Calc-alkaline volcanic rocks and zircon ages of the late Tonian: early Cryogenian arc-related Big Naryn Complex in the Eastern Djetim-Too Range, Middle Tianshan block, Kyrgyzstan

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Abstract
The Big Naryn Complex (BNC) in the East Djetim-Too Range of the Kyrgyz Middle Tianshan block is a tectonized, at least 2 km thick sequence of predominantly felsic to intermediate volcanic rocks intruded by porphyric rhyolite sills. It overlies a basement of metamorphic rocks and is overlain by late Neoproterozoic Djetim-Too Formation sediments; these also occur as tectonic intercalations in the BNC. The up to ca. 1100 m thick Lower Member is composed of predominantly rhyolites-to-dacites and minor basalts, while the at least 900 m thick pyroclastic Upper Member is dominated by rhyolitic-to-dacitic ignimbrites. Porphyric rhyolite sills are concentrated at the top of the Lower Member. A Lower Member rhyolite and a sill sample have LA-ICP-MS U–Pb zircon crystallization ages of 726.1 ± 2.2 Ma and 720.3 ± 6.5 Ma, respectively, showing that most of the magmatism occurred within a short time span in the late Tonian–early Cryogenian. Inherited zircons in the sill sample have LA-ICP-MS U–Pb zircon crystallization ages of 726.1 ± 2.2 Ma and 720.3 ± 6.5 Ma, respectively, showing that most of the magmatism occurred within a short time span in the late Tonian–early Cryogenian. Inherited zircons in the sills and the major and trace element compositions, the presence of Neoarchean to Neoproterozoic inherited zircons and a depositional basement of metamorphic rocks point to formation of the BNC in a continental magmatic arc setting.

Keywords Tianshan orogenic belt · Big Naryn complex · Tonian–Cryogenian · Magmatic arc · Calc-alkaline · Kuilyu complex

Introduction
Volcanic and plutonic rocks are widespread in the central part of the Kyrgyz Middle Tianshan block (MTS) and were long considered as part of a once-continuous continental arc related to eastward subduction of oceanic crust below the MTS (e.g., Alexeiev et al. 2011; Safonova et al. 2017). However, correlations between the various volcanic-plutonic units, such as the Big Naryn and Sary-Djaz units, remain uncertain. In the Kyrgyz part of the MTS, volcanic and plutonic rocks extend in a north–south direction from the contact with the North Tianshan (NTS) to the South Tianshan blocks (STS) and overlie and intrude Precambrian igneous and metamorphic units of the MTS, including the telescoped units in the study area, the East Djetim-Too Range (Fig. 1a–c). The discontinuous nature of the magmatic arc in the MTS is the result of a complex tectonic setting during the Paleozoic, which involved intracontinental
extension and probably arc break-up and dispersion related to the opening of the Sak and Ishym-Karatau paleo-oceans in the Early Paleozoic (Bakirov et al. 2014; Alexeiev et al. 2019). Later, early Paleozoic oblique subduction of oceanic crust and accretion of the STS continent in the Carboniferous (Hegner et al. 2010; Alexeiev et al. 2011; Terbishalieva 2018 [327–343 Ma]) played an additional role; long distance strike-slip transfer of arc segments has been suggested for the volcanic units in the Djetim-Too Range (Şengör et al. 1993; Mikolaichuk et al. 2016).

Abundant volcanic and sub-volcanic rocks are exposed in the East Djetim-Too Range (EDTR) constitute a narrow domain that extends from Lake Issyk-Kul in the north to the western Kyrgyz Range in the south (Fig. 1b). It contains metamorphosed basement rocks of the Kuilyu Complex, Neoproterozoic volcanic rocks of the Big Naryn Complex (this study) and younger Neoproterozoic, glaciogenic rocks of the Djetim-Too Formation of the Late Vendian to Early Cambrian (2014). e Simplified geology of the Djetim-Too Range (without Quaternary sediments) with locations of dated samples; modified after Mikolaichuk et al. (2016).

Kiselev et al. (1993) reported U–Pb multi-grain zircon upper intercept ages that range widely between ca. 716 Ma and ca. 1280 Ma. Apart from many Mesoproterozoic and earliest Paleoproterozoic zircon ages, Glorie et al. (2011) also obtained a U–Pb spot ablation age for one zircon from gneiss of the Atbashi Metamorphic Complex of 788 ± 26 Ma. A felsic sill cutting the Atbashi Metamorphic Complex in the same area yielded an 842 ± 16 Ma zircon crystallization age and contains inherited zircons with ages in the range of 1866—2060 Ma (this sample was reported as a felsic tuff by Glorie et al. (2011)). Rojas-Agramonte et al. (2014) reported a zircon crystallization age of 836 ± 4 Ma for a dacite sampled as a clast in a late Neoproterozoic diamictite of the Djetim-Too Formation in the West Djetim-Too Range. Detrital zircons within the clastic diamictite matrix from the same area yielded ages in the range of 629 ± 8 to 2345 ± 20 Ma (Rojas-Agramonte et al. 2014).

The rocks exposed in the East Djetim-Too Range (EDTR) constitute a narrow domain that extends from Lake Issyk-Kul in the north to the western Kyrgyz Range in the south (Fig. 1b). It contains metamorphosed basement rocks of the Kuilyu Complex, Neoproterozoic volcanic rocks of the Big Naryn Complex (this study) and younger Neoproterozoic, glaciogenic rocks of the Djetim-Too Formation of the Late Vendian to Early Cambrian.
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Djetim Group (Chumakov 2009, 2011). In summary, it probably constitutes a crustal fragment or basement-cored horst.

Neoproterozoic arc rocks appear to be widespread in the MTS (Safonova 2017); however, reliable data on the internal structure, thickness, geochemistry and age of the Neoproterozoic BNC are limited. This study presents whole-rock major and trace element analyses of volcanic rocks and sills of the BNC to establish their composition and geological setting, and two new U–Pb zircon ages from a rhyolite lava and a rhyolite sill to determine the age of the BNC. In addition, 40Ar/39Ar step-wise heating dating of amphibole from a metagabbro of the Kuilyu Complex was carried out to obtain a minimum age for the amphibolite-facies metamorphism of the basement, and to confirm the field relations between the Kuilyu and Big Naryn complexes. The results are discussed in combination with published studies to better assess the geodynamic implications of Neoproterozoic magmatism in the MTS.

### Regional setting

The BNC is exposed in the eastern part of the 690 km² Djetim-Too Range. The tectonic map of the BNC was assembled by Mikolaichuk et al. (2016) and was accepted as the basis for the geological map of the East Djetim-Too Range (EDTR) by the Geological Survey of Kyrgyzstan. The study area is situated in what is known in the Russian language literature as the “Djetim geosynform zone” of the MTS.

The Kyrgyz Tianshan is subdivided into three tectonic zones. The Middle Tianshan block (MTS) occurs between the North Tianshan (mainly early Paleozoic accretionary complexes) and the South Tianshan block (a late Paleozoic fold and thrust belt) and comprises Precambrian metamorphic units, late Neoproterozoic magmatic and glaciogenic rocks as well as middle Devonian to late Carboniferous limestones and clastic sediments, deformed in the late Paleozoic (Alexeiev et al. 2019, and references therein).

