrust over tonalite–trondhjemite rocks and greenstone complexes, and they consist mainly of enderbite– and charnockite–gneisses and paragneisses including amphibole– and pyroxene-bearing gneisses and schists, and garnet–biotite gneisses. Age data for the granulites are scarce but protoliths of the garnet–biotite gneisses were derived from rocks with a Nd model age of ~3.5 Ga (Kovach et al., 1995a) whilst protoliths of two-pyroxene crystalline schists were formed at ~3.15 Ga (Levchenkov et al., 1987). The upper age limit of metamorphism of all complexes is constrained by the emplacement of the Charodakan Granite Complex at ~2.6 Ga (Smelov and Beryozkin, 1997). Paleoproterozoic metasedimentary rocks of the Udokan and Uguy series overlie various Archean rocks unconformably. U–Pb ages of ~2.18 Ga have been obtained from volcanogenic zircons from metagraywacke and tuffaceous sandstone of the Udokan series (Berezhnaya et al., 1988). The metasedimentary rocks are intruded by granite of the Kodar Complex dated between ~1.9 and ~1.8 Ga (Rublev et al., 1981).

The *Central Aldan Superterrane (CA)* consisting of the Nimnir and Sutam terranes.

- (1) The Nimnir Granulite–orthogneiss Terrane is composed of domes of granite–gneiss. The cores of the domes are granite-, charnockite– and enderbite–orthogneisses and comprise more than 50% of the terrane. Orthogneisses with Nd model ages of ~2.5 to ~2.3 Ga contain xenoliths of granite–gneisses and tonalite–trondhjemite gneisses older than ~3.35 Ga (Nutman et al., 1992). The external parts of the domes are composed of a paragneiss complex consisting of the Kurumkan and Fedorov Groups. The Kurumkan Group includes quartzite and high-alumina gneisses (Dook et al., 1986). The high-alumina gneisses are similar in chemical composition to pelite and siltstone and are interlayered with biotite–hypersthene plagiogneisses, chemically similar to greywacke. Sm–Nd isotopic data show that protoliths of the former formed from rocks of ~3.06 to ~2.85 Ga in age, while those of the latter were derived from younger rocks ~2.4 to ~2.33 Ga in age (Kovach et al., 1995b). Thus, the Kurumkan Group is no older than ~2.3 Ga. The Fedorov Group includes amphibole, diopside–amphibole, and two pyroxene–amphibole plagiogneisses, corresponding to andesite, andesite–basalt and basalt in composition. Rocks of the Fedorov Group resulted from metamorphism of protoliths with Nd model ages of ~2.3 to ~2.0 Ga (Kovach et al., 1995a).
- (2) The Sutam Granulite–paragneiss Terrane is composed of 60% paragneisses of the Seim Group and 40% granite– and enderbite–gneisses. The Seim Group consists of 80% garnet–biotite gneisses and plagiogneisses, including hypersthene–biotite, two-pyroxene, and diopside–amphibole plagiogneisses. The remaining 20% of the group comprises two-pyroxene, two-pyroxene–amphibolite, and rarely olivine–two-pyroxene crystalline schists and magnetite quartzite (Khil'tova et al., 1988). Sm/Nd data indicate that the protolith of the paragneisses is between

~2.9 and ~2.5 Ga in age, whereas the orthogneisses are as old as ~3.0 Ga (U/Pb zircon ages, Kovach et al., 1995b). All lithologies were metamorphosed after ~2.5 Ga.

The East Aldan Superterrane including the Uchur Granulite–paragneiss Terrane and the Batomga Granite–greenstone Composite Terrane.

- (1) The Uchur Granulite–paragneiss Terrane (UC) is intruded by granite–gneiss domes with cores of granite–, charnockite– and enderbite–gneisses. The paragneisses are of two assemblages comprising: (i) garnet–biotite plagiogneisses interlayered with calc–silicate rocks, quartzite, sillimanite– and cordierite-bearing gneisses, and hypersthene–, diopside–, and two-pyroxene–plagiogneisses, and (ii) hypersthene–, hypersthene–diopside–, and hypersthene–diopside–amphibole–plagiogneisses. Sm–Nd data indicate that the paragneiss protoliths are between ~2.6 and ~2.1 Ga in age and that the metamorphism occurred after ~2.1 Ga. The high-temperature metamorphism is estimated to have finished between ~2.0 and ~1.8 Ga from U–Pb ages on zircon from charnockites of the intrusive Emelyali Pluton (Glukhovskiy et al., 1993).
- (2) The Batomga Granite–greenstone Composite Terrane (BT) is a basement uplift located at the northeastern margin of the Aldan–Stanovoy Shield and is dominated by tonalite–trondhjemite orthogneisses (Batomga Complex) incorporating thin bodies of basic schists. Granite gneisses and granites are also present. Metamorphism is generally to amphibolite facies but the basic rocks locally contain paragneisses with granulite facies mineral paragneisses (Fed'kin et al., 1996). Rocks of the Batomga Complex make up five terranes separated by four blastomylonite zones containing tectonic wedges of volcano-sedimentary rocks (Chumikan Complex) interpreted as greenstones (Petrov, 1990). The Chumikan Complex consists of biotite dominant, two-mica–microgneisses, meta-sandstone, quartzite, and marble as well as fine-grained amphibole schists and amphibolites interpreted to be metamorphosed tholeiitic basalts. Until recently, the Batomga Composite terrane was regarded as an analog of Archean granite–greenstone terranes although reliable age determinations were unavailable to confirm this (Rosen et al., 1994). More recently, A. B. Kotov and V. P. Kovach (personal communication) measured Nd model ages of ~2.4 to ~2.1 Ga from samples of the Batomga Composite terrane, showing them to be Proterozoic in age.

