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NEOARCHEAN SANUKITOIDS FROM THE KARELIAN AND BUNDELKHAND CRATONS: COMPARISON OF COMPOSITION, REGIONAL DISTRIBUTION AND GEODYNAMIC SETTING

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This study presents the comparative distribution and composition of Neoarchean sanukitoid massifs from the Karelian (Fennoscandian Shield) and Bundelkhand (Indian Shield) Cratons. It has been established that sanukitoid massifs from both the cratons are localised in linear zones nearly parallel to their respective greenstone belts. Neoarchean (2.56–2.53 Ga) sanukitoids from Bundelkhand are geochemically similar to those from Central and Western Karelian zones (2.72–2.68 Ga) while they are less differentiated as compared to the sanukitoids from Eastern Karelia (2.74–2.73 Ga). The geochemical similarities in sanukitoids from both these cratons, their proximity with coeval arc-type volcanic rocks and location in linear zones are suggestive that subduction related processes might have been responsible for their formation in both Karelian as well as Bundelkhand cratons.

K e y w o r d s: Sanukitoids; Karelian Craton; Bundelkhand Craton; Archean; Geodynamics.

К. Б. Джоши, А. И. Слабунов. НЕОАРХЕЙСКИЕ САНУКИТОИДЫ КАРЕЛЬСКОГО И БУНДЕЛКХАНДСКОГО КРАТОНОВ: СРАВНЕНИЕ ПО СОСТАВУ, ПРОСТРАНСТВЕННОМУ РАСПРЕДЕЛЕНИЮ И ГЕОДИНАМИЧЕСКОЙ ОБСТАНОВКЕ

В данной работе проводится сопоставление распределения в пространстве и состава неоархейских санукитоидных массивов Карельского (Фенноскандинавский щит) и Бунделкхандского (Индийский щит) кратонов. Показано, что в обоих рассматриваемых кратонах массивы санукитоидов локализуются в линейных зонах, близких по ориентировке зеленокаменным поясам. Неоархейские (2,56–2,53 млрд лет) санукитоиды Бунделкхандского кратона по петрохимическим особенностям сходны с аналогичными породами Центрально- и Западно-Карельской зон Карельского кратона с возрастом 2,72–2,68 млрд лет, вместе с тем они менее дифференцированы по сравнению с санукитоидами Восточно-Карельской зоны (2,74–2,73 млрд лет). Санукитоиды обоих рассматриваемых кратонов сходны по геохимическим характеристикам и сопоставимы с субдукционными комплексами, кроме того, с ними ассоциируют близкие по возрасту островодужные вулканиты. Все это, наряду с линейным характером распределения в пространстве, позволяет рассматривать их как субдукционные образования.

Ключевые слова: санукитоиды; Карельский кратон; Бунделкхандский кратон; архей; геодинамика.

Introduction

Sanukitoids (High Mg, Ba, Sr diorites-granodiorites-monzogranites) are typical Archean rocks as are komatiites, tonalite-tondhjemite-granodiorites (TTGs), and Banded Iron Formations (BIFs). Despite the fact that the Archean represents the dominant period of crustal growth, its preservation and the geodynamic framework is controversial and straddles between plate tectonic [De Wit, 1998; Condie and Benn, 2006; Shchipansky, 2012; Hölttä et al., 2014] and non-plate tectonic models [Hamilton, 1998, 2011; Harris and Bédard, 2014]. Higher mantle temperature and compositionally different atmosphere during the Archean resulted in the formation of typical Archean lithologies like sodium rich TTG suite, komatiites, BIFs, the late high-K granitoids and the rocks of sanukitoid series [Brown, 1985, 2007; Sylvester, 1994; Reddy and Evans, 2009; Herzberg et al., 2010; Martin et al., 2010; and references therein]. Additionally, arc-type basalt, andesite, dacite and ryolite (BADR), adakites, boninitic series rocks [Polat and Kerrich, 2002; Malviya et al., 2006; Svetov, 2009] are common lithologies in Archean cratons. There have been reports of Archean eclogites and eclogitic facies rocks in both Fennoscandian and Indian shields [Volodichev et al., 2004; Mints et al., 2010; Saha et al., 2011; Li et al., 2015].

TTGs are the major component of the Archean crust. They are sodic, rich in silica often have high La_N/Yb_N abundances and moderate to high Sr/Y at low Y abundances [Hoffmann et al., 2011; Condie, 2014]. The origin of these rocks has been widely debated with models ranging from subducting hydrous basaltic slab [Arth and Hanson, 1972; Martin and Moyen, 2002 and references therein; Foley et al*.,* 2002; Laurie and Stevens, 2012] to an over thickened mafic crust [Hoffman et al*.,* 2011] as a source in plume related plateau basalt [Condie, 2005, 2014; Foley, 2008; Smithies et al., 2009; Willbold et al., 2009] or within tectonically thickened island arc crust [Adam et al., 2012; Nagel et al., 2012; Hoffmann et al., 2014], while some propose a role of intracrustal differentiation which later evolved by crystal fractionation of primitive andesitic melt [Kelemen et al., 2014]. However, the most widely accepted mechanism for the origin of TTG magmas is by partial melting of hydrous metabasaltic rocks [Rapp et al., 1991; Patiño Douce and Beard, 1995; Rapp and Watson, 1995].

In addition to the abundant TTG suites, K-rich granitoids (sanukitoids and granite-granodiorite-monzogranite (GGM) series) are prominent (Fig. 1) in many Neoarchean cratons [Sylvester, 1994; Egorova, 2014]. The several generations of these K-rich granites have been attributed to partial melting of a lower crust [Champion and Sheraton, 1997; Mikkola et al., 2012 and references therein] and mantle derived source contaminated by continental crust as in the case of sanukitoid suite of rocks [Shirey and Hanson, 1984; Stern et al., 1989; Smithies and Champion, 2000; Halla, 2005; Heilimo et al., 2011; Feio and Dall'Agnol, 2012; Joshi et al., 2017]. Sanukitoids, first identified by Shirey and Hanson [1984], have been reported from Neoarchean terranes all around the world (Fig. 1). Sanukitoids have geochemical characteristics typical of both Archean TTGs and modern BADR series [Laurent et al., 2011] and are considered to have formed up to the Neoarchean. However, Phanerozoic analogues of Neoarchean sanukitoids have been reported from Caledonian Scotland [Fowler and Rollinson, 2012]. Recently, granitoids with sanukitoid affinities but lacking typical sanukitoid features have been reported. The most notable granitoid with such character is the Closepet granitoid in the Dharwar Craton, India [Jayananda et al., 1995; Moyen et al., 2001]. However, similar compositions have also been reported from Wyoming [Frost et al., 1998], Shandong (China) [Jahn et al., 1988], Limpopo [Barton et al., 1992], Aravalli and Bundelkhand Cratons (India) [Mondal and Raza, 2013; Joshi, 2014; Joshi et al., 2017]. Martin et al. [2005] considered that similar petrogenitic processes were responsible for the formation of Closepet granite and sanukitoids. Therefore, both these suites will be considered as part of sanukitoids in the following text.

Sanukitoids range from high-Mg diorites, monzodiorites to granodiorites and are often associated with syenites, lamprophyres, and coeval mafic enclaves which were emplaced between 2.9 and 2.5 Ga [Laurent et al., 2011; Fowler and Rollinson, 2012]. Sanukitoids can compositionally range from mafic to felsic end members with typical silica concentration ranging from 50 to 75 wt. % and MgO contents of ~ 0.1 to 8 wt. % [Martin et al., 2010]. A distinct feature that separates sanukitoids from TTGs is the relatively high content of both compatible (e. g. Mg, Ni, Cr) and incompatible elements of sanukitoids at a given silica content [Heilimo et al., 2011]. The petrogenesis of sanukitoids is still