### Table 1 Published zircon ages for the Big Naryn Complex, Djetin-Too Formation (Middle Tianshan), Djetim-Too Range, and the Archaly area (North Tianshan)

| Sample No. | Rock Type | Latitude | Longitude | Zircon age (Ma) | Older ages in parentheses | Laboratory, method | References |
|------------|-----------|----------|-----------|----------------|---------------------------|-------------------|------------|
| 10,538     | Plagiogranite | 41,705,326 | 77,651,654 | 791 (1016) *    | Institute of Geology NAS KR, ID-TIMS | Rubtsov (1984) |
| 4528       | Rhyolite   | 4,179,173 | 7,812,271 | 764 *          | Institute of Geology NAS KR, ID-TIMS | Baev (1989) |
| 4029       | Subvolcanic granosyenite | 4,198,779 | 7,841,915 | 791 *          | Institute of Geology NAS KR, ID-TIMS | Baev (1989) |
| 57–85      | Rhyolite   | 41,561,111 | 77,391,389 | 825 ± 20       | Institute of Geology NAS KR, ID-TIMS | Kiselev et al. (1986) |
| 9-81a      | Rhyodacite | 4,151,944 | 7,711,342 | 801 *          | Institute of Geology NAS KR, ID-TIMS | Kiselev et al. (1986) |
| 9-81b      | Rhyodacite | 4,151,944 | 7,711,342 | 836 *          | Institute of Geology NAS KR, ID-TIMS | Kiselev et al. (1986) |
| 210a       | Rhyodacite tuff | 4,149,623 | 7,650,879 | 692 *          | Institute of Geology NAS KR, ID-TIMS | Kiselev et al. (1986) |
| 210b       | Rhyodacite tuff | 4,149,623 | 7,650,879 | 716 ± 20 (820–1280) | Institute of Geology NAS KR, ID-TIMS | Kiselev et al. (1986) |
| AI-31      | Tuff (see text) | 4,173,667 | 7,806,639 | 842 ± 16 (2057 ± 55) | Ghent, LA-ICP-MS | Glorie et al. (2011) |
| KG 22      | Rhyolite   | 4,149,144 | 7,640,936 | 764 ± 4        | Beijing, SHRIMP II | Kröner et al. (2013) |
| JT-4       | Subvolcanic rhyolite | 4,156,111 | 7,739,139 | 747 ± 58 (877 ± 17), (1691 ± 30) | Potsdam, LA-ICP-MS | Mikolaichuk et al. (2016) |
| KG 20      | Dacite clast (Djetim-Too Fm.) | 4,127,022 | 7,617,573 | 836 ± 4 (2340) | Beijing, SHRIMP II | Rojas-Agramonte et al. (2014) |
| AB-3462    | Granite (Archaly, North Tianshan) | 4,615,172 | 7,744,412 | 743 ± 7 (847 ± 60) | St. Petersburg, SHRIMP II | Mikolaichuk et al. (2016) |

*ID-TIMS isotope dilution thermal ionization mass spectrometry, LA-ICP-MS laser ablation inductively coupled plasma mass spectrometry, SHRIMP sensitive high-resolution ion microprobe
*Reported without analytical uncertainties
The MTS has been labelled as a composite terrane, superterrane or allochthonous geological province (Mikolaichuk et al. 2016). To the south, the MTS is bounded by the Abtashi-Inylchek fault against the South Tianshan block, and to the north by the “Nikolaev Line” or “Main structural line of the Tianshan” (Fig. 1b), against the North Tianshan block. The Nikolaev Line is a strike-slip fault that possibly formed in the Permian–Triassic, and was reactivated in the Cenozoic (Korolev 1956; Mikolaichuk and Dzhenchuryayeva 2000; Bazhenov and Mikolaichuk 2004).

**Geology of the East Djetim-Too Range**

**Big Naryn complex**

Neoproterozoic volcanic rocks are well exposed in the East Djetim-Too Range, in contrast to other parts of the MTS, where they are either divided by numerous faults or not exposed at all. No reliable stratigraphic framework existed for the upper Neoproterozoic volcanic sequence of this study area. Schulz (1948) was the first to report the presence of volcanic rocks and named it the “quartz porphyry of the Naryn anticline” after the nearby Bolshoi (big) Naryn River. The majority of later published studies noted that the volcanic complex in the EDTR is made up of volumetrically dominant felsic pyroclastic and effusive rocks that are intruded by rhyolitic sills, and it was subsequently described as the “large assemblage of Naryn” or the “Big Naryn” complex (Korolev 1956; Dodonova and Goretskaya 1972; Sagyndykov and Sudorgin 1984; Kiselev 1993).

The Big Naryn Complex makes up to 40% of the study area (EDTR) and occupies the slopes and watershed of the upper parts of the Djetim-Too Range, with the remaining 60% covered by Cenozoic sediments and glaciers (Fig. 1c). The volcanic rocks, together with the overlying Djetim Formation of younger Neoproterozoic basal conglomerates (containing BNC-derived clasts) and diamicites, make up several north-vergent tectonic sheets. Accordingly, the primary stratigraphic sequence of the formation is restored based on the correlation of a series of partial geological sections mapped between 2010 and 2014 on the exposed southern and northern slopes of the range. This geological field work was led by the Northern Kyrgyz Geological Expedition (northern branch of the Kyrgyz Geological Survey), in which the first author (BT) was actively involved. Based on field observations and thin section petrography performed for this study and Terbishalieva (2018), the sequence was subdivided into a Lower Member of predominantly rhyolite and rhyodacite lavas and tuffs with subordinate basalt flows, and an Upper Member largely composed of dacitic to rhyolitic ignimbrites. Discordant porphyric rhyolite sills are situated mainly at the top of the Lower Member and intruded into zones of weakness, such as faults and along the contact between the Lower and Upper Members (Fig. 2). Dykes, stocks and plutons are not present.

In the East Djetim-Too Range, BNC lithologies occur tectonically intercalated with rocks of the Djetim-Too Formation and Kuilyu Complex (Fig. 1c). Metagabbro, metadolerite and chlorite-mica schists of the Kuilyu Complex were only found in and along main thrusts that also placed conglomerates and diamicites of the Djetim-Too Formation.
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Accordingly, the primary stratigraphic sequence in the East Djetim-Too Range is restored based on the correlation of a series of cross-sections (Figs. 2 and 3) mapped on the southern and northern slopes of the range (Online Resource 1). The cross-sections show that the BNC constitutes a faulted sequence of lavas and tuffs containing sill intrusions. Korolev (1956) and Kiselev (1984) found that greenschist-facies metamorphism of the BNC had developed along the “Nikolaev Line”, and Dodonova and Goretskaya (1972) noted that the metamorphism had only developed locally and that primary structures and textures of lavas, pyroclastic rocks, and the sills are generally well preserved macroscopically and in thin section.

Kuilyu Complex

Schulz (1948) noted that the Big Naryn Complex unconformably overlies metamorphic rocks of the Kuilyu Complex in the Irisu River, the left tributary of the Naryn River (Korolev and Maksumova 1984). Sagyndykov et al. (1988) described felsic effusive rocks of the BNC overlying quartzites and marbles of the Kuilyu Complex in the eastern, Akshiyar part of the EDTR. Hence, the Kuilyu Complex formed the original depositional basement to the BNC.

