

Archaean granitoids: an overview and significance from a tectonic perspective

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Abstract: This special publication presents a collection of papers on Archaean igneous rocks which aim to provide evidence of a tectonic scenario that is increasingly accepted by scientists studying the evolution of the early Earth. Papers on diverse igneous rocks from the North Atlantic Craton, as well as Archaean terrains of the Fennoscandian, Indian and Ukrainian shields, have a common focus on crust–mantle interactions and granitoid diversification, especially at the end of the Archaean, accompanied by insights into metamorphic rocks. This volume, together with present research, provides evidence for a change in global tectonic regime close to the Archaean–Proterozoic boundary. After the long-term episodic formation of tonalite–trondhjemite–granodiorite (TTG) suites of oceanic origin, convergent continental margins with abundant batholiths of potassic granitoids appeared for the first time at 3.0–2.5 Ga. The batholiths involve both mantle-derived and recycled crustal material. It seems that the diversification of granitoids was caused by increased crust–mantle interactions, reflecting a significant change in mantle dynamics and plate tectonics during the Neoarchaean.



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The Archaean Eon began about 4 billion years ago with the formation of Earth's first crust and continued until the start of the Proterozoic Eon, 2.5 billion years (gyr) ago. Records of Earth's primitive atmosphere and oceans emerge in the earliest Archaean, and evidence of the earliest primitive life forms appears in rocks about 3.5 gyr old. During the Archaean, the first continents were formed and their remnants are now dispersed all around the world (Fig. 1). These fragments can be recognized by their isotope ages in combination with distinct geochemical features.

The geochemical compositions of granitoids reflect the physical conditions of their formation and the nature of their source. The geochemical and geochronological characteristics of Archaean granitoids and related rocks, and their implications for evaluating the initiation of modern-style plate tectonics, have been an object of extensive research and lively speculation for decades. Since the advancement of analytical methods, numerous papers

have reported data on Archaean granitoids and presented different hypothesis for early plate tectonics on Earth. As a result of these studies, it is now well known that the present continents have grown through time since the beginning of the Archaean at approximately 4.0 Ga. Archaean parts of the continents, known as Archaean cratons or provinces, were formed episodically by igneous magmatism over 1.5 billion years. It has been well documented that the geochemical systematics of Archaean igneous rocks differ from those of modern ones in many ways.

Within Archaean cratons all over the world, previous research has identified a sodic tonalite–trondhjemite–granodiorite (TTG) suite and a group of high-K calc-alkaline granitoids (from granodiorites to monzogranites), as well as ultramafic, gabbroic, dioritic and syenitic rocks, and explained their formation by a variety of tectonic processes such as plumes, rifting, subduction, slab breakoff, delamination and sagduction.

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Fig. 1. Major Archean cratons and provinces – the fragments of the oldest continents on Earth. Research areas addressed in this volume are indicated by red type and arrows. Map modified from Bleeker (2003).

Despite recent efforts, research on Archean granitoids in general suffers from some critical deficiencies, such as the lack of systematic classification and nomenclature that has led to vague terms and misunderstandings, uninterpreted geochemical signatures, unconnected geochronology and geochemistry, a lack of systematic compilation and comparison of data, tectonic models that do not take into account physical barriers, and prevalent theories that are not valid in light of rapidly increasing analytical and numerical data. As a result, no comprehensive theory of Archean plate tectonics appears to exist and the tectonic triggers of crust formation have remained unclear.

This special publication provides a collection of papers written by the participants of the IGCP-SIDA 599 project ‘The Changing Early Earth’ funded by UNESCO-IGCP (International Geoscience Programme) with extra funds from the SIDA (Swedish International Development Agency) 2011–14. The objectives of this volume are to focus on Archean igneous rocks, especially granitoids, and to resolve problems in their petrogenesis and relationships to tectonic processes, and especially to provide evidence of increasing crust–mantle interactions, diversification of granitoids and, hence, for a change in the plate tectonic style towards the end of the Archean.

This introductory overview gives the background needed to understand the terminology and current controversies in research on Archean granitoids. First, we go through the nomenclature and classification of granitoids, explaining some quite ambiguous terms in use and point out some problems in the current classifications. Secondly, we explore the main geochemical features and age relationships of granitoids from different Archean cratons to find spatial and temporal patterns in their formation. Thirdly, we introduce the contributions by topic groups, and, finally, we present a tectonic scenario supported by the results of this special publication.

Geochemical types of Archean granitoids

Nomenclature

The nomenclature of Archean granitoids is based on more or less established terms introduced by single studies, such as ‘TTG’ (Barker 1979), ‘sanukitoid’ (Shirey & Hanson 1984) and ‘Closepet-type’ granitoids (Moyen *et al.* 2003). With the rapid development of element analytical methods and increasing interest in Archean crust formation, it has become clear that Archean granitoids, often formerly all lumped together under the term ‘basement

gneisses', actually represent a variety of granitoids with different SiO₂, K₂O and MgO contents and trace element geochemical signatures.

There is no generally accepted classification for the different geochemical types of Archaean rocks, and the aim of this volume is not to provide such but, instead, the terms currently in use are explained below. Table 1 gives a representative chemical composition for each rock type and Figure 2 illustrates examples of typical lithologies in the field as photographs of outcrops or hand specimens. For additional information, the reader is referred to a detailed review of Archaean granitoids recently presented by Laurent *et al.* (2014). The following granitoids and related rocks are found in almost all Archaean provinces, but their age and abundance vary.