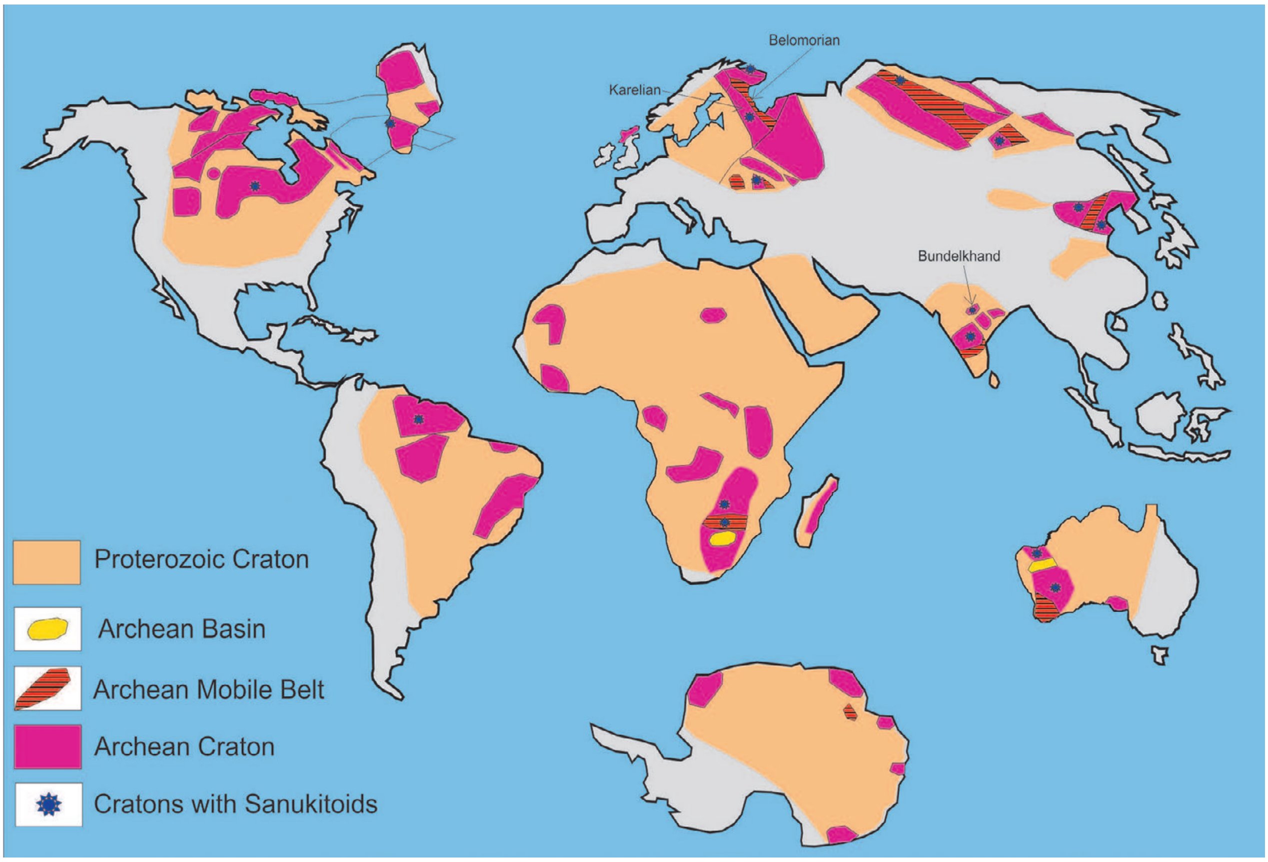

Fig. 1. Global distribution of main Archean structures [modified after: Bleeker, 2003; Slabunov, 2008] and sanukitoids (data in text)

a topic of discussion. Some believe their derivation by direct melting of an enriched mantle source [Stern, 1989; Stern and Hanson, 1991; Stevenson et al., 1999] while others believe in variable extents of interactions between mantle peridotite and TTG magmas in subduction environments [Jayananda et al., 1995; Smithies and Champion, 1999, 2000; Martin et al., 2005; Moyen, 2011]. The agent of enrichment might range from slab derived adakite melt [Martin et al., 2010] to subducted terriginous sediments [Laurent et al., 2011]. Mikkola et al. [2011] suggested that the Neoarchaean appearance of several distinct mantle derived suites, i. e., sanukitoid series of rocks displaying compositional similarities as well as differences, can be explained with a two phase metasomatism model [Halla et al., 2009; Heilimo et al., 2010] wherein the mantle source is metasomatized first during subduction by fluids and melts from the subducting slab and / or sediments and later by upwelling alkaline fluids, following slab breakoff, which, based on numerical modeling [van Hunen and van den Berg, 2008], were more frequent in the hotter Archean mantle. However, some researchers even suggest mantle plume as a probable cause for melting of metasomatised mantle [Kovalenko et al., 2005; Egorova, 2014; Mints et al., 2015] and formation of sanukitoids.

The distribution of sanukitoids in space and time is crucial to understand the geodynamic setting in which they formed. In this study, we 1) compare the petrology, geochemistry and distribution of Neoarchean sanukitoids from the Karelian (Fennoscandian Shield) and Bundelkhand (Indian Shield) Cratons; 2) try to establish a time-space relationship between sanukitoid massifs and volcanogenic complexes; and further 3) synthesize the data obtained to understand the geodynamic processes that were operative for the formation of sanukitoids.

Geological setting

Karelian Craton

The Karelian Craton (Fig. 2) is the oldest core of the Fennoscandian Shield. It is subdivided into five blocks (or Provinces) viz. Norrbotten, Murmansk, Kola, Belomorian and Karelian [Slabunov et al., 2006a, b; Hölttä et al., 2008, 2012, 2014]. The Karelian and Murmansk blocks form the cratonic nuclei and therefore, have been referred

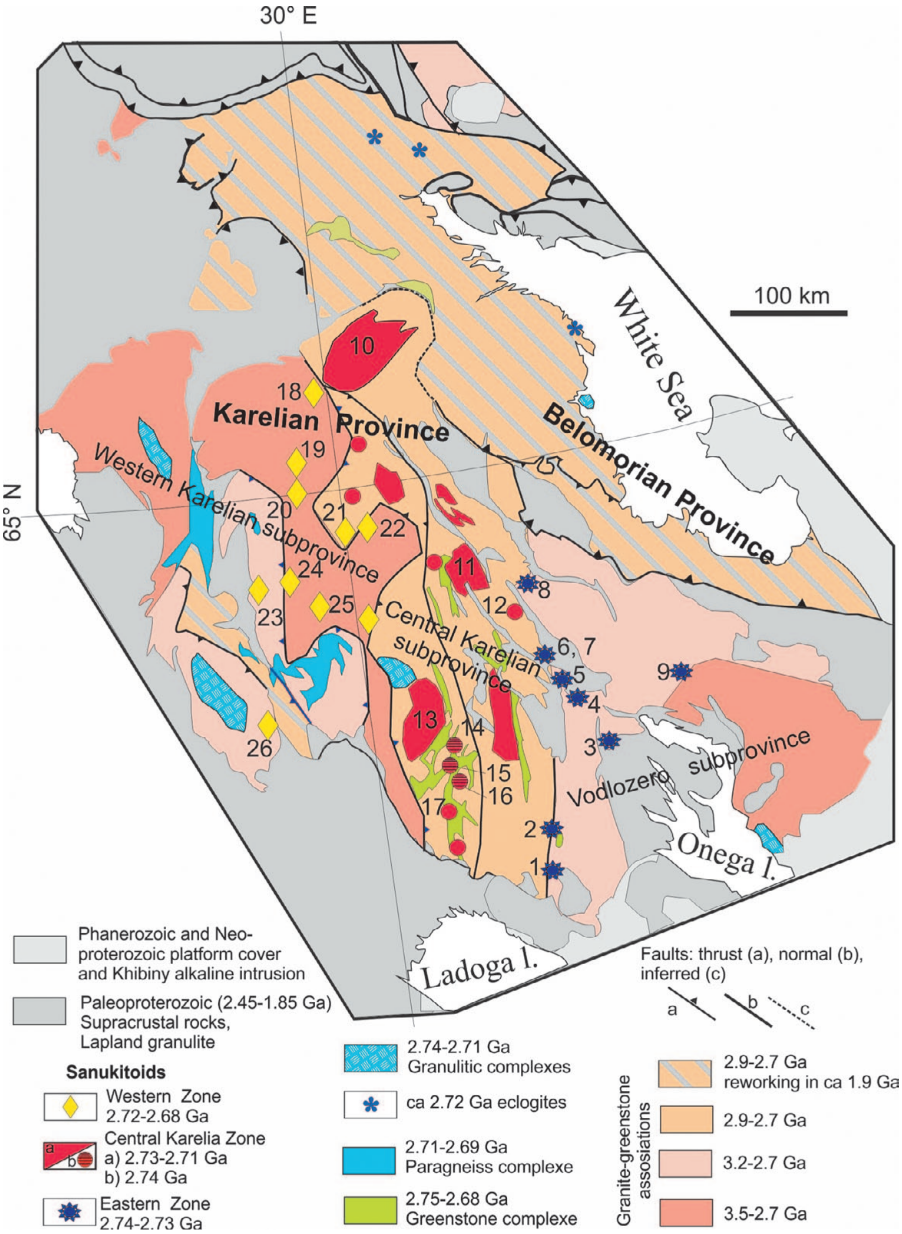

Fig. 2. A generalised geological map of the Archean of the Karelian and Belomorian Provinces, Fennoscandian shield [modified after: Slabunov et al., 2006a, b, 2011a; Hölttä et al., 2008, 2014; Kulikov et al., 2017] and distribution of sanukitoids (more data in text and table 1)

to as the Karelian and Murmansk Cratons [Slabunov et al., 2006a, b] while the Belomorian Province is a mobile belt, which is a superposition of Archean (2.9–2.7 Ga) and Paleoproterozoic (2.0–1.9 Ga) orogens [Daly et al., 2006; Balagansky et al., 2015]. Sanukitoid massifs are common in the Karelian Craton, there are a few reported in the Murmansk Craton and Kola Belt, but absent in the Belomorian Belt [Slabunov, 2008; Egorova, 2014]. The Norrbotten Craton has not been studied in detail but there are no reports of sanukitoids in that area [Lauri et al., 2016].