The Kuilyu Complex in the Middle Tienshan Block is at least 2500 m thick and is mainly made up of amphibolite-facies metasediments, metabasalts, metagabbros and granitoid migmatites that underwent a greenschist-facies overprint. For the Sary-Djaz area to the east of the EDTR, Mikolaichuk et al. (2008) cite an imprecise 2431 ± 200 Ma K–Ar amphibole age for Kuilyu Complex amphibolite, and much younger 646–950 Ma K–Ar ages for amphibole and (altered) biotite from Sary-Djaz granitoids. Locally, metadolerites, metagabbros and chlorite-mica schists of the Kuilyu Complex occur intercalated with the Lower Member lithologies of the BNC, as shown particularly in cross-sections Kyzykbel, Karachunkur and number 123 (Online Resource 1).

In addition, the BNC was thrust northwards over younger, late Neoproterozoic glaciogenic sediments of the Djetim-Too Formation (e.g. sections Kyzybel, 123 and bn-08-13, Online Resource 1), while the latter are also present among and between BNC lithologies within thrust-bound units (e.g. the Karanchunkur section). Thus, during northwards thrusting of the BNC, fragments or sheets of both basement material and overlying Djetim-Too Formation sediments were incorporated.

Djetim-Too Formation

The Djetim-Too Formation of diamictites and conglomerates occurs widespread in the Middle Tienshan Block, and in the study area is locally tectonically intercalated with BNC and basement rocks. It was originally unconformably deposited onto the BNC and constitutes the lowest part of the tripartite Djetim Group that comprises the lower Djetim-Too Formation, the middle Dzhakbolot Formation of variegated carbonates and shales and the upper Baykonur Formation of upper Ediacaran glacial deposits (Chumakov 2009). Both diamictite formations contain locally derived clasts of BNC rocks and comprise thin-bedded shales with dropstones (Chumakov 2009). Microfossils (microphytolites) point to a Neoproterozoic deposition age for the Djetim-Too Formation (Mikolaichuk et al. (2008) and references therein).

The Djetim-Too Formation in the EDTR is made up of different terrigenous rocks (conglomerates, gravelites,
sandstones, siltstones, shales) and mixed, debris-like rocks that are typically very weakly sorted and tillite-like. They are found as dark gray or greenish-gray clastic rocks containing rare pebbles, boulders and blocks of volcanic rocks and limestone. The Djakbolot Formation is overlain by the Djetim-Too Formation that starts with up to 10 m carbonaceous limestones that may be the equivalents of post-glacial cap carbonates (Chumakov 2009).

### Petrography

Abbreviations for rock-forming mineral names are from Whitney and Evans (2010).

#### Lower Member of the Big Naryn Complex

The Lower Member is dominated by rhyolite to dacite lavas, which are interlayered with tuffs and tuff-derived sediments (Fig. 4a). Rhyolites and rhyodacites have a fine-grained groundmass with a flow fabric containing small, idiomorphic, up to 1 mm-sized phenocrysts of quartz and feldspar, the latter albitized to various degrees (Fig. 4d). The amount of phenocrysts is less than 10% of the rock volume. The bulk of the planar fabric is microcrystalline (Fig. 4d). Rhyolitic and rhyodacitic tuffs vary from coarse-grained lithoclastic, vitro- and crystalloclastic, volcano-sedimentary breccias to medium-grained crystalloclastic and fine-grained tuffaceous volcaniclastic rocks. Lithoclasts are fine- to very fine-grained volcanic rocks (felsite, micro-felsite) and porphyric rhyolithes with millimeter-sized phenocrysts of mostly alkaline feldspar. In crystalloclastic tuffs, sharply angular quartz fragments dominate, plagioclase is rare, and the rocks are highly sericitized. Tuffaceous sedimentary rocks are fine-grained tuffaceous siltstones (Fig. 4a).

Thin basalt lavas occur in the lower part of the Lower Member. They are dark green and all samples are altered except for analyzed sample Ba-121, which is relatively fresh. Most are porphyric with phenocrysts of monoclinic pyroxene (augite) forming 0.5–1 mm-sized idiomorphic prisms that are nearly colorless with a weak greenish tinge. Groundmasses composed of former plagioclase and clinopyroxene have intertextual textures and amygdales are filled with secondary chlorite and feldspar (Fig. 4b). Opaque minerals are relatively large and may be primary magmatic.

#### Upper Member of the Big Naryn Complex

In contrast to the Lower Member, the Upper Member is characterized by a larger variety of rock types comprising rhyolitic, rhyodacitic, and dacitic ignimbrites with thin lavas and tuffs. The ignimbrites are enriched in ore minerals such as magnetite, chalcopyrite and pyrite. Volcanic and volcanoclastic breccias contain angular or flattened rhyolite and dacite fragments of widely varying sizes from several millimeters to 10 cm. The groundmass is cryptocrystalline and locally shows eutaxitic textures (Fig. 4e). Ignimbrites of rhyodacitic and dacitic composition are darker compared to the rhyolithic ignimbrites, and their textures vary from cryptocrystalline to fine-grained to eutaxitic. Segregation lenses and fiamme are noticeable and can be recognized by their shapes, color and (in some samples) compositions, with fiamme rims enriched in finely dispersed ore minerals causing darkening. Crystals are quartz, plagioclase and, less often, alkali-feldspar now completely replaced by albite. Crystal shapes range from isometric, comminuted to irregular with sinuous outlines. The groundmass of baked vitric tuffs is black (Fig. 4e).

#### Porphyric rhyolite sills

The porphyric rhyolite sills can be distinguished from porphyric rhyolite lavas by their textures. The textural variations of the sill lithologies range from aphyric to porphyric rhyolites. In endocontact zones and in thin bodies, textures vary from porphyric to aphyric, locally perlitic (Ba-130), and groundmass textures vary from fine-grained (Ba-133) to microgranophyric and granophyric (Fig. 4c). Small phenocrysts up to 0.5 mm in size are represented by quartz, alkali-feldspar (in some samples nearly completely albitized), and rare plagioclase. In the central parts of the rhyolitic sills, phenocrysts of several generations constitute up to 15–20% of the rock volume. Among the large grains of the first generation, with sizes up to 4 mm, perthite predominates while quartz crystals, locally corroded down to 3 mm, occur in subordinate amounts. Locally, granophyric intergrowths of quartz and orthoclase, as well as single plagioclase crystals (oligoclase) are present.

#### Alteration and secondary minerals

Samples from the Lower and Upper members and the porphyric rhyolite sills are altered to varying degrees, with propylitic alteration dominating the Upper Member lithologies. Most samples retained primary magmatic textures, but many are altered to various degrees, mostly propylitization with formation of dispersed pyrite, chalcopyrite, magnetite and hematite (Fig. 4f). In addition, sericitization of groundmass alkali feldspar is observed in thin section. Alteration is more common in the Upper Member than in the Lower Member; in the former, most of the fiamme are propylitized and sericitized to fine-grained secondary minerals. Veins and breccias are typically filled by propylitic alteration minerals, such as epidote, chlorite, with pyrite, chalcopyrite, magnetite and hematite as the main ore minerals. Alteration is mainly manifested as sericitization (Ba-49) and secondary silicification.

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(Ba-130) of varying intensity, occurring as sericite-quartz veins or nests.

Deformation in fault zones resulted in local cleavage formation and complete obliteration of primary minerals and textures. Some samples underwent deformation and alteration under low grade, greenschist-facies conditions that occurred locally and appear to be related to the activity of the main faults and thrusts.

**Kuilyu Complex metagabbro**

The least altered metagabbro sample Ba-27 (Kyzylbel cross-section, Online Resource 1) that was selected for
amphibole $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating dating contains magmatic clinopyroxene remnants. It contains a planar fabric formed by mafic layers of mainly chlorite, epidote and amphibole (hornblende), and felsic layers made up of lens-shaped plagioclase and opaque minerals, mainly magnetite, hematite, pyrite and/or chalcopyrite (Fig. 5a, b). Most of the amphiboles occur as hypidiomorphic prisms showing undulose extinction.