Volcano-sedimentary rocks of the Ulkan Series overlie rocks of the Batomga and the Uchur terranes as well as the Ulkan Fault that separates them. Analyses of zircons separated from rhyolite in the Ulkan Series have yielded ages of ~1.8 to ~1.7 Ga and ages of ~1.72 to ~1.7 Ga have been determined from zircons from intrusive granite and hornblende–syenite (Neymark et al., 1992).

The Tynda Tonalite–trondhjemite Composite Terrane (TY) is made up mostly of various Archean rocks. These may be classified into two complexes namely the Stanovoy Complex (amphibolite facies) and the Larba Complex (granulite facies). The Stanovoy Complex includes diorite–tonalite–trondhjemite gneisses, metabasite, and paragneisses (metagraywacke and metapelite) (Godzevich, 1986). Zircon analyses from the tonalite–trondhjemite gneisses yield U–Pb ages of 2941 ± 80 and 2785 ± 5 Ma (Nutman et al., 1992; Mironyuk et al., 1996) whilst analyses of the rims of these zircon grains and zircon from metabasite dikes yield U–Pb ages of ~1.9 Ga (Nutman et al., 1992).

The Larba Complex forms relatively small tectonic slabs bounded by faults (Rosen et al., 1994). Tectonic wedges of metamorphosed volcanic and volcano-sedimentary rocks (Gilyui Complex) have recently been mapped within the fault zone and interpreted as fragments of greenstone belts (Korsakov, 2000). Lithologies within the Larba Complex include enderbitic and amphibole–biotite gneisses, ultrabasic schists interbedded with pyroxene gneisses and kinzigites, calc–silicate rocks, and quartzite (Kastyrkina, 1983). U–Pb analyses of zircons from within garnets of the granite–sillimanite–cordierite gneisses yield an age of 2585 ± 20 Ma interpreted by Bibikova et al. (1986) to be the age of granulite metamorphism. Rosen et al. (1994), however, were unable to exclude the possibility that the zircons were derived from source rocks partially melted to form the protoliths of the paragneisses. The Gilyui Complex is characterized by a predominance of hornblende and biotite–hornblende schists and amphibolite at the base of the section, and biotite and hornblende gneisses at the top of the section. Numerous concordant diorite and granodiorite bodies intrude the complex. Pb–Pb analyses of zircons from amphibolites, biotite–hornblende schists, and biotite gneisses indicate ages of ~2.1 Ga whilst the dioritic gneisses are dated ~1.94 Ga (Korsakov, 2000).

The Chogar Granulite–orthogneiss Terrane (CG). This is exposed on the southeastern margin of the Aldan–Stanovoy Shield and is approximately 500×100 km in size. It comprises two blocks roughly equal in area and separated by a northeasterly striking fault. The eastern block consists of hornblende–two-pyroxene and garnet–hornblende–two-pyroxene schists and, locally, of ultrabasic schists; amphibolites and quartzites (including Fe-rich) are also present. In the upper section, aluminous gneisses, quartzite, and garnet granulites occur. K–Ar data indicate that the terrane is composed mainly of Archean rocks (Karsakov, 1983). The western block is characterized by a wide distribution of the rocks metamorphosed at high-pressure amphibolite facies. The dominant rocks are diorite–gneisses with lenses and bands of amphibole schists; quartzite and aluminous gneisses are subordinate.

3.2. Anabar Shield

The Anabar Shield includes three terranes, Magan, Daldyn and Khapchan, differing in composition and structure (Fig. 1): (Lutz and Oxman, 1990; Rosen et al., 1994).

The Magan Tonalite–trondhjemite Gneiss Terrane (MG) consists mainly of granulite facies, homogeneous biotite and biotite–amphibole orthogneiss, derived from tonalite, granodiorite and granite with lesser amounts of garnet-bearing, highly aluminous gneisses and carbonate rocks. The average Sm–Nd model age for basement rocks of the Magan terrane is ~ 2.94 Ga (Rosen and Fedorovsky, 2001).