The Karelian Craton has been divided into three subprovinces i. e. Vodlozero, Central Karelia and Western Karelia based on lithology, structural and age relations [Lobach-Zhuchenko et al., 2005; Hölttä et al., 2012]. In general, the Vodlozero and Western Karelia sub-provinces include Neo- to Paleoarchean TTGs and greenstone complexes while the Central Karelia sub-province is generally Neoarchean and consists of recycled Mesoarchean crustal material [Slabunov et al., 2006a, b; Hölttä et al., 2012, 2014, 2017; Käpyaho et al., 2017].

The Vodlozero sub-province is in the south-eastern part of the Karelian Province and consists of TTGs (3.24–2.8 Ga) and greenstone (3.05–2.74 Ga) complexes which are cut by 2.98 Ga, 2.4 Ga, 2.0 Ga mafic intrusions, and Neoarchean granitoids [Chekulaev et al., 2009; Svetov et al., 2010; Hölttä et al., 2012, 2014, 2017, 2019]. The 2.75–2.73 Ga sanukitiod massifs (Fig. 2, Table 1) are common in the western part of this sub-province [Bibikova et al., 2004; Egorova, 2014; Kulikov et al., 2017]. Three age groups of greenstone complexes have been reported in Vodlozero: 1) 3.05–2.97 Ga basalt-komatiite and basalt-andesite-dacite-rhyolite suites; 2) ~2.86–2.8 Ga – a) basalt-komatiite and adakite suites, b) rift-type quartz arenites with komatiite; 3) ~2.76–2.74 Ga – felsic volcanic rocks [for review see Slabunov et al., 2006a, b; Svetov et al., 2010 and Hölttä et al., 2012, 2014]. These complexes form the Vedlozero-Segozero, South Vygozero and Sumozero-Kenozero greenstone belts. Meso- (3.1 Ga) and Neoarchean (2.7–2.74 Ga) low-pressure granulitic complexes have also been reported in this terrane [Slabunov et al., 2006a, b, 2013] along with felsic volcanic rocks (2.74 Ga) that have ages similar to those of the sanukitoids.

The Western Karelian sub-province is divided into the Ranua, Iisalmi, Ilomantsi, Rautavaara and Kianta terranes [Sorjonen-Ward and Luukkonen, 2005; Slabunov et al., 2006a, b]. Siurua gneisses (~3.5 Ga) located in the Ranua complex are the oldest dated rocks in the Karelian Province [Mutanen and Huhma, 2003]. The Western Karelian sub-province consists of Meso-Neoarchean TTG, granitoids, greenstones and paragneisses complexes. Two age groups of greenstone complexes have been reported in the province 1) ca 2.94 Ga – adakite-type felsic volcanogenic rocks (Luoma Group) and 2) 2.84–2.79 Ga – basalts-komatiites, Fe-basalts, felsic volcanite, BIF and sediments [Sorjonen-Ward and Luukkonen, 2005; Slabunov et al., 2006a, b; Huhma et al., 2012; Hölttä et al., 2012, 2014; Lehtonen et al., 2016]. These complexes formed the Tipasjarvi, Kuhmo, Suomussalmi, Kostomuksha, Oijärvi and Kovero greenstone belts. The youngest supracrustal Archean rocks in this sub-province are Neoarchean (2.71–2.69 Ga) Nurmes paragneisses with minor metabasalts (amphibolite) [Kontinen et al., 2007]. Local TTGs, sanukitoids and mafic rocks have been suggested as a probable source for these wackes, which formed in a back-arc or intra-arc basin [Kontinen et al., 2007]. Neoarchean medium-pressure granulites complexes have also been reported in Iisalmi terrane [Hölttä et al., 2000]. Sanukitoids (Fig. 1) with age 2.73–2.72 (up to 2.69) Ga (Table 1) are common in the Western Karelia sub-province, together with slightly younger (~2.70 Ga) granitoid groups like enderbites, quartz diorites, syenites and GGM suite [Käpyaho et al., 2006; Mikkola et al., 2013, 2017 and references therein; Hölttä et al., 2014]. Recently, new Neoarchean (ca 2.71 Ga) complexes of alkali-enriched gabbro and diorite were reported in the Western Karelia sub-province [Mikkola et al., 2017]. This complex formed the last collisional stage in a Himalayan-Tibetian style tectonic setting [Slabunov et al., 2016; Mikkola et al., 2017].

The Central Karelian sub-province is in the central part of the craton (Fig. 2) and mainly has younger (<2.80 Ga with a few occurances of 2.90 Ga) crust [Lobach-Zhuchenko et al., 2000; Slabunov et al., 2006a, b; Huhma et al., 2012; Hölttä et al., 2012, 2014]. Despite TTGs being the dominant lithology in this subprovince, the biggest Neoarchean sanukitoid intrusions are also located here (Fig. 2). Two generations of sanukitoids have been reported in the Central Karelian sub-province 1) 2.75–2.74 Ga and 2) 2.72–2.70 Ga [Sorjonen-Ward and Claoue-Long, 1993; Heilimo et al., 2011]. The greenstone complexes of this province (Ilomantsi and Gimoli-Bol'shozero greenstone belts) essentially consist of volcaniclastic graywackes with felsic and mafic volcanic rocks, BIFs and komatiites which were formed at ~2.75–2.73 Ga with intensive hydrothermal events at 2.73–2.71 Ga [Sorjonen-Ward and Claoue-Long, 1993; Slabunov et al., 2006a, b; Hölttä et al., 2014; Käpyaho et al., 2017]. Neoarchean low-pressure granulitic complexes (Tulos and Voknavolok) have recently been reported in this sub-province [Slabunov et al., 2006a, b, 2015; Heilimo et al., 2010; Mikkola et al., 2013; Hölttä et al., 2017].

Bundelkhand Craton

The Central Indian Tectonic Zone (CITZ) divides the Indian shield into two Archean blocks; Northern and Southern. Aravalli and Bundelkhand cratons form part of the northern block while Singhbhum, Bastar and Dharwar cratons form part of the southern block [Acharya, 2003]. The Bundelkhand Craton is situated to the north of the CITZ and covers an area of 26,000 km^2. The craton (Fig. 3) is overlain by Indo-Gangetic alluvium to the north, Paleoproterozoic Gwalior and Bijawar basin to the north, south, and southeast and Mesoproterozoic Vindhayan Supergroup to the southeast, southwest and west [Basu, 1986; Sarkar et al., 1996; Ramakrishnan and Vaidyanadhan, 2010]. The Bundelkhand Craton consists of the Archean (TTG-gneisses, greenstone, metasedimentary and mafic-ultramafic complexes [Slabunov et al., 2018a, b], surrounded by Neoarchean Bundelkhand granitoids [Singh et al., 2018], which are cut across by Paleoproterozoic quartz reefs

Table 1. The ages (in Ma) of sanukitoids from the Karelian and Bundelkhand Cratons

Intrusion	Rock Name	Age (Ma)	U-Pb method	References*	No on map
KARELIAN CRATON					
1) Eastern Sanukitoid Zone					
Hautavaara	Monzodiorite, granite	2743 ± 8, 2742 ± 23	SIMS	2	1
Chalka	Granodiorite	*2745 ± 5*	ID-TIMS	15	2
Elmus	Quartz monzonite	2742 ± 8	SIMS	2	3
Bergaul	Monzogranite	2730 ± 17	ID-TIMS		4
Panozero	1st Phase: Mafic-ultramafic, monozite, lamproite, lamprophyre	(2765 ± 8; 2785 ± 38), 2740 ± 14; 2744 ± 18 2737 ± 11	SIMS	2, 6, 17	5
	2nd Phase: diorites, quartz monozite	2739 ± 11; *2727 ± 4*	SIMS ID-TIMS	2, 4	
	3rd Phase: granodiorite, quartz monozite	2741 ± 8; *2736 ± 14* *2734 ± 17*	SIMS ID-TIMS	2, 4	
Sjargozero	Lamprophyre, granodiorite, syenite	2742 ± 16; 2738 ± 12 2735 ± 14 *2734 ± 15*	SIMS *ID-TIMS*	2, 3	6
Sharavalampi	Pyroxenite, gabbro, diorite	2726 (Tit)	*ID-TIMS*	*5*	7
Khizhjarvi	Syenite, pyroxenite	2748 ± 13 2744.5 ± 4 *2739.9 ± 4.1*	SIMS *ID-TIMS*	3	8
Konzhozero	Syenite, monzogranite	2762 ± 9; 2743 ± 15	SIMS	19	9
2) Central Karelia					
Pjozero	Gabbro, diorite, granodiorite	2724.4 ± 7.8; 2725 (Sm-Nd)	*ID-TIMS*	1, 14	10
Njuk-Bolshozero	Granodiorite, diorite	2709 ± 10; 2716 ± 11; *2705 ± 5;* *2732 ± 4*	SIMS *ID-TIMS*	2	11
Amindomoj	Gabbro, diorite	2725 ± 20	*ID-TIMS*	11	12
Koitere	Granodiorite	2722 ± 6	SIMS	9	13
Tasanvaara	Tonalite	2748 ± 6	ID-TIMS	18	14
Kuittila	Tonalite	2741 ± 9	SIMS	9	15
Sysmajarvi	Tonalite/quartz diorite	2744 ± 5	SIMS	9	16
Ilomantsinjärvi	Granodiorite	2728 ± 7	SIMS	9	17
3) Western Sanukitoid Zone					
Kuusamo	Granodiorite	2718 ± 5	SIMS	9	18
Kaapinsalmi	Tonalite	2722 ± 4	SIMS	9, 8	19
Raate	Granodiorite	2713 ± 3	ID-TIMS	10	20
Kaartojärvet	Gabbro	2715 ± 3	SIMS	13	21
Kurgelampi (Taloveis)	Diorite, Granodiorite	2725 ± 16; 2715 ± 5; 2710 ± 27	SIMS	2, 16	22
Loso	Diorite	2719 ± 19	SIMS	13	23
Arola	Granodiorite	2723 ± 6	SIMS	9	24
Siikalahti	Granodiorite	2683 ± 9	SIMS	13	25
Nilsiä	Granodiorite	2724 ± 28	SIMS	7, 9	26
BUNDELKHAND CRATON					
Karera	Granodiorite to granite	2563 ± 2; 2559 ± 7	SIMS	12	
Orccha	Granodiorite to granite	2560 ± 7	SIMS	12	
Khajuraho	Monzogranite	2544 ± 6	SIMS	12	