Tonalite–trondhjemite–granodiorite (TTG) rocks constitute the majority of the preserved Eoarchaeoan–Neoarchaeoan crust. As observed in the field, TTGs are often migmatitic and contain amphibolite enclaves, layers or bands showing a 'black and grey' appearance (Fig. 2a), but more homogeneous varieties with less or no amphibolite enclaves also exist. The main felsic mineral is plagioclase and the distinct main geochemical features are the high-Na and low-K characteristics, as well as high-silica content and low-Mg content (Table 1). TTGs are generally thought to have originated from the melting of hydrous metabasalts in oceanic environments, such as in tectonically thickened mafic island-arc crust (Hoffmann *et al.* 2011, 2014; Nagel *et al.* 2012; Huang *et al.* 2013) or subducting oceanic plateaus (Martin *et al.* 2014), remnants of which are considered to form Archaean greenstone belts.

Recently, it has been noted that TTGs form a much more heterogeneous group of rocks than was previously thought. TTGs with both low- and high-HREE end members have been recognized and observed to be closely associated, but their spatial and temporal relationships have not been studied in detail. At the moment, there is no consensus on the nomenclature of the groups. Names related to HREE content (low- and high-HREE end members of Halla *et al.* 2009), pressure (low-, medium- and high-pressure groups of Moyen 2011) or general characteristics (transitional or enriched TTGs) have been variably used. A type of 'transitional' large ion lithophile element (LILE)-enriched TTG is reported from the Pilbara Craton (Champion & Smithies 2001), but it is unclear how this relates to TTGs *sensu stricto*.

Sanukitoids were named by Shirey & Hanson (1984) on the basis of geochemical characteristics resembling high-Mg andesites (sanukites) in Japan. Sanukitoids are igneous rocks that share several common characteristics in their element

concentrations, such as the contradictory combination of high incompatible (especially K, Ba, Sr, P and LREE) and compatibles (Mg, Cr and Ni), which requires both crustal input and mantle involvement in their petrogenesis (Table 1). The specific high K–Mg–Ba–Sr–P signature is overprinted on mafic, intermediate and felsic rocks. Thus, the signature does not correlate with the silica content, which indicates that the signature comes from an enriched mantle source.

Most commonly, sanukitoids crop out as intermediate quartz diorite–quartz monzodiorite associations or more evolved granodiorite–monzogranite batholiths, which may occur either together or separately. The typical mode of occurrence of sanukitoids is as chains or clusters of relatively small plutons, with few exceptionally large granodiorite batholiths. Sanukitoids are found intruding granite–greenstone belts, as well as high-grade gneiss–granite and metasedimentary terrains in many Archaean Cratons.

In the field, sanukitoid granitoids can be identified by their often K-feldspar porphyritic structure, relatively high content of mafic minerals and abundant mafic magmatic enclaves (Fig. 2b). Fine-grained versions of sanukitoid granodiorites are dark and homogeneous, and therefore are more difficult to identify by appearance (Fig. 2c). Since sanukitoids include several plutonic or volcanic rock types from mafic to felsic, the term should be suffixed by the Streckeisen name: for example, sanukitoid granodiorite or sanukitoid andesite.

Closepet-type represents granitoids that resemble sanukitoids by having a high K–Ba–Sr–P signature but which show lower Mg characteristics (Table 1). The name is derived from the 2.5 Ga Closepet granitoid in the Dharwar Craton of the Indian Shield which was recognized to show some sanukitoid affinities, and was explained by interactions between enriched mantle-derived melts and pre-existing crust (Moyen *et al.* 2003). The crustal contribution in these rocks is supported by occasional inherited zircons (Joshi *et al.* 2016). They also resemble sanukitoids in appearance and mineralogy, and contain mafic magmatic enclaves (Fig. 2d).

Crust-derived granitoids, leucogranites or monzogranites are the names used for granitoids whose geochemistry, such as high SiO₂ and low MgO (Table 1), indicates a derivation from pre-existing continental crust, either TTGs or sedimentary rocks. In this volume, Joshi *et al.* (2016) divide the monzogranitic group into three subgroups: monzogranites (Fig. 2e); low-Eu monzogranites (Fig. 2f) including A-type with a Rapakivi texture, manifested by large ovoids of K-feldspar mantled by a rim of plagioclase (Fig. 2g); and low-HREE monzogranites (Fig. 2h). All these rocks have a 'true

Table 1. Examples of major and trace element contents of different types of Archaean granitoids

Granitoid type*	Low HREE TTG* Average	High HREE TTG* Average	Sanukitoid granodiorite* Average	Sanukitoid monzogranite† BSTM 104	Closepet-type granodiorite† BCTG 129	Monzogranite† BMG 105	Low Eu monzogranite† BLEM 103	Low HREE monzogranite† BLHM 127	Alkali-enriched gabbro‡ STHA-2008-301.1	Alkaline-rich quartz monzonite§ ASMS-2009-504.1
<i>Major elements (wt%)</i>										
SiO ₂	70.8	67.3	64.7	67.1	63.9	72.5	73.4	73.2	44.3	63.0
TiO ₂	0.31	0.59	0.49	0.61	0.45	0.15	0.19	0.15	1.83	0.49
Al ₂ O ₃	15.5	15	15.8	15.8	16.5	14.2	14.9	15.9	16.5	16.5
Fe ₂ O ₃ T	2.44	4.81	4.56	3.72	4.02	1.36	1.70	1.06	13.6	3.31
MnO	0.03	0.07	0.07	0.05	0.08	0.04	0.05	0.02	0.13	0.09
MgO	0.82	1.7	2.48	4.08	1.55	0.58	0.33	0.46	7.33	1.29
CaO	2.88	3.76	3.5	1.40	3.70	0.90	0.98	0.52	9.74	3.29
Na ₂ O	4.81	4.23	4.48	2.98	4.11	3.35	3.71	3.95	3.07	5.66
K ₂ O	1.99	1.93	2.74	4.20	3.18	4.98	4.87	6.08	1.37	5.57
P ₂ O ₅	0.10	0.17	0.21	0.34	0.17	0.07	0.06	0.04	0.78	0.26
<i>Trace elements (ppm)</i>										
Ba	663	485	1182	1063	815	230	503	459	576	1466
Rb	60.3	68.4	85.0	147	158	228	342	268	26.2	102
Sr	427	314	729	541	398	136	110	200	1064	1136
Pb	8.61	9.15	31.8	22	26	35	38	37	<30	18
Th	7.44	7.60	6.52	26.7	22.2	41	42	82	2.15	9
U	0.64	1.05	1.21	5.58	6.35	5.1	12.2	20.0	0.61	2.43
Hf	3.31	4.32	3.2	na	na	na	na	na	2.12	3.5
Zr	120	171	135	264	249	102	227	180	69.9	128
Nb	3.44	8.26	6.45	15	13	13	29	11	4.38	13.8
Ta	0.19	0.57	0.6	na	na	na	na	na	0.36	0.94
Y	4.5	18.6	10.9	28	21	16	51	6	25.6	11.5
Sc	3.48	9.37	8.53	16.4	11.4	15	bd	20	30.6	4.58