**Sampling and analytical methods**

This study is based on a set of 73 rock samples collected during the period of 2014–2018. XRF major element whole rock analyses were carried out on all samples and a subset of 21 samples was analyzed for trace element concentration (Online Resources 2A and 2B). The sample set comprises 44 acid to intermediate volcanic rocks, 4 basalts and 25 rhyolite sill samples and one metagabbro of the Kuilyu Complex basement (Ba-27, Online Resource 2A).

A rhyolite (lava) with large alkali-feldspar phenocrysts from the Lower Member (Ba-150) and a porphyric rhyolite sill sample (Ba-133) were selected for U–Pb zircon dating to determine crystallization ages and the timing of volcanism of the BNC. In addition, an amphibolite-facies metagabbro of the Kuilyu Complex (Ba-27) was chosen for $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole step-heating dating to determine a cooling age for the basement and establish an upper age limit for its amphibolite-facies metamorphism.

**XRF and ICP-AES methods**

Altered surfaces and veins were removed from all samples prior to sample preparation and geochemical analysis.

59 whole rock analyses were carried out at the Geological Agency of Mineral Resource of the Kyrgyz Republic. After sample dissolution, $\text{Al}_2\text{O}_3$, $\text{TiO}_2$, and $\text{P}_2\text{O}_5$ concentrations were determined by classical photo-voltaic colorimetry, using a KFK-2MP photo colorimeter in the 315–980 nm wavelength range. $\text{CaO}$, $\text{MgO}$ and $\text{MnO}$ concentrations were determined by atomic absorption spectrometry, and $\text{K}_2\text{O}$ and $\text{Na}_2\text{O}$ by flame photometry. $\text{SO}_3$ and Loss On Ignition (LOI) values were determined gravimetrically.

For the 24 whole rock analyses carried out in Germany, clean fragments were crushed with a jaw crusher and subsequently powdered, using an agate mill at the Institute of Geosciences of the University of Potsdam, Germany. The powdered rock samples were dried in an oven for more than 6 h at 105–110 °C before processing. Major oxide and selected trace element concentrations (Ba, Cr, Ga, Nb, Ni, Rb, Sr, Y, Zn, Zr) were determined on fused lithium-tetraborate glass disks at the Helmholtz Centre Potsdam—GFZ German Research Centre for Geosciences,
using a Phillips PW-2400 X-ray fluorescence (XRF) spectrometer. The detection limits for major oxides is <0.01 wt% and <10 ppm for the trace elements. International natural standards were used for calibration and monitor analytical precision, which is better than 1–3% for major elements and better than 10% for trace elements (Zuleger and Erzinger 1988).

The concentrations of H₂O and CO₂ were determined on 20 mg of powdered samples weighed on tin foils using a Euro EA 3000 Elemental Analyzer at the University of Potsdam. Sulfanilic acid and BBOT (2.5-Bis-(5-tert-butyl-2-benzo-oxazol-2-yl) thiophene) was used to calibrate the instrument. Internal natural and synthetic standards (sulfanilic acid, BBOT and Odinit) were used to monitor analytical precision. Measurements were carried out twice to check measurement precision, which is better than 1% (Dietrich and Schwandner 2004).

Scandium (Sc), yttrium (Y), and rare-earth element (REE) concentrations were determined by inductively coupled plasma atomic emission spectrometry (ICP AES) at the GFZ and the University of Potsdam. Sample dissolution was done at the University of Potsdam; rock powders were dissolved using standard Na₂O₂ fusion and dilution techniques (Zuleger and Erzinger 1988). The analytical accuracy of the method is <1% and the precision for the REE ranges between 5 and 10% based on comparison with international reference standards. 1 g of powdered sample was mixed with 5 g Na₂O₂ in a nickel crucible, then covered by 1 g Na₂O₂ and heated at 500 °C. After cooling down, deionized water was added to the sinter cake until the reaction stopped. The sinter cake was then taken up in 40 ml deionized water, and the mixture was transferred to a centrifuge tube and centrifuged (Eppendorf Centrifuge 5702) for 15 min at 4000 ppm. To remove the soluble silica salts, the centrifugation procedure was repeated three times. After removing the solute from the sinter cake by decanting, the remaining sinter cake was dissolved in 1 molar HCl and 42 ml deionized water and transferred to a 100 ml bottle. Ion exchange columns were used for chromatographic separation of the Sc, Y and REE. 500 ml 1.7 molar HCl was used to elute the major constituents and most of the trace elements. Sc, Y and REE were eluted in 550 ml 4 molar HCl. The eluates containing the Sc, Y and REE were filtered, evaporated and dried overnight. The residue were then dissolved in exactly 10 ml 10% HCl and stored in 10 ml bottles. REE concentrations were determined using a Vista MPX at the Institute of Geosciences, University of Potsdam. Sc and Y were determined at the GFZ with an ICP-AES 5100 spectrometer, using a fast automated curve-fitting technique (FACT) correction model.

For the determination of Hf, Pb, Th, U, Cs concentrations, a selection of four samples covering all units, Ba-27 (metagabbro), Ba-150 (Lower Member rhyolite lava), Ba-46 (Upper Member ignimbrite) and Ba-133 (porphyric rhyolite sill), were crushed and powdered to less than 0.63 µm. Concentrations were determined at the GFZ by inductively coupled plasma mass spectrometry (ICP-MS), using a Perkin–Elmer/Sciex Elan Model 500 using the method of Dulski (1994). The major and trace element data are presented in Online Resources 2A and 2B.

**Zircon separation and LA-ICP MS analyses**

Heavy mineral concentration took place at the Institute of Geosciences, University of Potsdam. Rhyolitic lava Ba-133 from the Lower Member and porphyric rhyolite sill sample Ba-133 (both from the Egizkol-1 cross-section, Online Resource 1) were crushed and then sieved to <500 µm. Subsequently, heavy minerals of the crushed samples were segregated with a Humboldt Wedag shaking table and then were cleaned in 10% acetic acid for over 12 h and in 3% H₂O₂ for more than 12 h. Following separation of ferromagnetic grains using a hand magnet, the heavy mineral concentrates were repeatedly passed through a Frantz magnetic separator at increasing field strengths and angles of 12, then 5°. Separator funnels filled with sodium polytungstate (SPT, 2.87 g ml⁻¹) were used to remove lighter minerals (e.g. quartz, feldspar) from the least magnetic fractions by floatation. The heavy fractions were washed with deionized water and dried at >50°C, followed by removal of heavier minerals (mainly apatite) by floatation in methylene iodide (MEI, 3.3 g ml⁻¹). The zircon-rich heavy fractions were first washed with acetone and dried.