The Daldyn Granulite–orthogneiss Terrane (DL) is mainly composed of enderbite gneisses, charnockitic gneisses and basic crystalline schists with subsidiary quartzite and carbonate rocks. Two-pyroxene and hypersthene basic schists in combination with enderbite (the enderbite–schist unit) form two bands in the central part of the terrane and are thought to have originated from the metamorphism of tholeiitic basalts. The igneous rocks of the terrane are divided into three geochemical series: calc–alkaline, alkaline, and subalkaline and are compatible with an island arc assemblage (Rosen et al., 1994). The structure of the terrane is defined by linear northwest-trending folds verging to the west and southwest and exhibiting steeply dipping hinges and axial surfaces. Analyses of zircons from the enderbite yield U–Pb an age of 3.2 ± 0.32 Ga. Analyses of granulites yielding a Sm–Nd isochron age of 3.1 ± 0.8 Ga (Rosen et al., 1994).

The Khapchan Granulite–paragneiss Terrane (KH) is composed mainly of paragneisses of the Khapchan Group: garnet–paragneisses and marble, calciphyres, calc–silicate rocks (Rosen et al., 1994). The chemical compositions of the Khapchan Group paragneisses suggest that they were derived from sediments similar in composition to greywacke (garnet gneiss), limestone and dolomite (marble), and marl (calc–silicate rocks). Subsidiary enderbites and schists are also present and the rocks in the central and southern parts of the terrane are deformed into tight linear folds. Nd isotopic data and Sm/Nd ratios for rocks of the Khapchan Group yield model ages of ~ 2.44 to ~ 2.32 Ga (Rosen and Fedorovsky, 2001).

3.3. Olenek uplift

Basement rocks exposed in the Olenek Uplift are overlain by the flat-lying Riphean sequence of the Siberian Platform (Fig. 1). They are referred to the Aekit Series and include metasandstone, metasiltstone, metapelite, and metavolcanic rocks. Metamorphosed rhyolite and dacite are found at the bottom of the section and comprise up to 10% by volume. Chemical analyses of metavolcanic rocks suggest a derivation from basalts and basaltic andesite. The metamorphic grade ranges from prehnite–pumpellyite to greenschist facies, and primary sedimentary structures such as bedding, rhythmic alternations and ripples are well preserved (Shpount et al., 1979). The Aekit Series is deformed into linear isoclinal folds and intruded by dikes of acid and intermediate composition, potassic granite stocks, and gabbro, diorite and granodiorite plutons. Muscovites from the granites have been dated by the K–Ar method at ~ 2.0 to ~ 1.95 Ga and biotites at 2.08 to ~ 1.85 Ga (Vishnevskiy and Krasil'nikov, 1963) and these ages may record the time of uplift.

3.4. Near-Sayan Uplift

The Near-Sayan Uplift is located to the west of Lake Baikal and four terranes, namely the Sharizhalgay, Onot, Urik-Lay and Biryusa, have been identified within it (Fig. 1).

The Sharizhalgay Granulite–orthogneiss Terrane (SHA) is over 300 km long and up to 50 km wide and consists of several large blocks. It is composed of amphibolite to granulite facies rocks comprising biotite–hornblende, hornblende–pyroxene, and two-pyroxene gneisses with subsidiary schists and amphibolites containing bands and interlayers of biotite–garnet and biotite–garnet–sillimanite gneisses, marbles and calciphyres. Metamorphosed peridotite, pyroxenite, gabbro and volcanic rocks, which are chemically similar to an ophiolitic suite, occur in the western part of the terrane. The rocks of this terrane have had a long and complex history and syncollisional, granite dated ~ 2.5 Ga has been identified (Gladkochub et al., 2005). U–Pb, Rb–Sr and Sm–Nd ages range from ~ 2.42 and ~ 2.27 Ga for the protoliths of the granulites and charnockite, and from ~ 1.9 and ~ 1.8 Ga for the time of metamorphism (Aftalion et al., 1991).

The Onot Granite–greenstone Belt (OT) is a sub-terrane within the Sharizhalgay terrane consisting of high-alumina, tonalitic to trondhjemitic gneisses and tholeiitic amphibolite. U–Pb analyses of zircons from the tonalitic to trondhjemitic gneisses indicate an age of ~ 3.25 Ga. Metamorphosed volcano-sedimentary rocks from the Onot Terrane mostly comprise biotite and amphibole–biotite gneisses and amphibolites containing interlayers of talc–serpentine rocks, meta-graywackes, marbles, and quartzites (Bibikova et al., 1981).

The Urik-Lay Greenschist Terrane (UK) consists mainly of terrigenous sedimentary rocks of presumed Paleoproterozoic age. In the lower section, they comprise interbedded quartz sandstones and siltstones with thin lenses of black carbonaceous shale. Layered diabase, lava, and tuff–breccia occur in the middle section together with terrigenous sedimentary rocks. Immature oligomictic sandstone and graywacke predominate in the upper section. In the northwestern part of the terrane, these units are covered by basalt, andesite, rhyolite, tuff, and tuffaceous conglomerate; these rocks are intruded by the Sayan granite and unconformably overlain by the orogenic Ingashin Unit comprising unmetamorphosed conglomerate, gritstone, sandstone, and siltstone of presumed Neoproterozoic age (Nozhkin, 1999).