V	26.5	56.8	69.7	68.6	43.7	10	8	4	356	37.3
Cr	<30	43.6	75						<30	16
Ni	<20	26.6	35.2	29	9	25	13	14	24	32
Co	4.96	10.8	12.1	10	5	4	2	5	42.8	9.6
Cu	114	30.8	11.7	31	3	4	5	7	28	33
Zn	49.1	78.2	77.3	65	61	40	42	22	132	93
<i>REE (ppm)</i>										
La	25.6	26.4	37.8	109	47.3	37	63.3	77.5	27.6	61
Ce	48.6	55.5	72.8	225	94.0	72.2	132	148	74.1	125
Pr	4.9	6.3	8.1	22.0	9.21	6.43	13.1	12.8	11.1	14.3
Nd	17	24.3	30.4	80.4	33.6	21.2	47.1	37.9	52.1	51.7
Sm	2.4	4.6	4.8	11.8	5.85	3.57	8.71	4.05	11.6	7.44
Eu	0.6	1	1.1	2.09	1.08	0.41	0.62	0.67	2.94	1.6
Gd	2	4.7	3.9	9.12	4.65	2.95	7.26	3.19	10.3	5.41
Tb									1.22	0.6
Dy	1	3.7	2	5.18	4.52	2.59	7.96	1.07	6.05	2.82
Ho									1	0.41
Er	0.4	2.1	1	1.75	1.77	1.01	3.10	0.40	2.47	1.14
Tm									0.32	0.16
Yb	0.4	2	0.9	2.16	2.51	1.49	4.40	0.47	1.95	1.01
Lu	<0,1	0.3	0.1	0.38	0.41	0.25	0.73	0.09	0.27	0.15

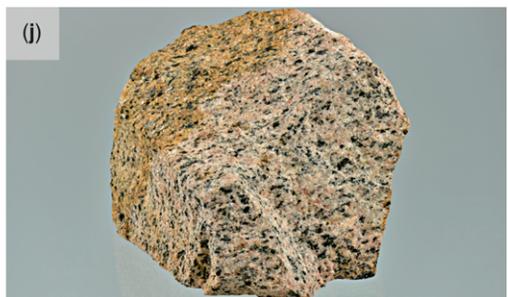
*Average data from the western Karelia and Kola cratons (Halla *et al.* 2009).

†Representative samples from the Bundelkhand Craton (Joshi *et al.* 2016).

‡Selected sample from the western Karelia Subprovince (Mikkola *et al.* 2016).

§Selected sample from the western Karelia Subprovince (Heilimo *et al.* 2016).

na: not analysed.



granite' appearance: mostly even-grained texture, with a low proportion of mafic minerals and lacking mafic enclaves. Differences in their geochemical features, such as in the REE content, probably reflect their depth of formation and variable source material, as well as the nature of their metasomatism and hydrothermal activity.

Minor groups of alkali-enriched gabbros (Fig. 2i) and ultramafics, as well as granitoids with alkaline affinity such as alkaline-rich quartz syenites (Fig. 2j), are often also found in Archaean terrains. The alkali-enriched gabbros may have Ba and Sr concentrations as high as approximately 3800 and 1600 ppm, respectively (Mikkola *et al.* 2016). A heterogeneous enriched mantle source has been proposed to be the source for alkaline rocks, where the LREE and LILE would derive from the enriched source. These rocks show an elevated K–Ba–Sr–P content (Table 1), but a lower Mg content that is related to fractional crystallization.

Archaean igneous rocks include volcanic rocks from tholeiitic basalts to the calc-alkaline basalt–andesite–dacite–rhyolite (BADR) association, which, together with sedimentary rocks, form the low-grade greenstone belts that are also termed Archaean supracrustal belts. When metamorphosed, they may transform to amphibolites and leuc-amphibolites, and, with increasing metamorphic stage, to mafic, intermediate and felsic granulites.

Classifications

In this special publication, Joshi *et al.* (2016) present a rough classification to TTGs and high-K calc-alkaline granitoids and divide the latter into two groups by their main geochemical features: the silica and Mg content. The first group includes low-silica – high-Mg (LSHM) rocks such as sanukitoids and, to some extent, Closepet-type granitoids, which point to a contribution from a mantle source. The second group consists of HSLM rocks, the origin of which can be related purely to the melting of pre-existing continental crust.