At the Institute of Geology of the Czech Academy of Science in Prague, zircons were handpicked, mounted in epoxy and then polished. Their internal structures were documented by cathodoluminescence (CL) imaging and, after spot selection, these zircons were analyzed by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). A Thermo Scientific Element 2 sector field ICP-MS coupled to a 193-nm ArF excimer laser was used to measure the Pb/U and Pb isotopic ratios in zircons. The laser was fired at a repetition rate of 5 Hz and fluence of 3.17 J/cm² with 20-micron spot size. The He carrier gas was flushed through the two-volume ablation cell at a flow rate of 0.75 L/min and mixed with 0.81 L/min Ar and 0.004 L/min N₂ prior to introduction into the ICP. The in-house glass signal homogenizer (design of Tunheng and Hirata 2004) was used for mixing all the gases and aerosol, resulting in smooth, spike-free signal. The signal was tuned for maximum sensitivity of Pb and U, Th/U ratio close to unity and low oxide level, commonly below 0.2%. Typical acquisitions consisted of 15 s measurement of blank followed by measurement of U, Th, and Pb signals from the ablated zircon for another 35 s. The total of 420 mass scans of data were acquired in time resolved-peak jumping-pulse counting mode with one point measured per peak for masses 204Pb + Hg, 206Pb, 207Pb,
from 235U intensities if the 238U was acquired in analogue mode. Data reduction was then carried out off-line using the Iolite data reduction package, version 3.4 with Visual Age utility (Petrus and Kamber 2012). No 204Pb (common lead) correction was applied to the data due to the high Hg contamination of the commercially available He carrier gas, which precludes accurate correction of the interfering 204Hg on the very small signal of 204Pb. Primary concentrations of common Pb in zircon are considered very low and were controlled by observing the 206Pb(radiogenic)/204Pb ratio. Residual elemental fractionation and instrumental mass bias were corrected by normalization to the natural zircon reference material Plešovec (Sláma et al. 2008; Online Resource 3). The U–Pb isotope data are presented in Online Resource 3 and the CL images in Figs. 9 and 11. Age calculations and data plotting were done with Isoplot 4.15 (Ludwig 2009).

\[ \frac{^{208}\text{Pb}}{^{232}\text{Th}}, \frac{^{235}\text{U}}{^{238}\text{U}}. \] The intensities of \(^{238}\text{U}\) were left unchanged if measured in a counting mode and recalculated from \(^{235}\text{U}\) intensities if the \(^{238}\text{U}\) was acquired in analogue mode. Data reduction was then carried out off-line using the Iolite data reduction package, version 3.4 with Visual Age utility (Petrus and Kamber 2012). No 204Pb (common lead) correction was applied to the data due to the high Hg contamination of the commercially available He carrier gas, which precludes accurate correction of the interfering 204Hg on the very small signal of 204Pb. Primary concentrations of common Pb in zircon are considered very low and were controlled by observing the 206Pb(radiogenic)/204Pb ratio. Residual elemental fractionation and instrumental mass bias were corrected by normalization to the natural zircon reference material Plešovec (Sláma et al. 2008; Online Resource 3). The U–Pb isotope data are presented in Online Resource 3 and the CL images in Figs. 9 and 11. Age calculations and data plotting were done with Isoplot 4.15 (Ludwig 2009).

\[ ^{40}\text{Ar}/^{39}\text{Ar} \text{ step-heating dating} \]

Metagabbro sample Ba-27 was crushed, cleaned with water and sieved to a 250–500 μm size fraction and then washed in an ultrasonic bath to remove fines. After drying, 100 hornblende grains were handpicked under a stereo-microscope (up to 40 times magnification). Sample Ba-27 was selected for \(^{40}\text{Ar}/^{39}\text{Ar} \text{ dating because of its higher, amphibolite-facies grade of metamorphism that contradicts with that of the surrounding rocks of the BNC, suggesting that it could be a fragment of the basement. The picked hornblende grains were irradiated with fast neutrons for four hours in August 2017 at the CLICIT (Cadmium-Lined In-Core Irradiation Tube) facility of the Oregon State TRIGA Reactor (OSTR) of Oregon State University, USA. The international age standard Fish Canyon Tuff sanidine, which was prepared by the Geological Survey of Japan (FC-3, 27.5 Ma; Uto et al. 1997; Ishizuka 1998), was irradiated together with the samples. To correct for the interference of Ar isotopes produced by the reactions of Ca and K in the samples, additional crystals of K₂SO₄ and CaF₂ were co-irradiated with the unknowns.

\[ ^{40}\text{Ar}/^{39}\text{Ar} \text{ dating was done at the } ^{40}\text{Ar}/^{39}\text{Ar Geochronology Laboratory of the Institute of Geosciences of the University of Potsdam. Sample gases were released from amphibole by stepwise heating for 30 s by increasing the laser power of a New Wave Research Dual Wave CO₂ infrared laser (wavelength 10.6 μm, maximum output 50 W) with 1450 μm beam diameter for each heating step. After each heating step, the released sample-gas was purified for 10 min in the gas purification line with SAES Zr-Al getter pumps (one at room temperature and the other at 400 °C) and a cold trap kept at – 90 °C with an electric immersion cooler, close to the freezing temperature of ethanol. After purification, Ar gas was introduced into the mass spectrometer and analyzed. The mass spectrometer was operated using the peak-jumping method in a static mode in which the intensities of Ar isotope beams were measured with a single electron multiplier for a total of 900 s. Zr-Al getter pumps in the mass spectrometer are running continuously during analysis to maintain the purity of Ar and to assure a constant low level of the residual active gases.\]

The natural isotope ratios of Ar and K and decay constants of \(^{40}\text{K}\) used for \(^{40}\text{Ar}/^{39}\text{Ar} \text{ age calculation are adopted from Steiger and Jäger (1977). Data reduction, age calculations and diagram construction were done with the “MassSpec” software made by Dr. Alan Deino, Berkeley Geochronology Center, USA. The argon isotope data are presented in Online Resource 4.\]

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minerals such as sericitic white mica, chlorite etc.) have lower Na$_2$O + K$_2$O contents (purple crosses in Fig. 6a). This probably reflects mobility of Na, K and Si during alteration processes. Signs of alteration in other ignimbrite

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![Graph A](image1)

**Basic samples**

![Graph B](image2)

**Intermediate samples**

![Graph C](image3)

**Acid samples**

_Fig. 7_ Chondrite normalized whole rock REE abundances of basic (a), intermediate (b), and (c) acid samples of the BNC, using the C1 normalization values of McDonough and Sun (1995). Basic samples lack Eu negative anomalies or developed very small ones (a), which appear and increase with increasing SiO$_2$ contents (b, c), pointing to plagioclase fractionation. Intermediate samples: dacites and andesites. Basic samples: basalts and basaltic andesites. Acid samples: rhyolite-dacite lavas
and porphyric rhyolite samples may explain the scatter in Na2O + K2O contents within the rhyolite field (Fig. 6a).

Only samples with LOI values (Kyrgyzstan analyses) and CO2 + H2O abundances (Potsdam analyses) less than 0.75 Wt% and SiO2 contents between 48 and 75 Wt% were plotted in the K2O vs. SiO2 diagram of Peccerillo and Taylor (1976) (Fig. 6c), thus excluding the host samples that have SiO2 ≤ 45 Wt%. Lava samples define a trend from the calc-alkaline to high-potassium calc-alkaline fields (blue squares in Fig. 6c).

In the AFM diagram of Irvine and Baragar (1971), all samples define a calc-alkaline trend, as in the TAS diagram (Fig. 6a). Three least-fractionated lava samples have high MgO (Fig. 7d). AFM diagram showing that most of the samples form a calc-alkaline series, but that some altered samples plot in the tholeiite field (MgO from 13 to 22 Wt%) and in the lower right corner (blue squares, samples 2008, 3024, 3024/1). Sills have high Al2O3 concentrations and the more fractionated samples (samples 2051, 2059, 3150A, 2051/2 2079, 2070/2) have similar FeO and MgO contents and form a cluster, apart from sample 2059 (Fig. 6d; Online Resources 2A and 2B).