Note. *1 – Bibikova et al., 1997; 2 – Bibikova et al., 2005; 3 – Bibikova et al., 2006; 4 – Chekulaev et al., 2003; 5 – Dmitrieva, Kuleshevich, 2018; 6 – Guseva et al., 2009; 7 – Halla, 2005; 8 – Heilimo et al., 2007; 9 – Heilimo et al., 2011; 10 – Heilimo et al., 2013; 11 – Ivanikov, 1997; 12 – Joshi et al., 2017, 13 – Käpyaho et al., 2006; 14 – Larionova et al., 2007; 15 – Ovchinnikova et al., 1994; 16 – Samsonov et al., 2004; 17 – Sergeyev et al., 2007; 18 – Vaasjoki et al., 1993; 19 – Zhitnikova et al., 2012.

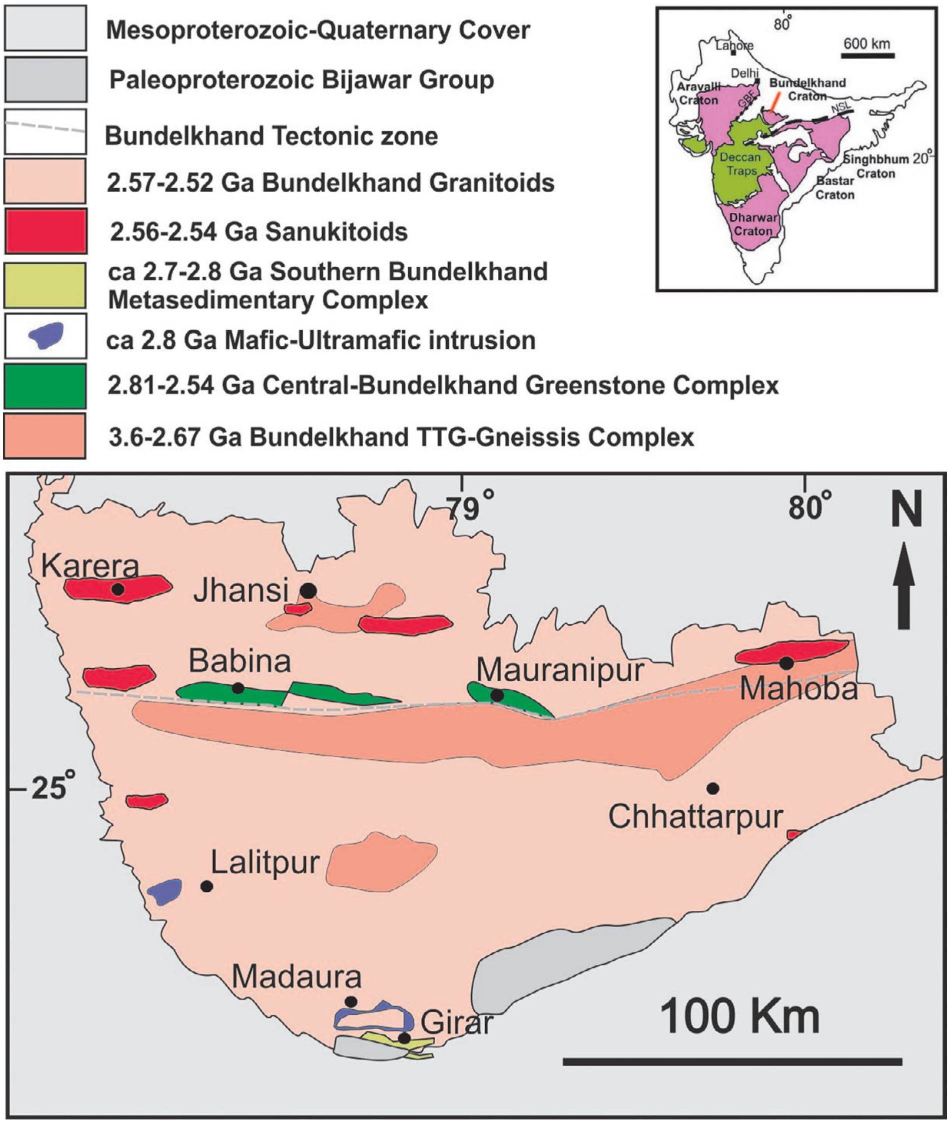

Fig. 3. Generalized geological map of the Bundelkhand Craton [modified after: Basu, 1986; Singh, Slabunov, 2016; Joshi et al., 2017; Slabunov, Singh, 2018b]. The inset shows an outline map of India with the different cratons of the Indian Shield [modified after: Radhakrishna, 1989]

[Pati et al., 2007; Slabunov et al., 2017b] and mafic dyke swarms [Sharma and Rahman, 2000]. The gneissic complex encompasses highly deformed TTGs of variable ages from Palaeoarchaean to Neoarchaean, while the high-K calc-alkaline granitoids are mostly late Neoarchaean.

The gneissic complex is easily distinguishable from the granitoids based on deformation and intrusive relationship, and forms the basement along which low-grade (greenschist to lower amphibolite facies) metasedimentary and metavolcanic rocks are exposed. Joshi et al. [2017] divided TTGs from the craton on the basis of geochemistry into low HREE and enriched TTGs which were formed by low-degree partial melting of basalt or amphibolite while *in situ* melting of amphibolite enclaves formed the enriched varieties. The oldest ages from TTGs (~ 3.5 Ga) are reported from Mauranipur and Babina areas from the central part of the craton [Sarkar et al., 1996; Kaur et al., 2014; Saha et al., 2016]. Ages as old as ~3.3 Ga have been reported from the eastern part (Mahoba) of the craton [Mondal et al., 2002; Joshi et al., 2017] while Verma et al. [2016] reported an age of 2.66 Ga from a trondhjemite sample in Babina.

The Bundelkhand metasedimentary and metavolcanic rocks (greenstone complexes) [Singh and Bhattacharya, 2010; Singh, 2012] are mainly exposed along two east – west-trending lineaments in the central and southern parts of the Craton [Singh and Slabunov, 2013, 2015, 2016; Slabunov and Singh, 2018b] (Fig. 3). The Central-

Bundelkhand Greenstone belt consists of a metamorphosed tholeiitic basalt and high Mg-basalt association, two age (2.81 and 2.54 Ga) groups of felsic volcanics and banded iron formation (BIF) while the Southern Bundelkhand greenstone (schist) complex consists of basic quartzites, BIF and lenses of dolomitic marble and chlorite schist near the quartzite/BIF boundary [Malviya et al., 2006; Singh and Slabunov, 2015, 2016; Slabunov et al., 2017a]. Singh and Slabunov [2015], Slabunov and Singh [2018b] dated porphyritic dacites from Babina and Mauranipur and metadacite from Mauranipur and reported zircon ages of 2.54–2.56 Ga and 2.81 Ga, respectively. The U-Pb age of a detrital zircon grain from the BIF of the Southern Bundelkhand greenstone (schist) complex from Girar is estimated at 2898 ± 26 Ma, and the age of metamorphic varieties at ca 2.7 and 2.4 Ga [Slabunov, Singh, 2018c]. Quartzites with interbeds of fuchsite-bearing (i. e. Cr-enriched) varieties that occur below BIF contain numerous igneous zircons from granitoids of Paleoarchean (3.43 and 3.25 Ga) age and display a similar Sm-Nd model age [Slabunov et al., 2017a], indicating that they were formed by recycling Paleoarchean granitoids and Mesoarchean mafic-ultramafic rocks in the period 2.8–2.7 Ga.