Laurent *et al.* (2014) suggested a corresponding classification into TTGs, sanukitoids, biotite- and two-mica granitoids (crust-derived granitoids), and hybrid granitoids (e.g. Closepet-type). However, the problem with this classification is that the term

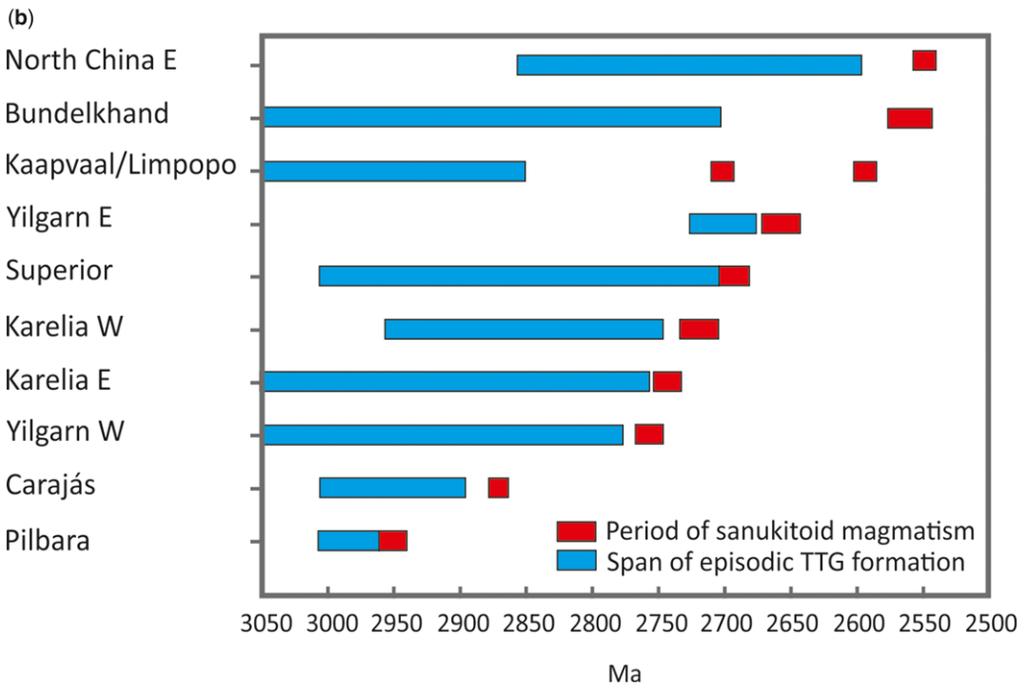
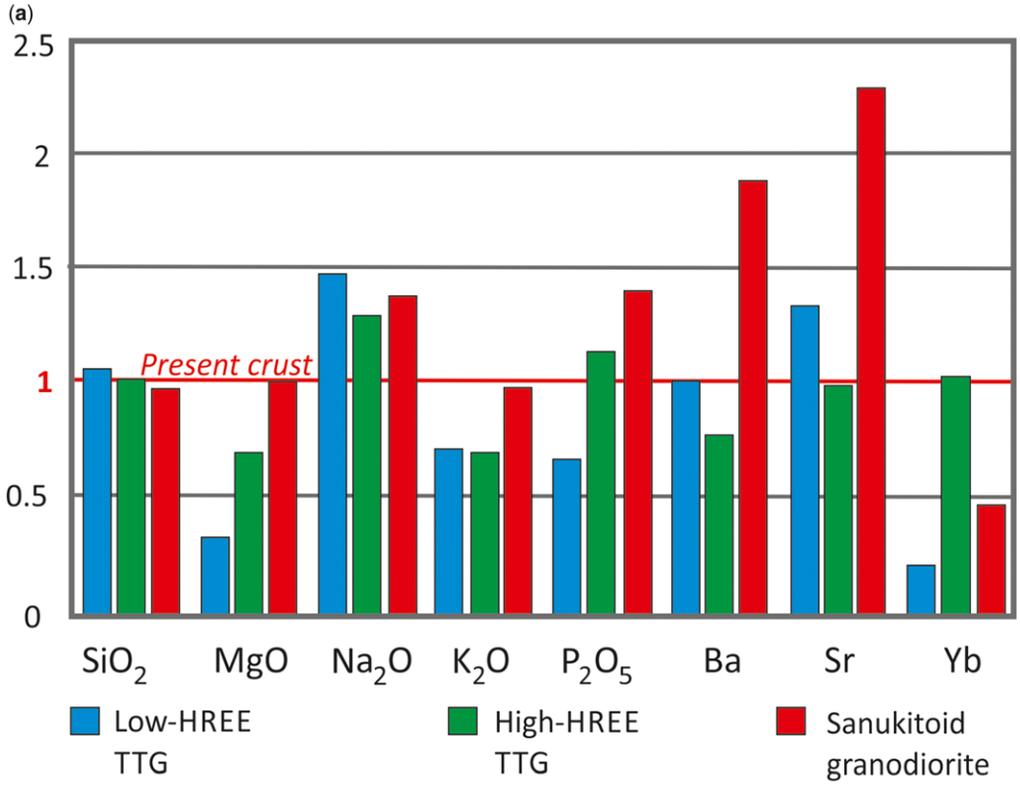
'biotite gneiss' can be adopted to a metamorphosed member of any of the granitoid groups, because all deformed orthogneisses might contain abundant biotite as a result of retrograde processes. Furthermore, the term 'hybrid' includes the presupposition that the rock is formed by the mixing of two types of rock, which might not be the case in reality. The same comment applies to 'high-pressure' and 'low-pressure' TTGs – we do not know for sure whether the difference in the composition of TTGs depends on the pressure conditions or the source mineralogy. Therefore, this volume aims to avoid rock names based on mineralogy, or assumed processes or conditions. For similar reasons, the term 'transitional TTGs' might be inappropriate, although often used. Furthermore, the term GGM (granite–granodiorite–monzonite) has been used to distinguish between TTGs and K-rich granitoids.