The sill samples cluster at the high SiO2 end of the trend and have variable Na2O + K2O contents (Fig. 6c), which probably reflect varying modal amounts of alkali feldspar phenocrysts. Lava samples plot in the calc-alkaline field and those with higher SiO2 contents in the high-K calc-alkaline field. Only porphyric rhyolite sill samples with 74 to 76 Wt% SiO2 were plotted in the aluminum saturation diagram of Maniar and Piccoli (1989), excluding samples with high volatile or LOI values of > 0.77 Wt% (Online Resources 2A and 2B). Compositions of these 17 sill samples vary between metaluminous and peraluminous, with many analyses clustering in the I-type granite field (Fig. 6e).

Trace and rare earth elements

In the Nb/Y vs. Zr/Ti diagram of Pearce (1996), the samples belong to the subalkaline series and define a basic to acid trend (Fig. 6b). Specifically, lavas show a continuous trend from basic to acid compositions, ignimbrites and tuffs have intermediate compositions, and rhyolite sills are acid and plot close to the alkaline rhyolite field boundary.

The Nb/La vs La/Yb diagram (Fig. 6f) shows that most samples of the Big Naryn Complex plot in the continental arc field with Nb/La varying between 0.3 and 0.7, and La/Yb between 4 and 35. Most of the lava samples have similar Nb/La values of 0.3–0.7 and similar La/Yb of 20–35; ignimbrites and tuffs have lower La/Yb of 4–20 (Fig. 6f). The sill samples have much higher La/Yb values up to 33 and trend towards the alkaline arc field (Fig. 6f).

Chondrite-normalized REE diagrams for basic to acid samples show similar patterns with Eu negative anomalies that increase from basic to acid rocks (Fig. 7a–c). The patterns for the basic rocks are relatively flat from Ho to Lu and show light REE (LREE) enrichment (LaN/SmN = 2.2–4.76 and LaN/LuN = 1.71–11.15, Fig. 7a). Middle to heavy REE ratios for the basalt samples are low (Sm2N/LuN = 0.71–3.53) and do not support the presence of residual garnet in the source during parent melt generation. Eu anomalies (Eu/Eu* = EuN/sqrt (SmN* GdN)) increase from 0.04 for one basic sample (Fig. 7a) to 0.72 for the acid samples (Fig. 7c), and clearly developed in samples with SiO2 between 55 and 77 Wt%. Eu is depleted relative to the other REE, which can be explained by fractional removal of plagioclase.

The primitive mantle normalized multi-trace element diagrams for all samples show relatively large variations of trace element abundances from basic to felsic samples (Fig. 8a–c). The basic samples are OIB-like (Fig. 8a) and their Ti, Nb, Zr and LREE concentrations are slightly elevated and lie between those of N-MORB and OIB. Nb- and Ti-negative anomalies develop in more fractionated samples of intermediate to acid compositions (Fig. 8b, c) and P negative anomalies develop first in samples of intermediate composition (Fig. 8b).

U-Pb zircon dating results

Rhyolite lava Ba-150

Zircon dating of rhyolite lava Ba-150 resulted in 24 spot analyses. In CL images, yellow circles denote the beam size and are labeled with analysis number followed by spot age (e.g. Ba_150_207: 735 ± 10 Ma in Fig. 9, top left).

Zircons from Ba-150 vary from euhedral to broken euhedral crystals and are idiomorphic with rounded prismatic habits with oscillatory, magmatic-type zoning (Fig. 9). Some of the dated grains are present only as crystal fragments and breakage must have occurred during sample crushing. The average size of the analyzed zircons varies between 450 and 550 µm, while zircon grains Ba-150_217 and Ba-150_233 are larger than 650 µm.

The 24 zircon analyses of sample Ba-150 show a relatively narrow 206Pb/238U age range between 712 and 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3). From this age cluster, a pooled or average age of 732 Ma with a concordance of 95 to 101% (Fig. 10; Online Resource 3).

Porphyric rhyolite sill Ba-133

Zircon dating of sample Ba-133 resulted in 40 spot analyses. The zircons vary in size from 450 to 950 µm and in shape from euhedral to subhedral, with many being broken
probably due to sample crushing. Euhedral grains are rather rare compared to subhedral ones. Zoning, cores and rims are easily recognizable. Zircon grains with sizes close to 450 µm are idiomorphic with rounded prismatic habits (such as Ba-133_298, _296). Grains with sizes close to 950 µm are rounded and have internal structures with cores and zoned rims (such as Ba-133_250, _258) that can be distinguished by their different CL intensities (dark grey-to-black cores, light grey-to-grey rims, Fig. 11).

Sill sample Ba-133 yielded a large spread of zircon ages that, in addition, are slightly more discordant than those of Ba-150 (Fig. 12a). For this reason, 84 to 116% concordant analyses were used for age calculations. Of the 40 analyses, 16 are from the outer rims of zircon crystals and yielded the youngest 206Pb/238U ages in the range 714 ± 10 to 741 ± 11 Ma. This spread in ages is too large to allow a pooled (Concordia) age to be calculated and instead we prefer the 720.3 ± 6.5 Ma weighted mean of the 206Pb/238U ages (Fig. 12b). Six concordant analyses of inner rims (green in Fig. 12a) give ages between 791 ± 14 and 849 ± 16 Ma. The 720.3 ± 6.5 Ma youngest 206Pb/238U age average for the outer rims is interpreted as the crystallization age of the sill, although some spots overlap inner zones. One zircon yielded two ages, a Neoarchean 207Pb/206Pb age for core BA133_249 (2628 ± 24 Ma) and a Neoproterozoic 206Pb/238U age for rim BA133_250 (797 ± 13 Ma; Online Resource 3).

Zircon core analyses yielded much older ages, which can be divided into two broad groups marked in red and blue in Fig. 12a. Cores marked with blue circles (such as Ba-133_249, _257) yielded the oldest 207Pb/206Pb ages of 2628 ± 24, 2644 ± 22 Ma, 2119 ± 35 Ma and 2329 ± 29 Ma.
In addition, metamict cracks are present in zircon core of sample Ba-133_257 (Fig. 12a). Cores marked in red (e.g. Ba-133_294, _295; Fig. 12a) have younger 207Pb/206Pb ages between 1551 ± 30 Ma and 1811 ± 33–2030 ± 28 Ma and, in addition, are slightly more discordant (up to 20%) compared to the older cores marked in blue (Fig. 12a). The latter are clearly of xenocrystal origin and must have been inherited from much older basement material that was partly assimilated by the parent melt of porphyric rhyolite sill Ba-133.

40Ar/39Ar amphibole step-heating dating results

Amphibole from Kuilyu Complex metagabbro Ba-27 found below and in tectonic contact with the Lower Member of the BNC yielded a plateau age of 1751 ± 7 Ma for steps 4 to 6 of nine gas fractions. The age spectrum is shown in Fig. 13 and the analytical data are listed in Online Resource 4, where the data are presented at 1 sigma levels of analytical uncertainty, whereas apparent ages in the age spectrum are shown at 2 sigma level. Apparent ages for steps 1 to 3 decrease from 2300 to 1515 Ma, and the last 3 steps have different apparent ages of 1560, 1712 and 1794 Ma. The three gas fractions 4, 5 and 6 have similar Ca/K ratios (resp. 6.3, 8.6 and 7.1) and comprise 65% of the 39Ar released, allowing a 1751 ± 7 Ma plateau age to be calculated (Fig. 13). The plateau definition is from Fleck et al. (1977) and McDougall and Harrison (1999).