The Bundelkhand Granitoid Complex, the dominant lithological unit of the Bundelkhand craton, constitutes about 80 % of the exposed area (Fig. 3). The granitoids were emplaced into a previously deformed basement [Mondal et al., 1998, 2002; Malviya et al., 2004, 2006]. The diversity of igneous rocks includes syeno- and monzogranites, granodiorites, diorites, alkali feldspar syenites and granite porphyries [Rahman and Zainuddin, 1993; Mondal et al., 2002]. Joshi et al. [2017], on the basis of major and trace element geochemistry, suggested that the granitoid varieties were high-K calc alkaline and divided them into Sanukitoid type monzogranites, Sanukitoid type granodiorites and Closepet type granodiorites which belong to low silica high magnesium (LSHM) group and low-HREE monzogranites, low-Eu monzogranites and monzogranites which are part of high silica low magnesium (HSLM) group. Several geochronological studies have constrained the formation of the Bundelkhand Granitoid Complex between 2.55 and 2.49 Ga [Mondal et al., 2002; Verma et al., 2016; Joshi et al., 2017]. Geochemical and geochronological signatures from Paleo-Neoarchean TTGs, undeformed Neoarchean granitoids and volcano-sedimentary rocks suggest emplacement in a subduction environment with subsequent slab breakoff [Mondal et al., 2002; Singh and Slabunov, 2015, 2016; Joshi et al., 2017; Slabunov and Singh, 2018], wherein fluid assisted partial melting played a major role [Joshi et al., 2017]. It is believed that multiphase K-rich granite magmatism (2.55–2.49 Ga) in the early crust marks the transition from subduction setting to collision and the cratonization of the Bundelkhand craton [Crawford, 1970; Mondal et al., 1998, 2002; Meert et al., 2011; Verma et al., 2016; Singh et al., 2018]. The largescale granitic magmatism in the Bundelkhand craton overlaps temporally with similar events of granite magmatism [Verma et al., 2016] and mineralization in the adjacent Bastar (2490 Ma [Stein et al., 2004]) and Dharwar cratons (2510 Ma [Jayananda et al., 2000]).

All the above lithologies in Bundelkhand are traversed by NW trending mafic dyke swarms and NNE-SSW and NE-SW trending giant quartz veins that represent the last magma related hydrothermal activity in the Craton [Basu, 1986; Pati et al., 1997, 2007, 2008]. A variety of processes including crustal movements subsequent to stabilization, shear zones within granitic rocks and a role of late stage hydrothermal processes have been suggested for their origin [Roday et al., 1995; Pati et al., 2007]. The age of emplacement of the giant quartz veins (U-Pb zircon) is estimated at 1866–1779 Ma [Slabunov et al., 2017b]. However, the cross-cutting relationship with one of the mafic dyke generations suggests an age older than 2.0–1.1 Ga [Crawford, 1970; Rao et al., 2005; Pati et al., 2007; Pradhan et al., 2012].

Age and distribution of sanukitoids

Archean sanukitoid intrusions have been extensively investigated over the past three decades and have been discovered worldwide, however, information on their distribution is limited. Sanukitoids are typically K-rich, high Mg intrusive rocks that range from ultramafic to felsic, which were emplaced abruptly around 3.0–2.5 Ga with a peak around 2.7 Ga, marking a sharp change in the Earth's geodynamics [Kovalenko et al., 2005; Laurent et al., 2011; Halla et al., 2017]. Sanukitoids have been found to form post episodic TTG magmatism either before or at the same time as crust-derived granitoids [Heilimo et al., 2011; Joshi et al., 2017]. The time gap between the youngest TTGs and sanukitoids is very short and variable in each craton, which, together with the abrupt and temporally restricted appearance of sanukitoids, indicates a sharp change (between 3.0 and 2.5 Ga) in Earth's geodynamics, contradicting previous hypotheses of a transitional change [Halla et al., 2017].

Karelian Craton

Sanukitoid intrusions have been reported in all sub-provinces of the Karelian Province (Fig. 2). Till date about ~20 sanukitoid intrusions have been reported here, a majority of which are small except for Koitere, Pjozero and Njuk sanukitoids [Bibikova et al., 1997; Heilimo et al., 2010]. Based on age, sanukitoid intrusions in the Karelian Province have been divided into the eastern and western sanukitoids zone [Lobach-Zhuchenko et al., 2005; Bibikova et al., 2005; Heilimo et al., 2011]. However, here we prefer the division into three groups, viz., Eastern, Western and Central sanukitoids.

The Eastern Sanukitoid zone is located in western part of the Vodlozero sub-province (Fig. 2). These sanukitoids are slightly older than those of the other groups with an age range of 2.76 to 2.73 Ga and consists of Hautavaara, Chalka, Elmus, Bergaul, Panozero, Sjargozero, Sharavalampi, Khizhjarvi and Konzhozero intrusions (Table 1). Sanukitoids in the Eastern zone intrude old volcanic rocks of the greenstone complex, however, they formed simultaneously with the 2743 ± 12 Ma dacitic tuffs [Svetov et al., 2010] from the youngest (2.76–2.74 Ga) greenstone complex.

Some of these sanukitoid intrusions are strongly differentiated and vary from pyroxenite to monzogranite [Lobach-Zhuchenko et al., 2005] and are related with lamprophyre dykes which are also considered as part of the sanukitoids series [Lobach-Zhuchenko et al., 2005, 2008]. Panozero sanukitoids range from ultramafic through mafic to felsic [Lobach-Zhuchenko et al., 2005], all of which are characterized by elevated K_2O contents. Ivanikov [1997] related the Panozero intrusion (2.74 Ga) to the Elmus, Sharavalampi sanukitoids and Sjargozero and Khizhjarvi syenites, all of which are of the same age and were generated in a single stage [Bibikova et al., 2005, 2006]. The Chalka sanukitoids (2.74 Ga) consist of granodiorites that cross-cut the Vedlozero-Segozero greenstone belt [Ovchinnikova et al., 1994; Bibikova et al., 2005] while the Bergaul intrusion compositionally ranges from diorite-granodiorite to granite and some of the zircon cores from this intrusion indicate inheritance of 2.84 Ga [Bibikova et al., 2005].

Koitere, Kuittila, Ilomantsinjärvi, Pjozero, Njuk-Bolshozero, Amindomoj, Tasanvaara, Sysmänjärvi and Jalonvaara plutons (Fig. 2, Table 1) are located in the Central Karelian sub-province [Lobach-Zhuchenko et al., 2005; Kovalenko et al., 2005; Heilimo et al., 2013] constituting the Central Sanukitoid zone. There are two age groups of sanukitoids reported in this zone with a majority having ages of 2.73–2.71 Ga, which makes them younger than the Eastern zone sanukitoids, but older than the Western zone sanukitoid intrusions. In addition, most of the larger sanukitoid intrusions like Pjozero, Njuk-Bolshozero are in the central zone and have the same age. The second group of sanukitoids (3 intrusions) in this zone is aged 2.75–2.74 Ga (Fig. 2, Table 1) and located in the southern part of the central zone. The greenstone complexes in the Central Karelian sub-province (e. g. Ilomantsi) with arc-related volcanites were formed around ~2.75–2.73 Ga i. e. together with the older generation of sanukitoids [Sorjonen-Ward, 1993; Hölttä et al., 2012, 2017].

The Western Sanukitoid zone [Bibikova et al., 2005; Lobach-Zhuchenko et al., 2005] in the Western sub-province consists of Kaapinsalmi, Raate, Kaartojärvet, Kurgelampi, Loso, Arola, Siikalahti and Nilsiä sanukitoid intrusions (Fig. 2). The age of sanukitoids in this zone ranges from 2.72 Ga to 2.71 Ga (in some cases up to 2.68 Ga; Table 1). Porphyritic granodiorites in Nilsiä were first studied by Halla [2005] and were classified as sanukitoids [Halla et al., 2009]. Later, based on geochemical data, several felsic granitoids were considered to be part of the sanukitoids series including Kartojärvet [Käpyaho et al., 2006]. A majority of the sanukitoids in this zone are intermediate to felsic except for gabbros reported from Kaartojärvet [Samsonov et al., 2004; Bibikova et al., 2005; Heilimo et al., 2011, 2013]. These sanukitoids are slightly older than the 2.73–2.66 Ga granodiorite-granite-monzogranite (GGM) suite, 2.71 Ga alkaline gabbroids and ca 2.7 Ga quartz diorites as in the East Karelian sub-province [Hölttä et al., 2014; Mikkola et al., 2017 and references therein]. All these plutonic complexes excluding sanukitoids formed during the accretion-collision stage of crustal evolution. It is to be noted that the signatures of the Neoarchean (2.71–2.69 Ga) collisional orogen in the Belomorian Belt (Fig. 2), such as high-grade (kyanite sub-faces) metamorphism, migmatization, collison-type granites and nappe tectonics [Slabunov, 2008; Slabunov et al., 2006a, b, 2016; Hölttä et al., 2014], can also be observed in the western part of the craton [Mikkola et al., 2017]. The period between 2.72–2.71 Ga, which preceded the Belomorian collision, saw the formation of arc-type felsic volcanites (Kichani area of the Tikshozero belt), and Gridino eclogite in the Belomorian Belt [Hölttä et al., 2014; Li et al., 2015 and reference there]. The forming of Nurmes paragneisses may be one of the manifestations of this event in the Western Karelian sub-province. Therefore, the generation of sanukitoids in the Western zone preceded the collision and was connected with the last subduction process.