Temporal relationships of TTG and high-K–Mg magmatism

Sanukitoid granitoids appeared abruptly in the geological record at 3.0–2.5 Ga, seeming to mark a sharp change in the Earth's geodynamics. The bar diagram in Figure 3a presents the critical element compositions of the two end members of TTGs (Halla *et al.* 2009), as well as sanukitoid granodiorites normalized to the present average upper crust of Rudnick & Gao (2003). The graph shows that the elevation of Ba and Sr concentrations in sanukitoid granodiorites is remarkable. The characteristic high K–Mg–Ba–Sr–P signature of sanukitoid granodiorites is easily observable in the diagram, where the bars of these elements rise well above the average present crust. In addition, the differences between the high- and low-HREE TTGs are clear, the former showing, for example, higher Yb and MgO contents.

Sanukitoids have been found to form either before or at the same time as crust-derived granitoids (Heilimo *et al.* 2011; Joshi *et al.* 2016), and are therefore selected to represent the appearance of the high-K group of rocks in diagrams exploring the temporal relationships of sodic and potassic magmatism in different cratons. Figure 3b shows that there was a long period from the Eoarchaean

Fig. 2. Examples of outcrops and hand specimens of different types of Archaean granitoids. (a) Amphibolite-banded TTG from the Lake Inari Terrain, Kola Province, Finland (length of the scale is 50 cm). (b)–(h) illustrate granitoids from the Bundelkhand Craton, India: (b) porphyritic sanukitoid monzogranite with a mafic enclave showing feldspar crystals mechanically transferred from the host magma (the diameter of the lens cover is 5.8 cm); (c) fine-grained sanukitoid granodiorite; (d) Closepet-type granite; (e) monzogranite; (f) low-Eu monzogranite; (g) low-Eu A-type monzogranite with Rapakivi texture; (h) low-HREE monzogranite; and (i) alkaline-rich gabbro (the size of the sample is 9 × 9 × 5 cm). (j) Alkaline-rich quartz monzonite from the western Karelia Subprovince, Finland (the size of the sample is 9 × 7.5 × 4 cm). Photographs (i) and (j) are by J. Ranua, Geological Survey of Finland.



to the late Archaean when sodic TTG magmatism was dominant, although this occurred episodically. This period was followed by a very short period of sanukitoid magmatism. The time gap between TTGs and sanukitoids is variable, which, together with the abrupt and temporally restricted appearance of sanukitoids, indicates a sharp change in Earth's geodynamics, contradicting previous hypotheses of a transitional change. In each craton, the change occurred at different times between 3.0 and 2.5 Ga.

Based on these two diagrams, it is possible to conclude that a new geochemical signature appeared in granitoids at 3.0–2.5 Ga, indicating a contribution from an enriched mantle.

Contributions

This book consists of nine papers shedding light on the Archaean crust formation. First, we go through the main points of the papers and then, by summarizing and integrating the main outcomes, place them in a larger context in the Discussion and provide conclusions on the increase of crust–mantle interactions towards the end of the Archaean.

Mesoarchaeoan volcanic supracrustals from Greenland

In the first contribution, **Szilas *et al.* (2016)** provide evidence of Mesoarchaeoan subduction zone volcanism from andesites in one of the abundant supracrustal belts in southern West Greenland of the North Atlantic Craton (Fig. 1). The studied belt, the 3.07 Ga Qussuk supracrustal belt, comprises mainly tholeiitic meta-basalts (amphibolites) and, to a lesser extent, calc-alkaline meta-andesites (leucoamphibolites), and is surrounded by TTGs that formed at 3.05–3.00 Ga by the melting of probably local tholeiitic basalts. Based on whole-rock Lu–Hf isotope results, they conclude that the andesites were derived from a mantle source with

near-chondritic Hf isotope composition, whereas the basalts came from a depleted mantle source. Trace element modelling points to a large degree (c. 50%) of mixing between mafic and felsic (but mafic-source-derived) magma, which excludes crustal assimilation and fractional crystallization from being viable processes. The best explanation for the formation of the andesites is the large-scale mixing of mafic and felsic end members in a subduction zone environment, with a contribution from a primitive mantle reservoir or Hadean/Eoarchaeoan mafic crust.

Mantle origin of alkaline rocks from western Karelia

The next two contributions describe alkaline rocks with sanukitoid affinities from the Lentua Complex of the western Karelia Province, Fennoscandian Shield. The Archaean Karelia Province (Fig. 1) consists of three subprovinces: the Vodlozero, central Karelia and western Karelia. In the main, the western Karelia Province comprises 2.83–2.72 Ga TTGs (with <3.2 Ga fragments), 2.74 and 2.72 Ga sanukitoids, 2.70 Ga quartz diorites, and 2.73–2.66 Ga potassic granitoids (Hölttä *et al.* 2014).

Mikkola *et al.* (2016) present field observations, petrography, and whole-rock major and trace element contents, as well as whole-rock Sm–Nd and zircon O isotope data on 2.71 Ga alkali-enriched gabbros and diorites. The authors point out and explain elevated sanukitoid-type K₂O, Ba and Sr levels of the rocks by an enriched mantle origin; and lower Mg, Ni and Cr characteristics compared with sanukitoids by fractional crystallization of mafic minerals. The Sm–Nd model ages older than the crystallization age indicate a contribution from older material, interpreted to be derived from a mantle source variably metasomatized by subducted sediments. The zircon O isotopes with elevated δ¹⁸O indicate low-temperature fractionation, either in the hydrothermally altered oceanic crust or in subducted sediments. In conclusion, this