Discussion

Stratigraphy and petrography

The nine detailed cross sections (Fig. 2; Online Resource 1) and the stratigraphic columns (Fig. 3) show that the BNC is a folded, thrusted and faulted, and at least 2 km thick sequence of predominantly felsic volcanic rocks and sills, and also contains petrogenetically unrelated, older and younger material.

The Lower Member of the BNC is up to c. 1100 m thick and dominantly made up of rhyolite to dacite lavas, which are interlayered with tuffs and tuff-derived sediments, and
locally with minor basalts. The small amounts (× 10%) of small quartz and feldspar phenocrysts in the rhyolite-dacite lavas indicate that a short, late-stage fractionation of the magma chamber was quickly followed by eruption of mainly lavas with subordinate pyroclastic activity. The large amount of rhyolitic to dacitic ignimbrite in the > 900 m thick Upper Member illustrates that pyroclastic activity was here more prominent compared to the Lower Member. Altered fiamme and shards in the ignimbrites may be former pumice and glass bubble wall fragments, respectively. The eutaxitic textures resemble flow banding (“rheomorphic” textures), but can also be the result of post-eruption compaction. Alteration and the state of texture preservation do not allow distinguishing between origins as welded or non-welded ignimbrites. The rhyolite sills have margins that are aphyric or contain only a few, small quartz, alkali-feldspar and rare plagioclase phenocrysts. The centers of the sills are porphyric and contain up to 20 vol% phenocrysts of mainly alkali feldspar of several generations. Such an accumulation of phenocrysts in the center is probably due to subhorizontal flow differentiation during sill intrusion. The thin, clino- pyroxene phenocryst-bearing basalts in the lower parts of the Lower Member (see cross section Egizkol-1; Online Resource 1) must represent mantle-derived and much less fractionated melt batches that originated from greater depths or from a separate magma chamber. The presence of amygdales, now filled with secondary minerals, suggests that the basaltic magma contained enough gas to form vesicles during ascent and eruption.

**Major and trace element geochemistry**

The Lower Member is basaltic to rhyolitic in composition and the Upper Member andesitic to rhyolitic–dacitic, and all lava samples define a continuous subalkaline trend from basic to acid compositions, indicating a fractionation sequence, as do selected trace elements. Ignimbrites and tuffs have mainly intermediate compositions and the sills are acid and have higher K₂O and SiO₂ contents that are higher than those of the rhyolite lavas (Fig. 6c). This may indicate that they originated from different sources, or reflect contamination of parent magma with crustal material in a magma chamber. Alternatively, the higher K₂O and SiO₂ contents may be due to feldspar phenocryst enrichment in the central parts through flow differentiation during emplacement, as seen in the field. The metaluminous to peraluminous sills correspond to I-type, i.e. subduction-related granitoids. Both sills and volcanic rocks plot in the continental arc field.

The basic samples are enriched in LREE and Eu anomalies are absent or very small (Fig. 7a–c), which agrees with the absence of plagioclase phenocrysts in the basalts. REE concentrations and the degree of LREE enrichment increase
from basic to acid samples, and so does the magnitude of the Eu negative anomaly. The increasing Eu anomaly is most likely the result of feldspar removal (especially plagioclase) from the parent magma by fractionation processes, which is supported by the presence of feldspar phenocrysts in most rhyolite-dacite lavas. The multi-element patterns show similarities to OIB, but have Nb and Ti negative anomalies (Fig. 8a–c). Basic samples lack Ti anomalies, but have weak negative Nb and Zr anomalies. From basic to acid samples, the Nb and Ti anomalies increase and correlate with increasing SiO₂ content, which is typical for volcanic arc systems (e.g. Thirlwall et al. 1994). P negative anomalies in intermediate and acid samples reflect crystallization and removal of apatite (Fig. 8c, d).

The dominance of acid, calc-alkaline compositions and the trace element characteristics suggests formation of the BNC in a continental volcanic arc setting. Such volcanism is frequently highly explosive, leading to the eruption of tuffs and ignimbrites, as seen in the BNC. The presence of subalkaline to high-K calc-alkaline volcanic rocks may be explained by fractionation and eruption in continental crust of increased thickness, leading to the elevated K₂O concentrations of the most fractionated samples.

**40Ar/39Ar age and U–Pb ages**

**40Ar/39Ar** step-heating dating of amphibole from amphibolite-facies metagabbro Ba-27 yielded a ca. 1.75 Ga plateau age, which we interpret as the amphibole cooling age following amphibolite-facies metamorphism of the Kuilyu Complex units in Paleoproterozoic times.

U–Pb zircon ages of Lower Member rhyolite lava sample Ba-150 are all concordant and cluster, yielding a pooled age of 726.1 ± 2.2 Ma, which is interpreted as the crystallization age of the lavas, and thus to date the volcanic activity of the Lower Member of the Big Naryn Complex to the late
Neoproterozoic (late Tonian). No inherited zircon grains were found in this sample.

Zircons from rhyolite sill sample Ba-133 show complex internal textures (cores, inner and outer rims) that yield a wide spectrum of U–Pb ages, substantiating the presence of zircons of different generations. Sixteen spot analyses of zircon outer rims pool around 720.3 ± 6.5 Ma and this youngest 206Pb/238U age average is interpreted to date sill intrusion and crystallization. The oldest cores have Neoarchean (2.63 and 2.64 Ga) to Paleoproterozoic (2.12–2.33 Ga) 207Pb/206Pb ages, while younger cores show slightly discordant 1.55 Ga and 1.81 – 2.03 Ga Paleo- to Mesoproterozoic 207Pb/206Pb ages. These old ages must represent xenocrysts derived from recycled crustal material or assimilated crustal contaminants, which were later overgrown by younger magmatic rims. To a certain degree, the core ages must reflect the age spectrum of basement lithologies in which the parent melt fractionated or passed through. Six concordant analyses of zircon inner rims are older than the outer rim ages and vary between ca. 791 ± 14 Ma and 849 ± 16 Ma (238U/206Pb ages). The ca. 60 Ma age spread for inner rims may partly reflect mixed ages due to the laser beam overlapping different zircon parts, but may also reflect contributions from older late Neoproterozoic rocks not yet identified in the study area, but that have been recognized in the Sary-Dzhaz and Akshairak ranges to the east (Glorie et al. 2011; see below).

The youngest age clusters of the Lower Member rhyolitic lava and the sill samples are indistinguishable within analytical uncertainty and show that volcanic activity and sill emplacement occurred in the late Tonian to early Cryogenian around 726–720 Ma. The different zircon age spectra of the two samples indicate that they must represent magma batches derived from different parts of the magma chamber, or from different magma chambers.