Bundelkhand Craton

Sanukitoids in Central India have recently been reported from western as well as eastern part of the Bundelkhand Craton. All sanukitoid varieties reported in Bundelkhand have been emplaced within a short time span (2.56 to 2.54 Ga [Joshi et al., 2017]) and are much younger than those found in Karelia. In Central Bundelkhand, these sanukitoid intrusions are found along the narrow discontinuous belt running from Karera in the east to Mahoba in the west, parallel to the Central Bundelkhand Greenstone belt (Fig. 3). These intrusions are majorly felsic bodies belonging to the Low Silica High Magnisium rich granitoids (LSHM) and range compositionally from granodiorites to, less commonly, monzogranites. These LSHM granitoids have been geochemically classified into three subgroups: Sanukitoid granodiorites (2.56 and 2.55 Ga), Closepet granodiorites (2.56 Ga) and sanukitoid monzogranites (2.54 Ga) on the basis of their rare earth element abundances [Joshi et al., 2017]. The sanukitoids in this belt have similar ages and might have been generated as a single phase. All the reported sanukitoid varieties show slight deformation features like gneissic appearance and presence of schliren. An important feature of these sanukitoids is that they are contemporaneous to the felsic volcanics from Babina, which have been dated at ~2.54 Ga [Singh, Slabunov, 2015; Singh et al., 2018].

Sanukitoids from Eastern Bundelkhand are exposed near Khajuraho and Mahoba and range from mafic to felsic intrusions varying compositionally from monzogranites through monzodiorite to granodiorites. All these intrusions are coarse grained to porphyritic with numerous mafic enclaves. A majority of the sanukitoid type granodiorites in this zone intrude the 3.33 Ga TTGs exposed near Mahoba while the sanukitoid type monzogranites mostly intrude the sanukitoid type monzodiorites and High Silica Low magnesium (HSLM) monzograites near Khajuraho. An emplacement age of 2.54 Ga and 2.56 has been suggested by Joshi et al. [2017] for sanukitoid monzogranites and HSLM monzogranites while no age determinations have been done on the monzodiorite body.

Sanukitoid intrusions from the Western Bundelkhand Craton are essentially Sanukitoid granodiorites and Closepet granodiorites and are exposed near Babina, Orccha and Karera. These intrusions are commonly associated with mafic magmatic enclaves [Ramiz and Mondal, 2017]. Closepet granodiorites have an emplacement age of 2.56 Ga with some inherited zircon cores with older ages (2.84 and 2.91 Ga) suggesting crustal inheritance [see Joshi et al., 2017 for review] while the sanukitoid granodiorites have ages (2.56 and 2.55 Ga) similar to those reported from the eastern part. It is also noted that as in the case of Karelian sanukitoids the Bundelkhand counterparts also have similar age as reported for volcanic rocks from the Bundelkhand craton [Singh and Slabunov, 2015].

Comparitive geochemistry/discussion

Petrography and Mineral Chemistry

Mineral chemistry studies of sanukitoids from the Kurgelampi post-tectonic intrusion (Western zone) and Panozero, Elmus, Sharavalampi and Khizhjarvi intrusions (eastern zone) were done by Lobach-Zhuchenko et al. [2005, 2008] and Egorova [2014]. Major mineral assemblages of these intrusions are plagioclase, quartz, hornblende (which was altered to biotite) and K-feldspar while clinopyroxene is reported from the mafic-ultramafic rocks of the Panozero intrusion (Table 2). Apatite, sphene, carbonate, zircon, epidote and opaques are the main accessory phases reported. Plagioclase varies from labradorite to oligoclase while micas are high Mg-biotite and some phlogopite. Amphiboles are mostly calcic, ranging from Mg-hornblende, edenite, pargasite, with actinolite and tremolite rims. It is suggested that actinolite and biotite rims in hornblende were probably formed due to metamorphic imprint during the Svecofennian orogeny [Lobach-Zhuchenko et al., 2005]. Pressures of 1.6 ± 0.6 kbar at the time of amphibole crystallization are calculated, indicating shallow level crystallization [Lobach-Zhuchenko et al., 2008].

The dominant mineral assemblage in sanukitoids from Bundelkhand are quartz, feldspar, biotite, and hornblende (Table 2). Accessory minerals include apatite, Fe-oxides, chlorite, titanite, allanite, zircon, and epidote [Mondal et al., 2002; Joshi, 2014]. Plagioclase composition in these granitoids ranges from $Ab_{98}\,An_1$ to $Ab_{70}\,An_{30}$ while potash feldspars are rich in K_2O and are mainly sanidine. Mica in Bundelkhand sanukitoids is mainly Mg-rich biotite while all the analyzed amphiboles are calcic and belong to the group of calcium amphiboles [Joshi, 2014]. Chemical variation in these amphiboles ranges from magnesio-hornblende to ferro-hornblende and edinite to ferro edinite [Joshi, 2014].

Major and Trace Element

General aspects of major element data of sanukitoids from the Karelian and Bundelkhand cratons are shown in Table 2 and Fig. 4. It is noted that Karelian sanukitoids show a wide variation in silica content as compared to sanukitoids from the Bundelkhand craton. Sanukitoids from the Eastern Sanukitoid Zone (Karelian Craton) show maximum variation in terms of major oxides, however, there is

Table 2. Comparitive mineralogy and geochemistry of Bundelkhand and Karelian Sanukitoids

Feature	Bundelkhand sanukitoids	East Karelian Sanukitoids	Central/West Karelian Sanukitoids
Rock type	Monzodiorite, granodiorite and granite	Ultramafic to felsic, lamprophyres and associated syenites	Gabbro, tonalitie, granodiorites, quartz diorites and lamprophyres
SiO_2 range	52.19–71.86 wt. %	45.60–70.75 wt. %	52.30–71.03 wt. %
*Eu/Eu**	0.68	0.92	0.79
Ba+Sr (Avg.)	1328 ppm	2276 ppm	1890 ppm
Ni+Cr (Avg)			
Mg# (Avg)	45.05	53.4	51.27
(La/Yb) N (Avg)	20.35	31.08	31.74
Age	2.54–2.56 Ga	2.74 Ga	2.71 Ga

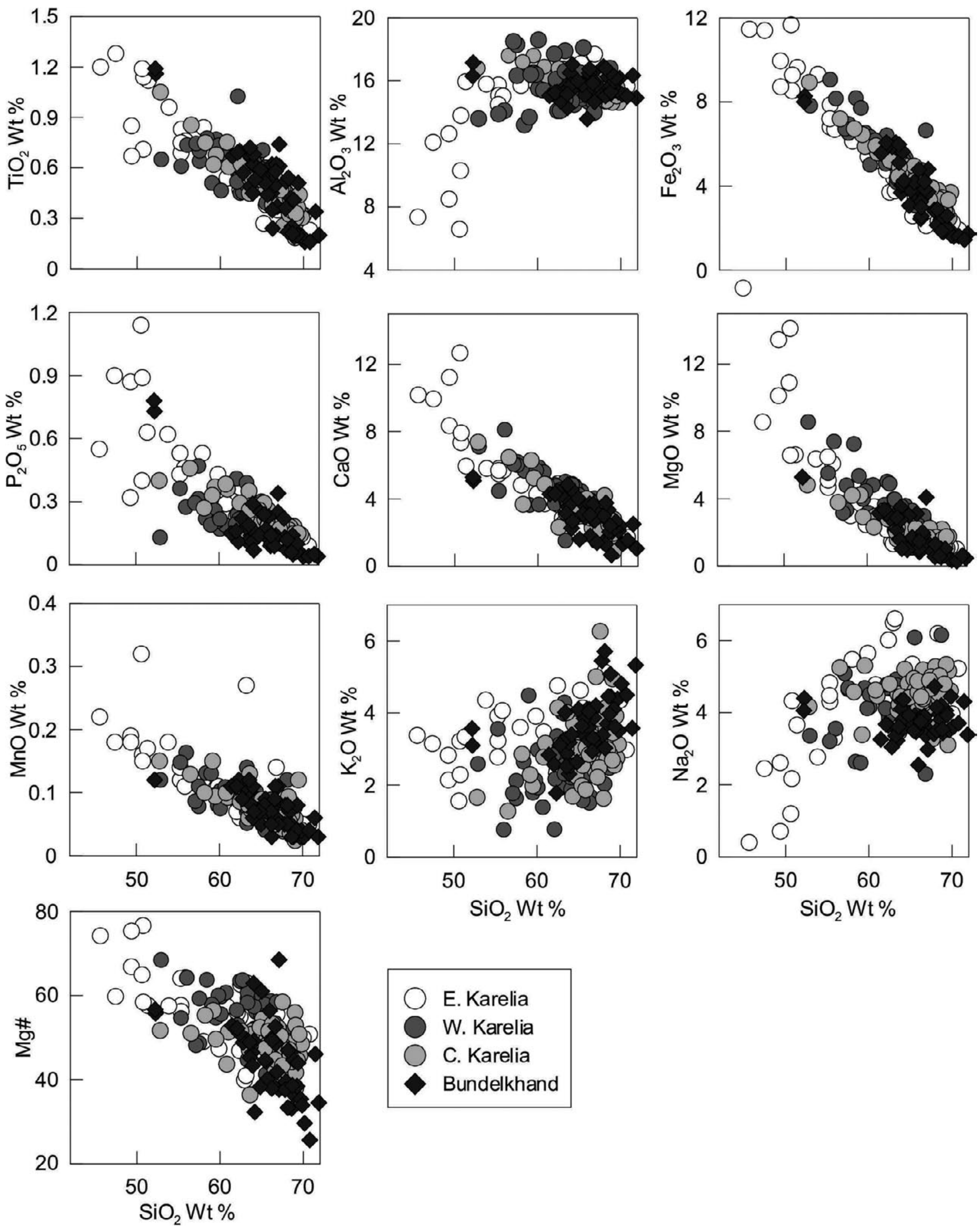

Fig. 4. Harker-type diagrams for major oxides and Mg# involving SiO_2 wt % as differentiation indices for sanukitoids from the Karelian and Bundelkhand Cratons. Data for Karelian sanukitoids and Bundelkhand sanukitoids are from [Vaasjoki et al., 1993; Halla, 2005; Heilimo et al., 2011, 2013 and references therein; Joshi et al., 2017]