The Biryusa Paragneiss Terrane (BI) comprises the Khailamin and Alkhadir Units. The Khailamin unit consists of amphibolite to granulite facies, biotite and garnet–biotite gneisses, plagiogneiss, amphibolite and two-pyroxene and pyroxene–hornblende gneisses. Migmatites are also widely distributed and amphibolites derived from mafic metavolcanic rocks and charnockite occur locally. The lower part of the Alkhadir Unit consists of high-magnesia orthoamphibolite, possibly derived from komatiite, serpentine–chlorite and biotite–actinolite schists and overlain by marbles and high-alumina (mainly biotite–garnet) gneiss. A well-marked unconformity defined by stratigraphic, metamorphic and structural evidence occurs between the Khailamin and Alkhadir Units. Most researchers have interpreted the age of the Khailamin Unit

as Archean to Paleoproterozoic, and the age of the Alkhadir Unit as Paleoproterozoic to Neoproterozoic (?). All the above rocks are unconformably overlain by Neoproterozoic terrigenous-carbonate deposits (Karagas and Oselok units) and in the northeast by the Paleoproterozoic and Mesoproterozoic terrigenous-carbonate deposits, including Devonian volcanogenic and volcanic-sedimentary rocks. This terrane is intruded by biotite, two-mica and muscovite granites, and leucogranite of the Sayan Complex, and by Early Devonian biotite granite and granosyenite of subalkaline and alkaline geochemical signatures. The age of Sayan granite is interpreted to be Paleoproterozoic although no radiometric data are available to substantiate this.

3.5. Akitkan uplift

The Akitkan Uplift occurs along the western shore of the Lake Baikal (Fig. 1). A number of exposures of basement rocks of the North Asian Craton occur within it, mainly within the Baikal-Patom Fold-and-thrust Belt.

The Chuya Paragneiss Terrane (CH) is composed of hypersthene–diopside–plagioclase–amphibole schists largely metamorphosed to granulite facies, plus amphibolites and plagiogneisses with several layers of quartzite, marble, amphibolite, bedded bodies of gneissic plagiogranite and diorite gneiss metamorphosed to amphibolite facies. In the south, there is an extensive metamorphic complex of biotite and biotite–amphibole gneisses. Of minor significance are amphibole and amphibole–diopside gneisses metamorphosed to lower amphibolite facies, and schists containing varying proportions of cordierite, sillimanite, andalusite, muscovite, biotite, phlogopite and garnet. The oldest rocks are highly metamorphosed metavolcanics, quartzite, and carbonate rocks (Chuya and Sarma suites), as well as the Chuya granites. U–Pb zircon data from the granites indicate ages of ~ 2.07 to ~ 2.02 Ga whilst TNd (DM) ages range from ~ 2.4 to ~ 2.3 Ga and metamorphism occurred between ~ 2.0 and ~ 1.9 Ga ago (Neymark et al., 1998). These basement rocks are overlain by volcano-sedimentary complexes of the Akitkan Volcanic Belt.

The Akitkan Belt (AK) consists of the Paleoproterozoic Akitkan Series comprising weakly deformed subalkaline to intermediate, acid lavas and minor amounts of basalt porphyry, as well as subaerial sedimentary and volcanogenic rocks. The series includes also some volcanogenic rocks that can be subdivided into two groups comprising (i) trachyte, trachyandesite and dacite, together with porphyrite equivalents of these volcanics and tuffs together with some sedimentary rocks and tuffs and (ii) a trachyrhyolite and rhyolite association including a thick sequence of pyroclastic rocks. The volcanics are dated at 1620 ± 20 Ma by the Rb–Sr whole rock isochron method (Brandt et al., 1978). Subvolcanic and hypabyssal intrusions of diorite, granodiorite and granite are important and are comagmatic with the extrusive formations mentioned above, as well as with rapakivi-like granitoids dated 1690 ± 40 Ma by the Rb–Sr whole rock isochron method (Brandt et al., 1978) and 1800 ± 30 Ma from U–Pb zircon data (Bibikova et al., 1992). The volcanic rocks of the Akitkan belt yield ~ 1.87 to ~ 1.82 Ga

ages and have Paleoproterozoic Nd model ages ranging from ~ 2.5 to ~ 2.3 Ga (Kovach et al., 2000).