Fig. 12 a Concordia diagram for 40 dated zircons from porphyric rhyolite sill sample Ba-133 showing a wide age spectrum and age clusters. Color coding as in Fig. 11; for the color image we refer to the online version of this paper. b Sixteen analyses of zircon outer rims have 206Pb/238U ages in the range 714 ± 10 Ma to 741 ± 11 Ma, for which a youngest 720.3 ± 6.5 Ma weighted mean of the 206Pb/238U ages can be calculated (horizontal line).
The zircon cores in Ba-133 represent contaminants derived from crustal material and this contrasts with previous studies that assume that much of the Neoproterozoic crust in the CAOB was derived from subduction-related, but juvenile melts (e.g. Safonova 2017). Glorie et al. (2011) found Paleo- (2500–1850 Ma) and Mesoproterozoic (1200–1000 Ma) inherited zircons in a migmatite and in Neoproterozoic granitoids (831 ± 6 Ma) and felsic tuff (842 ± 16 Ma) of the Middle Tianshan block exposed in the Sary-Dzhaz and Akshairak ranges, ca. 150 km along strike to the northeast of the BNC. The ca. 791 ± 14 Ma to 849 ± 16 Ma ages of inner zircon rims in BNC sill sample Ba-133 partly overlap these 830–840 Ma ages and may stem from related rocks that are not exposed or have not yet been recognized in the Djetim-Too area. Zircons from much older felsic gneisses of the Kuilyu Complex in the Sary-Dzhaz Range yielded Paleoproterozoic, ca. 1.83, 1.85, 1.93, 2.08, 2.32 and 2.33 Ga 207Pb/206Pb mean ages and upper intercept ages (Kröner et al. 2017). Neoarchean zircons appear to be absent in these studies, whereas 2.57–2.62 Ga upper intercept ages for multi-grain zircon fractions are reported by Kiselev (2014, and references therein). Although Neoarchean zircons appear to be absent in the studies of Glorie et al. (2011) and Kröner et al. (2017), and zircons with 1200–1000 Ma ages are lacking in BNC sill sample Ba-133, it is clear that much older crustal material must have made significant contributions to the Neoproterozoic arc rocks of the Djetim-Too, Sary-Dzhaz and Akshairak ranges.

The 726–720 Ma arc-related rocks of the BNC probably represent the youngest part of a long-lived, since 950–900 Ma active margin bordering a continent (Kheraskova et al. 2010). In their model, this continent formed after the break-up of Rodinia at 950–900 Ma and comprised the North China block, parts of the Tianshan block and the basement to the Tarim Basin. Subduction of the so-called Paleoasia ocean beneath these blocks appears to have given way to rifting at 755–690 Ma with attendant alkaline bimodal magmatism and opening of the Sak paleo-ocean (Kheraskova et al. 2010).
et al. 2010; Alexeiev et al. 2019, and references therein). However, the calc-alkaline, predominantly intermediate to acid, and explosive character of the Big Naryn Complex argues against a rift setting at 726–720 Ma in the Djetim-Too area, but instead favor an active continental magmatic arc situated on Kuilyu Complex type crust.

**Alteration**

Alteration of BNC lithologies is pervasive but varies in type and intensity, with most samples retaining their primary magmatic textures. The propylitic and sericitic alteration was clearly due to reaction with water-rich fluids that infiltrated permeable volcanic rocks (such as ignimbrites and tuffs). It is clear from the geological map and earlier studies that alteration was controlled by fluid flux along and near later faults, which in the Djetim-Too Range are also associated with local mineralization. In these much younger thrust and fault zones, complete obliteration of primary minerals and textures was accompanied by cleavage formation and reaction of Ca-rich plagioclase to sericite and epidote. Unpublished 40Ar/39Ar step-heating dating results of altered groundmass and altered feldspar phenocrysts of BNC volcanic rocks and sills clearly indicate that deformation and alteration occurred sometime between the mid-Carboniferous and early Permian (Hegner et al. 2010; Terbishalieva 2018). In the Djamanechky cross-section (Online Resource 1), BNC rocks are tectonically juxtaposed against mid-Carboniferous and early Permian (Hegner et al. 2010; Terbishalieva 2018). In the Djamanechky cross-section (Online Resource 1), BNC rocks are tectonically juxtaposed against mid-Carboniferous and early Permian (Hegner et al. 2010; Terbishalieva 2018).

Conclusions

The Big Naryn Complex exposed in the East Djetim-Too Range of the Kyrgyz Middle Tianshan block is a tectonized, at least 2 km thick sequence of predominantly felsic to intermediate volcanic rocks intruded by porphyric rhyolite sills. The BNC overlies a Kuilyu Complex basement of greenschist- to amphibolite-facies chlorite-mica schists, metadolerites and metagabbros, and is overlain by glacio- genetic clastic sediments of the late Neoproterozoic Djetim-Too Formation. Rocks of both the basement and Djetim-Too Formation also occur tectonically intercalated in the BNC, the former mainly in the lower parts of its Lower Member. Figure 14 shows the composite stratigraphic column for the Eastern Djetim-Too Range with approximate thicknesses of the Lower and Upper members and the geological relations between the Big Naryn Complex, Kuilyu Complex and Djetim-Too Formation. The dated samples are shown in their approximate (tectono-) stratigraphic positions.

The BNC comprises two volcanic members and discordant rhyolite sills. Rhyolite-to-dacite lavas containing quartz and alkali feldspar phenocrysts dominate the up to 1100 m thick Lower Member that also contains interlayered tuffs and tuff-derived sediments, and minor basalts. The at least 900 m thick Upper Member is dominated by pyroclastic rocks, mainly rhyolitic to dacitic ignimbrites, often with eutaxitic textures and altered glass shards and fiamme. Later porphyritic rhyolite sills are concentrated at the top of the Lower Member, and intruded into zones of weakness and along the contact between both members. Many sills have centers that are enriched in alkali feldspar phenocrysts, which is likely to be a result of flow differentiation during magma intrusion.

Volcanic rocks and sills form a basaltic to rhyolitic series of mainly calc-alkaline character; the rhyolite sills and many of the Upper Member ignimbrites have high SiO$_2$ contents. In addition, the rhyolite sills have high-K calc-alkaline, metaluminous-to-peraluminous I-type characteristics. All samples are enriched in LREE and basalts have smooth REE patterns. Eu negative anomalies are prominent in intermediate to acid rocks (including the sills) and increase with increasing silica contents, pointing to plagioclase fractionation. In primitive mantle normalized multi-element diagrams, all BNC samples show Ti negative anomalies suggesting formation in a supra-subduction zone setting.

A Lower Member rhyolite and a sill sample have ca. 726 and 720 Ma U–Pb zircon crystallization ages that overlap within analytical uncertainty. Most of the BNC magmatism therefore occurred within a short time span in the Neoproterozoic (late Tonian–early Cryogenian). The rhyolite lava lacks older, inherited zircons, while the sill sample contains zircon cores with Neoarchean (2.63, 2.64 Ga) ages. Paleo-protrozoic (2.33 to 1.81 Ga) and Mesoproterozoic (1.55 Ga) ages, and zircon inner rims have a ca. 815 Ma pooled age. The Neoarchean to Mesoproterozoic zircon components must have been inherited from basement rocks, whereas the ca. 815 Ma old zircons must originate from Neoproterozoic basement rocks that are older than the BNC, but have not yet been identified in the East Djetim-Too Range. 40Ar/39Ar step-heating dating of amphibole from a Kuilyu Complex metagabbro yielded a ca. 1.75 Ga plateau age, which is interpreted as the cooling age following metamorphism of basement in Paleoproterozoic times.

The large amount of pyroclastic rocks, especially in the Upper Member, in combination with major and trace element compositions, the presence of Neoarchean to Neoproterozoic inherited zircons and a depositional basement of metamorphic rocks (Kuilyu Complex) point to the formation...
Northwards thrusting resulting in tectonic intercalation of basement rocks and widespread alteration likely occurred in late Paleozoic times and was due to terrane accretion and the formation of a fold and thrust belt to the south, in the South Tianshan block.

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