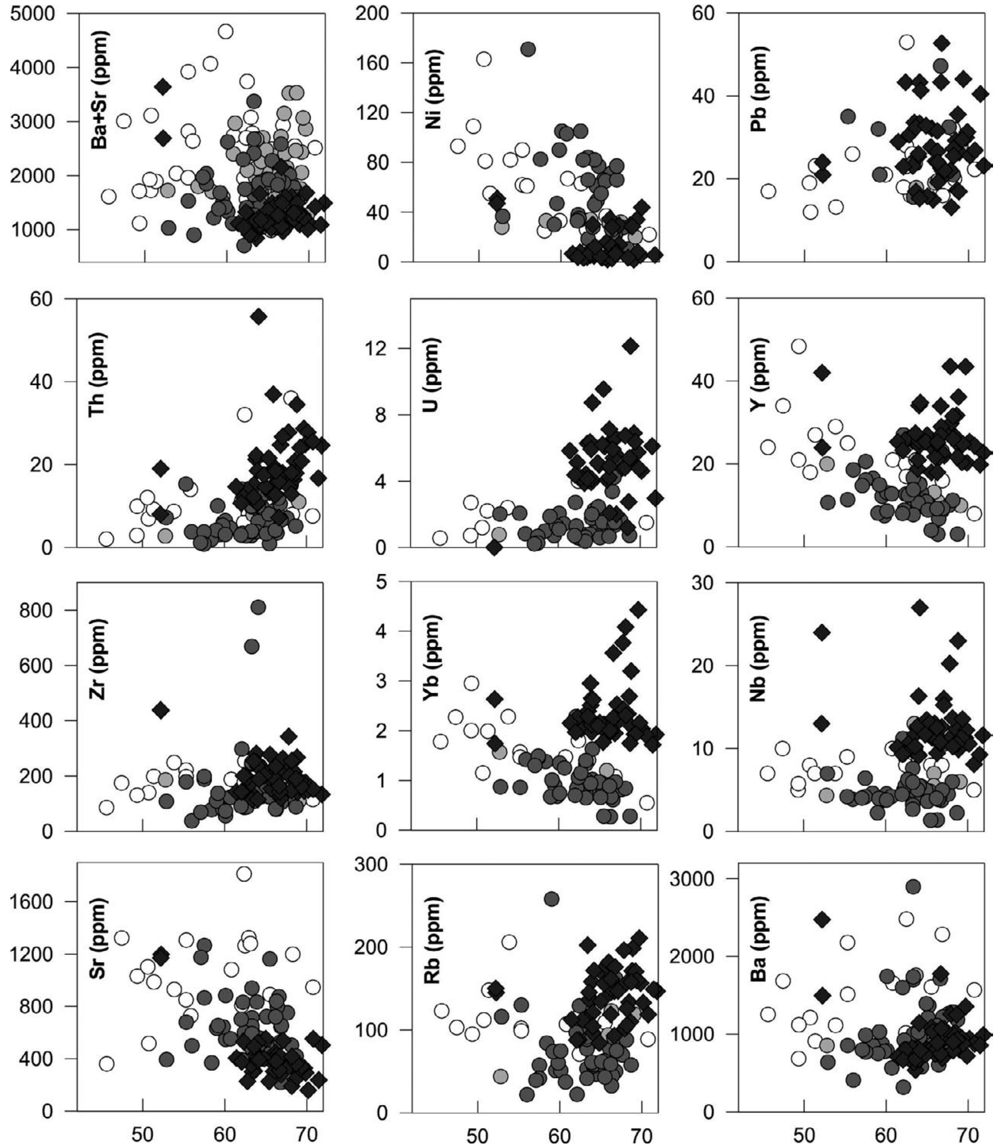

Fig. 5. Harker-type diagrams for trace elements involving SiO_2 wt % as differentiation indices for sanukitoids from the Karelian and Bundelkhand Cratons. Data for Karelian sanukitoids and Bundelkhand sanukitoids are from [Vaasjoki et al., 1993; Halla, 2005; Heilimo et al., 2011, 2013 and references therein; Joshi et al., 2017]

close similarity between Bundelkhand sanukitoids and sanukitoids from the Central and Western (Karelian) Sanukitoid Zone as they show substantial overlap at similar silica contents. It can be noted that there are more mafic varieties in the Karelian data set versus more granodiorites and granites in the Bundelkhand sanukitoid collection (Fig. not shown).

In terms of trace elements (Fig. 5), notable difference can be seen in sanukitoids from the Karelian craton as compared to those from the Bundelkhand craton. Sanukitoids from Bundelkhand have significantly higher concentrations of Th, U, Y, Nb, Rb and are depleted in Ni concentrations. A majority of the Karelain samples have higher Sr and Ba concentrations, however, some overlap can be seen between samples from Bundelkhand and Central and Western Sanukitoids from Karelia. In the mantle normalized trace element diagram (Fig. 6), all the samples show an increase in incompatible elements toward the left (mostly LILEs), negative Nb, P and Ti anomalies and positive Pb anomaly. Bundelkhand sanukitoids can be distinguished from Karelian sanukitoids in their lower Ba contents and higher Y and HREE concentration. In the chondrite normalized rare earth patterns (Fig. 7), all the samples show enriched LREEs and depleted HREEs. Sanukitoids from Eastern Karelia show slight to no Eu anomalies while those from Western Karelia and Bundelkhand show slight

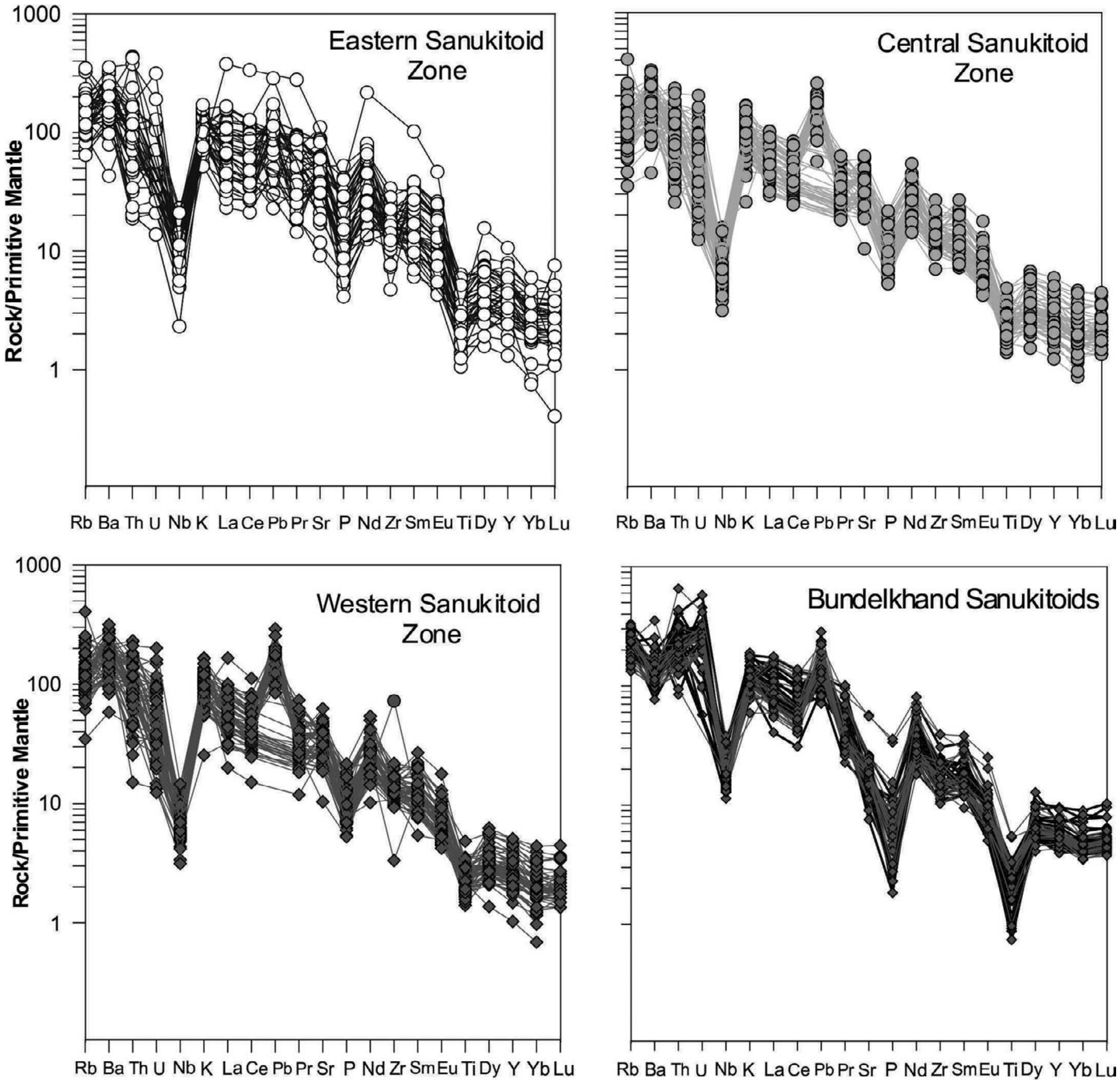

Fig. 6. Sanukitoids from the Karelian and Bundelkhand Cratons plotted on a primitive mantle-normalized spider diagram. Normalization values are from Sun and McDonough [1989]. Data for Karelian sanukitoids and Bundelkhand sanukitoids are from [Vaasjoki et al., 1993; Halla, 2005; Heilimo et al., 2011, 2013 and references therein; Joshi et al., 2017]