The basement rocks of the Tonod Greenschist Terrane (TF) are unconformably covered by the Riphean sediments of the Baikal-Patom Fold-and-thrust Belt. The succession begins with basal coarse clastic rocks overlain by metasandstones, metaaleurolites, phyllites and carbonaceous phyllites. The pre-granite greenschist facies metamorphism did not achieve precipitation of biotite although the syn-granite metamorphism reached high amphibolite facies and led to formation of migmatites at the contact of granite batholiths. A Pb–Pb isochron age of carbonaceous phyllites is ~ 2.46 Ga (Sharov et al., 1992). Granitoids occur over most of the terrane and are dated ~ 2.1 Ga from U–Pb zircon data (Bukharov et al., 1992).

The Nechera Granulite–paragneiss Terrane (NR) is part of a basement complex to the Riphean sediments of the Baikal-Patom Fold-and-thrust Belt. The lower part of the succession consists mainly of gneisses and crystalline schists with minor amounts of hypersthene, amphibole, and biotite, and of garnet enderbite and charnockite; these rocks experienced diaphthoresis under amphibolite facies conditions. They are concordantly overlain by biotite, garnet–biotite and amphibole–biotite plagiogneisses which include layers of crystalline limestone, calciphyre, and quartzite metamorphosed to greenschist and low amphibolite facies. They are intruded by granitoids of the Chuya–Nechera Complex from which U–Th–Pb zircon analyses yield ages of ~ 1.85 Ga (Ivanov et al., 1995) and U–Pb ages of ~ 2.11 Ga (Bukharov et al., 1992).

3.6. Terranes of the buried basement of the Siberian Platform

Information about the nature of the Tunguska, Tyung, Tyryn and Berehta terranes buried beneath the cover rocks of the Siberian Platform has been derived from petrological and isotopic-geochemical studies of basement xenoliths from different types of volcanics, and from intrusive rocks recovered from deep boreholes (Rosen et al., 1994; Kovach et al., 2000). The boundaries of the terranes can be delineated from aeromagnetic study (Fig. 2) because the tectonic mélange zones and the terrane-bounding faults generally form positive linear anomalies. The terranes themselves are characterized either by arcuate anomalies or by homogenous magnetic fields.

The Tunguska Tonalite–trondhjemite gneiss Terrane (TG) occurs in the western part of the North Asian Craton where aeromagnetic data allow for a more detailed delimitation of the terrane boundaries. On the other hand, petrographic information from borehole cores is scarce and only available for the Baikit anticline and the Malo-Botuobiya kimberlite field. The rocks of these latter two areas are biotite and amphibole plagiogneisses of tonalitic to trondhjemitic composition, granite, granitic gneisses and granodioritic gneisses. Nd model ages range from ~ 3.3 to ~ 2.6 Ga (Smelov et al., 1998; Kovach et al., 2000). The terrane is interpreted to be an extension of the Near-Sayan Uplift (Sharizhlgay and Onot terranes) in the western part of the Anabar Shield (Magan Terrane) (Rosen et al., 1994) and is likely to represent marginal parts of the Tunguska Archean Craton that underwent reworking during a Paleoproterozoic