Fig. 3. (a) Selected average element compositions (data from table 1) of high- and low-HREE TTGs and sanukitoid granitoids normalized to the average upper crust (Rudnick & Gao 2003) showing the main geochemical differences. (b) Examples of temporal relationships between TTGs and sanukitoid granitoids in different Archaean provinces. TTGs represent a long-term episodic magmatism from a mafic source. Sanukitoids are temporally restricted to 2.95–2.5 Ga, intruding after regional TTG magmatism. U–Pb ages (mostly SIMS or SHRIMP) from Smithies & Champion (2000) (Pilbara Craton, west Australia); Oliveira *et al.* (2009) and Almeida *et al.* (2011) (Carajás Province, Amazonian Craton, Brazil); Wiedenbeck & Watkins (1993) and Wang *et al.* (1995) (Murchison Province and Eastern Gold Fields, western Yilgarn Craton, west Australia); Bibikova *et al.* (2005) (eastern Karelia Province, Fennoscandian Shield, Russia); Heilimo *et al.* (2011) (western Karelia Province, Fennoscandian Shield, Finland); Whalen *et al.* (2004) and Davis *et al.* (2005) (Wabigoon and English River subprovinces, Superior Province, Canada); Cassidy *et al.* (1991), Hill *et al.* (1992) and Kent (1994) (eastern Yilgarn Craton, west Australia); Laurent *et al.* (2014) (Limpopo Belt and Kaapvaal Craton, southern Africa); Wang *et al.* (2009) (western Shandong Province, Eastern Block of the North China Craton); and Joshi *et al.* (2016) (Bundelkhand Craton, central Indian Shield).

contribution confirms the existence of a heterogeneously enriched lithospheric mantle under the western Karelia Province.

Heilimo *et al.* (2016) describe a group of alkaline granitoids from syenites to quartz monzonites with minor monzonites and granites, lumped together under the name 'quartz syenites', by providing U–Pb ages and whole-rock major and trace element contents, as well as whole-rock Sm–Nd and zircon O isotope data. The U–Pb ages of these rocks span between 2.74 and 2.66 Ga, overlapping with the sanukitoids, quartz diorites and potassic granitoids. The quartz syenites have affinities to enriched mantle-derived sanukitoids with respect to incompatible element contents, but they show lower Mg, Cr and Ni contents related to the fractional crystallization of mafic minerals. The Sm–Nd results do not show a significant contribution of considerably older crust. Zircon O isotope data indicate a heterogeneous mantle source, with a contribution from elevated $\delta^{18}\text{O}$ values. This paper provides evidence of a long-lived heterogeneously enriched subcontinental lithospheric mantle that has contributed to magmatism during the latest stages of the accretion of the western Karelia Province.

These two papers on the western part of the Karelian Province provide evidence of a convergent continental margin, below which a variably enriched lithospheric mantle contributed to several pulses of magmatism during a period of mantle–crust interactions that lasted at least 80 myr from 2.74 to 2.66 Ga.

From mantle to crustal melting in the Indian Shield

The Indian Shield comprises five Archaean cratons: the Aravalli, Bundelkhand, Singhbhum, Bastar and Dharwar cratons (Fig. 1). The Dharwar Craton is divided into older western (3.35–2.60 Ga) and younger eastern (2.70–2.51 Ga, with minor <3.3 Ga) blocks. The next two papers from the Eastern Dharwar and Bundelkhand cratons demonstrate the role of both mantle and crustal melting in forming the Archaean high-K granite batholith terrains.

The fourth contribution of the volume describes the tectonic evolution of the Eastern Dharwar Craton. **Dey *et al.* (2016)** present secondary ion mass spectrometry (SIMS) U–Pb zircon ages, as well as major and trace element data, for granitoids in the NW part of the craton. The granitoid magmatism involves both juvenile addition and reworking of felsic crust forming enriched TTGs. The oldest granitoids analysed in this study were formed at 2.68 Ga, and they represent an intermediate type between TTGs and sanukitoids. These granitoids were followed by 2.58 Ga LILE-enriched TTGs,

the formation of which points to the reworking of older crust. Finally, sanukitoids and Closepet-type granitoids, as well as crust-derived K-rich leucogranites, were intruded within a narrow time span of 2.53–2.52 Ga. Previously published Sm–Nd results, showing mostly negative initial ϵ_{Nd} values and Mesoarchaean depleted mantle model ages, suggest the effect of older crust in the area. The suggested tectonic setting for the diversity of granitoids is a Neoaarchaean convergent margin formed by the accretion of oceanic arcs, plateaus and microcontinents.

The fifth contribution of **Joshi *et al.* (2016)** gives major and trace element, and SIMS U–Pb, geochronological data for a diversity of granitoids from the Bundelkhand Craton, Central India. The oldest granitoids are represented by 3.5/3.3–2.7 Ga TTGs. After a time gap, a variety of high-K calc-alkaline granitoids were emplaced between 2.57 and 2.54 Ga. One group (LSHM) of the granitoids shows a low-silica high-magnesium signature indicative of a mantle derivation, whereas another group (HSLM) shows high-silica low-magnesium characteristics that point to a pure crustal origin. The emergence of both these types in a narrow time span of 30 myr indicates that partial melting occurred both in the mantle and crust at the same time. As a consequence, a variety of granitoids, the geochemical features of which point to an enriched mantle origin (sanukitoid granodiorites), mantle–crust mixing (Closepet-type granitoids) or pure crustal melting (monzogranites), were produced. The monzogranites show affinities to A-type granites and even Rapakivi granites. The diversity of the granitoids is best explained by: (1) mantle wedge enrichment by subduction and subsequent slab-breakoff-related alkaline fluid/melt activity; and (2) fluid-assisted partial melting of the mantle and crust at different depths.

The sixth contribution by **Ramiz & Mondal (2016)** deals with textures, and major and trace element contents, of mafic magmatic enclaves (MMEs) and their calc-alkaline host granitoids from the Bundelkhand Craton. Geochemical characteristics in MMEs, as well as sharp contacts, do not support magma mixing. Instead, sharp contacts, fine-grained sub-ophitic texture, acicular apatite and overgrowth of orthopyroxene over olivine crystals indicate rapid crystallization of mafic magma in the cooler felsic host magma. The authors relate the formation of both the enclaves and the host to the subduction setting, where they were formed at the same time as tholeiitic mafic magma was injected into the granitoid magma which was still crystallizing.