to variable Eu anomalies. Bundelkhand sanukitoids can be differentiated from those of the Karelian craton in their slightly elevated HREE contents.

Petrogenesis of Karelian and Bundelkhand Sanukitoids

In most Archean terranes, granitic plutons were emplaced after the main phase of TTG magmatism. It has often been suggested that the granitic magmas were formed by reworking of TTGs [Sylvester, 1994; Moyen et al., 2003], partial melting of meta-tonalites [Skjerlie and Johnston, 1993; Patiño Douce, 2005; Watkins et al., 2007] or as a result of interaction between mantle-derived magmas and anatectic crustal melts [Jayananda et al., 1995; Moyen et al., 2001; Halla, 2005]. Variable sources, viz. mantle peridotite, basaltic slab, pre-existing crust and terrigenous sediments, are considered responsible for the genesis of late Archean sanukitoids in most cratons around the world [Kovalenko et al., 2005; Halla, 2005; Rapp et al., 2010; Oliveira et al., 2011; Laurent et al., 2011; Heilimo et al., 2011, 2013].

Fowler and Rollinson [2012] considered Caledonian high Ba-Sr granites from the Northern Highlands of Scotland as petrological and compositional equivalents of Neoarchean sanukitoids. They further suggested sediment subduction and slab breakoff caused melting in the subcontinental lithospheric mantle (SCLM) as a possible mechanism for their generation. Lobach-Zhuchenko et al. [2008] also proposed slab breakoff and subsequent mantle upwelling as the trigger for

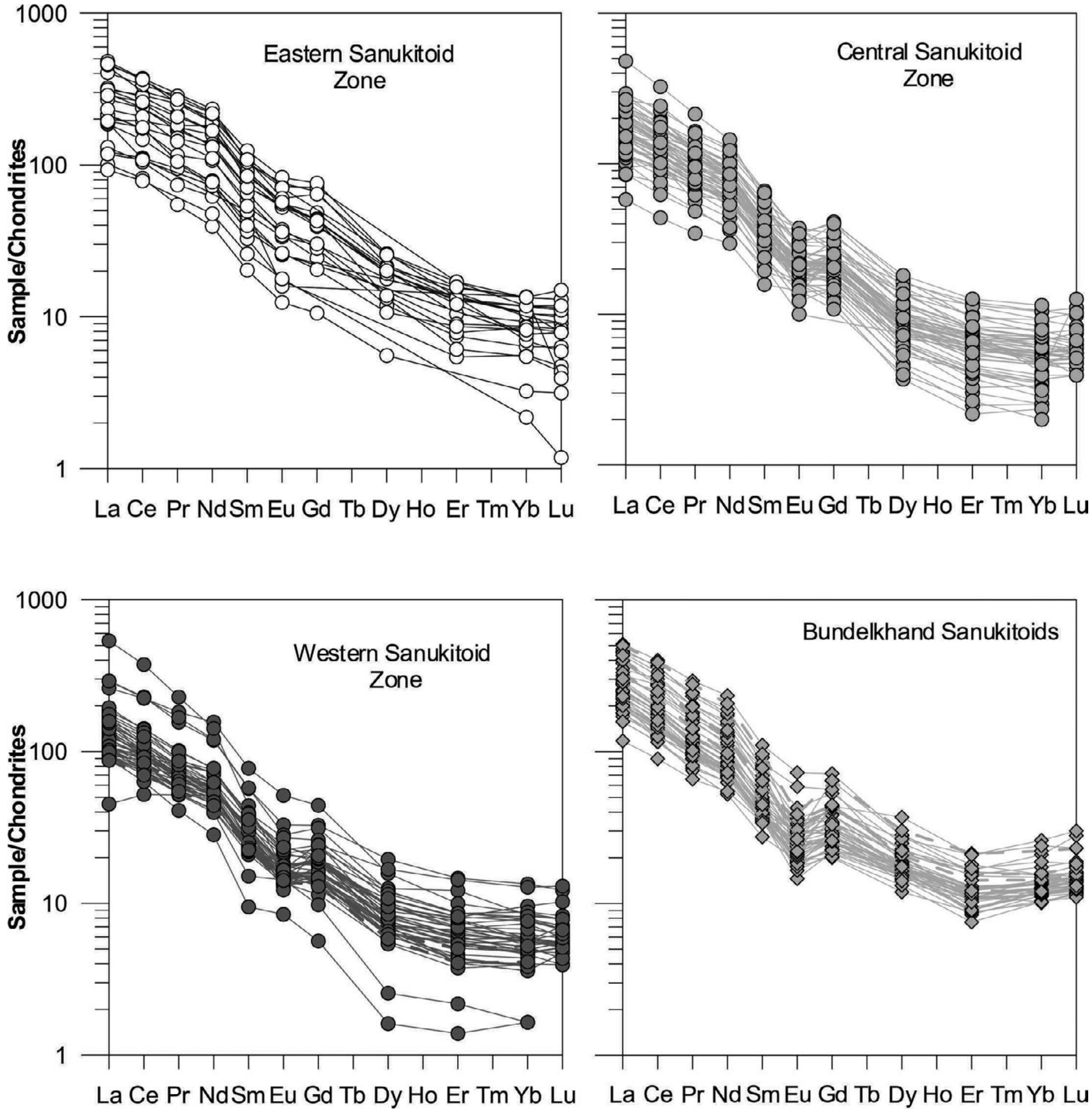

Fig. 7. Sanukitoids from the Karelian and Bundelkhand Cratons plotted on a chondrite normalized spider diagram. Normalization values are from Sun and McDonough [1989]. Data for Karelian sanukitoids and Bundelkhand sanukitoids are from [Vaasjoki et al., 1993; Halla, 2005; Heilimo et al., 2011, 2013 and references therein; Joshi et al., 2017]

Neoarchean sanukitoid magmatism in Karelia while Heilimo et al. [2013] suggested well-homogenized enriched SCLM as a potential source. Phlogopite-bearing lherzolite is suggested as the source of Karelian sanukitoids and related intrusions, which explains elevated LILE contents, while the enrichment of compatible and incompatible elements can be attributed to subduction related processes that were operative [Stern and Hanson, 1991; Lobach-Zhuchenko et al., 2008].

Geochemical data from Bundelkhand sanukitoids suggest their geochemical affinity with West Karelian sanukitoids. However, there are some compositional differences in Bundelkhand sanukitoids viz. lower Na_2O, Ba+Sr and Ni contents. These may be due to their formation in the shallow crust with relatively less inputs from the mantle. The emplacement ages of Bundelkhand sanukitoids (2.56–2.53 Ga) are younger than those reported in Karelia (2.74–2.72 Ga) but similar to the sanukitoid ages (2.95 to 2.54 Ga) from the rock record. The lack of isotopic data from Bundelkhand sanukitoids limits our conclusion regarding the exact processes that could have been responsible for their genesis. It has been suggested that Bundelkhand sanukitoids were produced in subduction environment and were affected by two different metasomatic events. The first subduction event caused enrichment of the mantle, which was followed by slab breakoff (as in the case of Caledonian high Ba-Sr granites), which allowed upwelling of the fluid and flux to the overlying crust thereby causing remelting and producing various potassic granites.

Conclusions

1) Sanukitoid massifs from the Karelian and Bundelkhand Cratons are localised in linear zones and are contemporaneous to arc-type volcanics, probably pointing towards similar geodynamic processes responsible for their formation.

2) Geochemically, Neoarchean (2.56–2.53 Ga) sanukitoids from Bundelkhand are similar to those from the Central and Western Karelian zones (2.72–2.68 Ga) while they are less differentiated as compared to sanukitoids (2.74–2.73 Ga) from the Eastern Karelian Zone. Geochemical similarities in sanukitoids from both these cratons indicate that similar petrogenetic processes might have been responsible for their formation.

3) Neoarchean sanukitoid magmatism in both the cratons is associated with subduction related processes followed by slab breakoff which preceded the accretion-collision events.

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