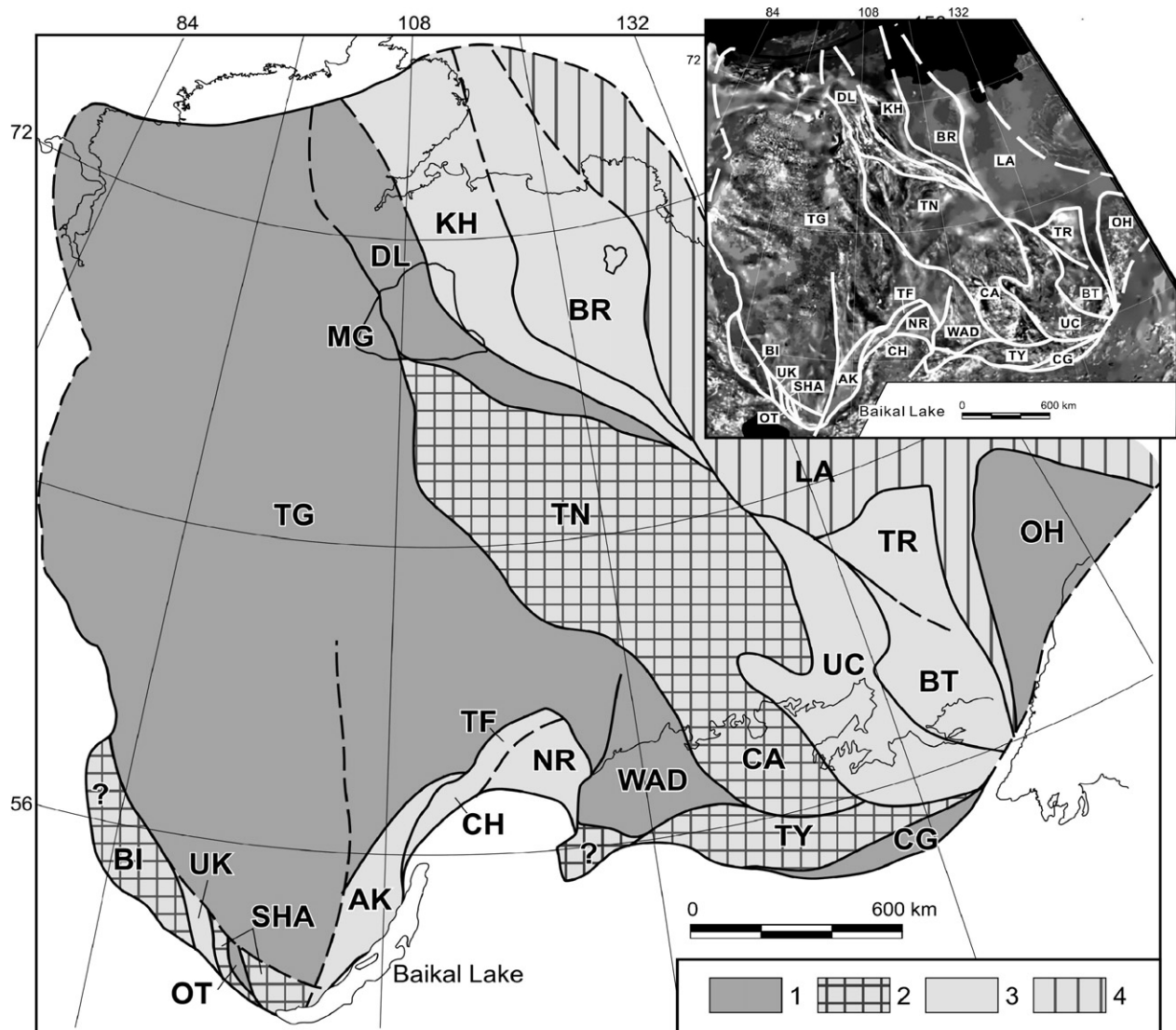


Fig. 2. Geological framework of the North Asian Craton and map of aeromagnetic anomalies and terrane boundaries (inset). 1 — Archean domain; 2 — Archean and Paleoproterozoic domain; 3 — Paleoproterozoic domain; 4 — Mesoproterozoic domain. Precambrian terranes are coded: West Aldan (WAD), Central Aldan (CA), Uchur (UC), Batomga (BT), Chogar (CG), Tynda (TY); Daldyn (DL), Khapchan (KH), Magan (MG); Akitkan (AK), Chuja (CH), Nechera (NR), Tonod (TF); Sharizhlgay (SHA), Onot (OT), Urik-Lay (UK), Biryusa (BL), Tunguska (TG), Tyung (TN), Berekta (BR), Tyryn (TR), Lena-Aldan (LA).

continental collision; it can thus be regarded as a part of the orogenic belts.

The *Tyung Terrane (TN)*, situated at the southeast margin of the North Asian Craton, is generally thought to be a fragment of an Archean craton (Rosen et al., 1994). However, Sm/Nd isotopic ages show that metamorphic rock xenoliths in the kimberlite pipes of this include two rock associations of granulite facies. The first comprises garnet–amphibole–clinopyroxene and amphibole schists with Tnd (DM) ages ranging from ~3.3 to ~2.9 Ga and the second is amphibole–two-pyroxene schist with a Nd model age of ~2.1 Ga. The latter value is fairly close to Tnd (DM) ages of ~2.5 Ga obtained from eclogitic xenoliths from the same kimberlitic pipe. The results of petrographic and geochemical studies reveal no differences in the metamorphic grade and degree of secondary alteration between the two rock associations. This suggests that the continental crust of the Tyung terrane formed in two stages

namely in the Archean (~3.3 to ~2.9 Ga) and in the Paleoproterozoic (~2.5 to ~2.1 Ga). The closing of Sm–Nd isotopic systems in minerals of garnet–clinopyroxene amphibolites of both age groups occurred at ~1.9 to ~1.7 Ga, suggesting a long cooling period of the lower crust following the granulite grade metamorphism, (Neymark et al., 1992).

The *Tyryn Terrane (TR)* is defined from geophysical data and may represent the northern part of the Batomga Terrane (BT) buried beneath the sedimentary cover of the Siberian Platform and the Verkhoyansk Fold-and-thrust Belt (Figs. 1 and 2).

The *Berekta Terrane (BR)* in the northeast part of the North Asian Craton is also defined from geophysical data although basement rocks are exposed in the arch of the Olenek Uplift, within the Sololi inlier. This terrane is overlain by flat-lying Riphean deposits of the Siberian Platform cover. The basement rocks are considered to belong to the Aekit Series (see discussion of the Olenek Uplift above) and are coeval with

the Udokan Series of the West Aldan Composite Terrane; both are interpreted as Archean gneiss complexes, an interpretation supported by the occurrence of xenoliths of amphibole leucocratic plagiogneisses with Nd model ages of ~3.3 Ga in the Obnazhonnaya kimberlitic pipe. However, these samples contain large $^{147}\text{Sm}/^{144}\text{Nd}$ ratios (0.1883), close to chondritic and depleted mantle values and the determination of model ages is impossible (Kovach et al., 2000).