The above-described papers from the Indian Shield indicate a peak of crust–mantle interactions and diversification of magmatism at around 2.5 Ga in the Eastern Dharwar and Bundelkhand cratons.

Insights from metamorphic rocks

The last three contributions deal with Archaean magmatic evolution from the vantage point of metamorphism. The seventh paper of the volume provides a long-time perspective from the Ukrainian Shield, the eighth paper sheds light on the tholeiitic origin of mafic granulites in central India and the ninth provides time constraints for magmatism by dating metamorphism in the Ilomantsi greenstone belt of the Karelia Province of the Fennoscandian Shield.

Lobach-Zhuchenko *et al.* (2016) approach a long-time Archaean evolution by a multimethod study of zircons from a single sample of hypersthene–plagioclase granulite from the Bug Granulite–Gneiss Complex in the SW Ukrainian Shield (Fig. 1), including SIMS U–Pb zircon geochronology, laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) Lu–Hf analysis, microprobe analyses of inclusions and microprobe REE analysis. The analysis of zircons was accompanied by major and trace element analysis of whole-rock samples and microprobe analysis of major minerals, as well as whole-rock Sm–Nd isotope analysis. The authors distinguish three major stages in a prolonged and multistage history (3.7–2.1 Ga) of the Bug Complex. First, an Eoarchaean mafic protolith was formed at 3.66 Ga and contaminated with older felsic materials, as evidenced by felsic inclusions in 3.74 Ga zircon xenocrysts. Secondly, the protolith underwent Mesoarchaean granulite-facies metamorphism at 3.59–3.55 Ga and was transformed into hypersthene–plagioclase granulites. Finally, Palaeoproterozoic metamorphic overprinting and mafic dyke intrusions affected the region at 2.1–2.0 Ga.

In the seventh paper, **Alam *et al.* (2016)** describe the major and trace element geochemistry, and the Sm–Nd results, of mafic two-pyroxene granulites from the Bhandara–Balaghat Granulite Belt in the Central Indian Tectonic Zone (CITZ) between the Bundelkhand and Bastar cratons (Fig. 1), which is a major shear zone separating the North and South India blocks. The authors show that the mafic granulites, containing ortho- and clinopyroxene, plagioclase, quartz and hornblende, and occasionally garnet, show geochemical features similar to Archaean island-arc tholeiites (basalts/gabbros) and have been derived from variably enriched mantle sources, followed by fractional crystallization and contaminated by older crustal components as indicated by Nd-depleted mantle model ages up to 3.2 Ga. The evolution of the protolith started with the overprinting of the isotope composition of its mantle source by crustal isotope signatures as a consequence of crustal recycling; this was continued by the emplacement and

crystallization of the protolith at 2.70 Ga, and was followed by tectonothermal events up to granulite-facies metamorphism and finalized by exhumation of the belt during the collision of the Archaean Bundelkhand and Bastar cratons and the formation of the Central Indian Tectonic Zone (CITZ) at 1.5 Ga.

The last paper, by **Hölttä *et al.* (2016)**, describes the metamorphic evolution of the approximately 2.75–2.70 Ga Ilomantsi greenstone belt in the central Karelia Province, Fennoscandian Shield (Fig. 1) by providing monazite U–Pb ages and pressure–temperature (P – T) paths for metamorphism. The LA-multi-collector (MC)-ICP-MS U–Pb age determinations on monazite show that the Ilomantsi greenstone belt was affected by two different metamorphic events: prolonged Neoproterozoic metamorphism between 2.66 and 2.62 Ga, a simultaneous metamorphism with the surrounding migmatite and granulite complexes; and another at 1.84 Ga indicating Palaeoproterozoic reworking. The study of the P – T development, based on petrography and microprobe analysis of minerals, provides an apparent clockwise P – T path and medium P – T -type metamorphism, which are consistent with collisional tectonic settings. Metamorphic grade increases from lower-amphibolite facies in the SW domain of the belt to mid-amphibolite facies in the NE, which can be explained by regional heat advection in a collisional setting associated with late orogenic high-K magmatism.

Discussion

This special publication compiles evidence for a change in magmatism and tectonics on early Earth from mafic magmas erupted as oceanic crust, plateaus or island arcs through to TTGs of accreting microcontinents and on to a diversity of late Archaean granitoids at thick convergent continental margins. The contributions to this volume have a significant impact on the discussion of the origin of Archaean igneous rocks and their role in resolving Archaean crustal evolution and tectonics, and thus help in compiling evidence for increasing crust–mantle interactions, diversification of granitoids and changing plate tectonic style towards the end of the Archaean.

There is a consensus among the authors of this special publication about some previously debated aspects. Convergent tectonics is favoured instead of plume tectonics as the major crustal growth mechanism since the Eoarchaean. Mixing of mafic and felsic material started by at least 3.66 Ga (Lobach-Zhuchenko *et al.* 2016) in the Ukrainian Shield, and also affected the composition of Mesoarchaean supracrustal belts in West Greenland

(Szilas *et al.* 2016) and the protolith of Neoarchaeoan mafic granulites in central India (Alam *et al.* 2016). Archaean calc-alkaline sanukitoid granitoids that appeared in the geological record between 3.0 and 2.5 Ga are related to a source in an enriched subcontinental lithospheric mantle, thus indicating the existence of an enriched mantle source for granitoid magmatism since that time. Several contributions from Karelia and the Indian Shield (Dey *et al.* 2016; Heilimo *et al.* 2016; Joshi *et al.* 2016; Mikkola *et al.* 2016; Ramiz & Mondal 2016) find evidence for a long- or short-lived enriched mantle source below the cratons (western Karelia, Bundelkhand and eastern Dharwar), as well as for subsequent or simultaneous mantle and crust melting. Metamorphic studies of Hölttä *et al.* (2016) provide further support for a collisional tectonic setting in the Karelia Province.