3.7. Basement of the Verkhoyansk Fold-and-thrust Belt

The eastern margin of the North Asian Craton is overlain by sedimentary rocks of the Verkhoyansk Fold-and-thrust Belt (Fig. 1). The composition and age of the basement (Lena-Aldan Terrane) have been determined from studies of crystalline basement rocks sampled in deep borehole cores (Ivanovskaya in the lower Aldan River) and xenoliths in different granitoid masses (Bolshye porogi, the Kolyma River; Chimalga, and the Indigirka River) that intrude Phanerozoic sedimentary rocks of the Verkhoyansk Fold-and-thrust Belt. The Ivanovskaya borehole penetrated crystalline rocks, including biotite and biotite–muscovite micro-paragneisses, metasandstones, quartzite schists, garnet–amphibole schists, at a depth of 3386 to 3518 m below the base of the overlying Permian sequence. The crystalline rocks are metamorphosed to greenschist and lower amphibolite facies and TNd (DM) ages of the micro-paragneisses fall into two groups: ~2.5 to ~2.3 Ga and ~1.5 to ~1.0 Ga. The Nd data indicate that both Paleo- and Mesoproterozoic rocks were the source of detritus for these rocks. The xenoliths of biotite-two-feldspar banded gneisses and biotite schist in granitoid rocks were metamorphosed to amphibolite facies and this may reflect contact metamorphism with the surrounding granitoid magma. They are characterized by $^{147}\text{Sm}/^{144}\text{Nd}$ ratios of 0.1080 to 0.1206 and TNd (DM) ages of ~1.5 to ~1.3 Ga, suggesting a Mesoproterozoic age for source rocks from which the metasedimentary cover rocks were derived.

The existence of Mesoproterozoic metamorphic complexes in the basement of the Verkhoyansk Fold-and-thrust Belt is supported by (SHRIMP) U–Pb ages of ~1.5 to ~1.05 Ga from detrital zircons in the Middle–Upper Riphean sediments of the southern sector (Rainbird et al., 1998). The Lower Carboniferous conglomerates in the northern Verkhoyansk Fold-and-thrust Belt contain clasts of granite and two-mica schist boulders with K–Ar ages of ~1.4 to ~0.9 Ga (Bulgakova et al., 1969). The conglomerates are composed of clasts of granite, metamorphosed sandstones and quartzites, and are interpreted to have been formed in the littoral zone near to basement uplift at the front of the foldbelt.

4. Results

Analysis of recent isotope data from the basement rocks of the North Asian Craton (Table 1) in combination with the previous data (Rosen et al., 1994) allows for an improved understanding of the age structure of the craton and an age scheme for the basement of the North Asian Craton as shown in Fig. 2. The oldest Archean domain consists of the West Aldan,

Table 1

Age of rocks and metamorphism of terranes in the basement of the North Asian Craton

Terrane	Type of terrane	Age of rocks (Ga)	Age of metamorphism (Ga)
<i>Archean terranes</i>			
West-Aldan (WAD)	Granite–greenstone	3.0–3.3, <u>2.7–3.0</u> *	=3.0, <u>2.6–2.7</u>
Tunguska (TG)	Tonalite–trondhjemite gneiss	<u>3.2–2.6</u>	≈2.6
Daldyn (DL)	Granulite–orthogneiss	<u>3.1</u>	≈2.7(?), <u>1.8–1.9</u>
Chogar (CG)	Granulite–orthogneiss	<u>3.0–3.7</u>	?
Tynda (TY)	Tonalite–trondhjemite gneiss	<u>2.78–2.94</u> , <u>1.9–2.1</u>	2.58(?), <u>1.87</u>
Onot (OT)	Greenstone	<u>3.25</u>	
<i>Archean and Paleoproterozoic terranes</i>			
Central Aldan (CA)	Granulite–orthogneiss	>3.0, <u>2.1–2.5</u>	3.0(?), <u>1.9–2.0</u>
Tyung (TN)	Granulite–orthogneiss	2.9–3.0, <u>2.1–2.5</u>	<u>1.7–1.8</u>
Sharizhlagay (SHA)	Granulite–orthogneiss	<u>2.5–2.4</u>	2.5, <u>1.82–1.95</u>
<i>Paleoproterozoic terranes</i>			
Batomga (BT)	Granite–greenstone	<u>2.4–2.0</u>	>1.72
Berekta (BR)	Tonalite–trondhjemite gneiss	<u>3.3</u> (?), <u>2.2–2.0</u>	<u>1.85–1.97</u>
Khapchan (KH)	Granulite–paragneiss	<u>2.4</u>	1.97
Uchur (UC)	Granulite–paragneiss	<u>2.1–2.6</u>	1.8–2.0
Akitkan (AC)	Greenschist	<u>2.0–2.4</u>	1.8–2.0
Biryusa (BI)	Paragneiss	<u>2.0–2.4</u>	1.8–2.0
Chuya (CH)	Amphibolite–diorite–granodiorite gneiss	> <u>2.0</u>	1.85
Tonod (TF)	Greenschist	<u>2.48</u>	< <u>2.1</u>
Nechera (NR)	Granulite–paragneiss	?	1.85
<i>Mesoproterozoic terranes</i>			
Lene-Aldan (LA)	Paragneiss	2.3–2.5, <u>1.0–1.5</u>	≈ <u>1.0</u>

*Underlined ages are the main periods of rock formation and metamorphism.

Tunguska (TG), Daldyn (DL), Sharizhlagay (SHA), Tynda (TY) and Chogar (CG) terranes. An Archean and Paleoproterozoic domain includes the Biryusa (BI), Central Aldan (CA) and Tyung (TN) terranes. To the east, lie two Paleoproterozoic domains composed of the Khapchan (KH) and Berekta (BR) terranes in the north and the Tyryn (TR), Uchur (UC) and Batomga (BT) terranes in the south. It is possible that the basement of the Verkhoyansk Fold-and-thrust Belt may contain older rocks.

The Neoarchean crust consists mainly of granite–greenstone and tonalite–trondhjemite gneiss terranes (West Aldan (WAD), Onot (OT), Biryusa (BI), Tynda (TY), and probably, Tunguska (TG)). Their metamorphic grade ranges from greenschist to amphibolite facies and the age of metamorphism is estimated at 2.6 to 2.5 Ga in most cases. Granulite rocks of this age have a limited distribution and comprise the Daldyn and Sharizhlagay terranes as well as small tectonic blocks and slabs in the West Aldan and Tynda terranes. The Daldyn and Sharizhlagay terranes may have experienced repeated metamorphism in the

Paleoproterozoic (Aftalion et al., 1991; Rosen, 2002). The timing of granulite metamorphism in the Chogar Terrane is not reliably known.

Thus, the formation of the core the North Asian Craton was completed by ~2.6 to ~2.5 Ga (Fig. 2) and the West Aldan and Tunguska terranes already formed part of the craton by these times. In the West Aldan terrane, weakly metamorphosed Paleoproterozoic rocks are recognized and unconformably overlie the Archean basement.

The Archean–Paleoproterozoic domain is characterized by granulite facies metamorphism but pressures during metamorphism vary greatly from 8 to 12 kbar (Dook et al., 1986). The timing of granulite metamorphism is determined as ~2.0 to ~1.9 Ga. Reliable data for the earlier metamorphic events are missing in spite of the presence of Meso- and Neoproterozoic rocks within the terranes (Smelov et al., 1998).

The Paleoproterozoic domain exhibits a wide range of compositions and metamorphic grades comprising the granite–greenstone Batomga, the granulite–paragneiss Khapchan, Uchur and Tonod and the greenschist Chuya and Urik-Lya terranes. Geophysical data and rare xenoliths in igneous rocks indicate that tonalite–trondhjemite gneisses predominate in the Berekta and Tyryn terranes. The age of metamorphism is ~1.9 Ga and coeval with granulite facies metamorphism in the Archean–Paleoproterozoic domain. Evidence of superposed metamorphism of this age is found in the Archean Daldyn terrane whilst superposed metamorphism at granulite and eclogite facies occurred in the Tynda and Sharizhalgay terranes. Zones of the tectonic mélange formed at the same time (~1.9 Ga). Thus at ~1.9 Ga, a collision of large blocks of the Archean and Paleoproterozoic continental crust appears to have occurred. The next stage in the development of the craton (~1.8 to ~1.7 Ga) is characterized by the formation of anorogenic volcanic–plutonic complexes in the Akitkan Belt and Ulkan Basin. Other Mesoproterozoic terranes may exist but are not yet properly documented.

In areal extent, the North Asian Craton appears to be underlain by Archean crust (55%), undifferentiated Archean and Proterozoic crust (13%), Paleoproterozoic crust (20%) and Mesoproterozoic crust (12%) thus suggesting that crust formation was most extensive during the Neoproterozoic.

5. Conclusion

This investigation shows that the North Asian Craton is not an Archean feature as formerly suggested (Rosen et al., 1994), but also contains a range of Paleoproterozoic and Mesoproterozoic terranes. Thus, the formation of the craton was complex and evidently extended over a long interval of Precambrian time (Smelov et al., 1998). Crust-forming processes were most extensive in the Neoproterozoic and major periods of metamorphism occurred between ~2.6 and ~2.5 Ga and at ~1.9 Ga and these times probably reflect times of tectonic amalgamation. Thus the North Asian Craton is predicted to have taken part in significant Mesoproterozoic and more recent plate tectonic processes, a conclusion supported by the presence of Mesoproterozoic crust in the Verkhoyansk Fold-and-thrust Belt.

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