This discussion deals with the evolution of crust-forming igneous magmatism from minor Eoarchaeoan crust–mantle interactions to the emergence of abundant multisource granitoids showing crustal recycling through mantle and intracrustal reworking at the end of the Archaean.

From the oldest rocks to microcontinents

The planetary accretion began about 4.6 gyr ago. From this eon, termed the Hadean, no rocks have survived except for some inherited zircons. The only Hadean remnants, and the oldest signs of felsic crust found so far, are the Jack Hills zircons from sedimentary rocks in the Yilgarn Craton of Western Australia. The oldest detrital zircon yielded a U–Pb date of 4.4 Ga, recently confirmed by atom-probe tomography sustaining the reliability of the chemical record inside the grain (Valley *et al.* 2014 and references therein). The 4.0 Ga Acasta granitic gneisses in the Superior Province, long known as the oldest rocks, are now challenged by rocks from supracrustal belts. One of the oldest volcanic units known on Earth, estimated at 4.3 gyr old (although controversial), are volcanic deposits (metamorphosed to amphibolites) of the Nuvvuagittuq greenstone belt in Quebec, Canada (O’Neil *et al.* 2012). The evidence points to the beginning of crust-forming igneous magmatism by volcanic activity on the Hadean Earth.

Archaean supracrustal belts (greenstone belts) consist of komatiites, tholeiitic basalts, andesites and rhyolites that formed near or on the surface of the Earth. The volcanic rocks represent primitive types of oceanic crust, oceanic plateaus and island arcs. The belts are dominated by tholeiites, but may also represent more evolved calc-alkaline basalt–andesite–dacite–rhyolite (BADR) series. Szilas *et al.* (2016) confirm that both a Hadean source and 50/50 mafic–felsic interactions contributed

to the formation of 3.07 Ga andesites in the Mesoproterozoic Qussuq supracrustal belt in southern West Greenland.

When metamorphosed, Archaean volcanic rocks may transform into mafic, intermediate and felsic granulites that are also common in Archaean terrains. U–Pb zircon and geochemical evidence of Eoarchaeoan crust–mantle interactions from granulites in the Ukrainian Shield come from Lobach-Zhuchenko *et al.* (2016). The protolith of mafic–intermediate granulites was a 3.66 Ga tholeiitic–andesitic rock that interacted with 3.74 Ga felsic material. Furthermore, Alam *et al.* (2016) show that mafic two-pyroxene granulites from the Bhandara–Balaghat Granulite Belt in the Central Indian Tectonic Zone (CITZ) have geochemical features of Neoarchaeoan island-arc tholeiites contaminated by crustal components.

According to a review by Polat (2012), it is generally accepted that the early basaltic crust was reworked and transferred to TTGs, but the nature of petrogenetic and geodynamic processes (thickened mafic island-arc crust *v.* plateaus) are still debated. The conversion of mafic crust into TTGs generated the oldest continental nuclei, known as Archaean microcontinents represented by current TTG–greenstone terrains. Joshi *et al.* (2016) describe TTG magmatism in the Bundelkhand Craton, where TTGs occur as rafts within younger granitoids, pointing out that the formation of sodic TTGs and later diversified high-K granitoids is not temporally related.

These results indicate that crust–mantle interactions contributed to some extent to the evolution of continents from the Eoarchaeoan to the Neoarchaeoan, but the next subsection shows that they became significantly more prominent towards the end of the Archaean.

Mantle–crust interactions and the diversification of granitoids

The papers by Dey *et al.* (2016), Heilimo *et al.* (2016), Joshi *et al.* (2016) and Mikkola *et al.* (2016) point out the geochemical diversification of granitoids and related rocks in the Neoarchaeoan by presenting geochemical and geochronological results of rock types such as alkali-enriched gabbros and granitoids, sanukitoids, and Closepet-type granitoids, as well as a heterogeneous group of monzogranitic rocks.

Several processes might be responsible for geochemical changes in magma sources, such as crustal recycling and mantle enrichment by subduction, mantle metasomatism, and melting, in addition to the melting of pre-existing continental crust and related hydrothermal activity, which complicates the petrogenetic studies of these rocks, and sets

the requirement of detailed trace element analyses and careful interpretations.

There are three important observations that should be explained when considering the reasons for the geochemical diversification. Firstly, the granitoids that have a silica content of less than about 68% seem to follow elemental fractionation trends, whereas granitoids with more than 68% silica show a prominent element scatter. The scatter probably indicates the involvement of multiple fluxes of enriched metasomatic fluids and melts in the crust.

Secondly, the granitoids with less than 68% silica (the LSHM group of Joshi *et al.* 2016) often carry a prominent high K–Mg–Ba–Sr–P signature. As the content of these elements is not dependent on the silica content of the rock – the signature can also be observed in mafic rocks – the conclusion that the source for these elements must be an enriched peridotite mantle is generally accepted.

Finally, it has been observed that the Hf, Nd and Pb isotope signatures of sanukitoids show variable mixed compositions between mantle and crust (e.g. Heilimo *et al.* 2013), and do not correlate with the strength of mantle or crustal geochemical signatures. This indicates that the crustal isotope signatures were inherited from the mantle source that acquired the signature by the recycling of continental sediments through subduction. Whether the mantle-derived granitoids show a crustal signature or not also depends on the age of the crustal segment present (Halla 2014). A signature appears when the mantle is contaminated with adequately old material; if material is about the same age, the crustal isotope signature is not observable.

The drastic increase in K, Ba and Sr in granitoids and gabbros, which does not correlate with either the silica content or the crustal isotope signatures, is best explained by a model of two-stage mantle metasomatism. In the first stage, the mantle was metasomatized by subduction-related processes and acquired crustal isotope signatures from adequately old sediments. In the second stage, partial melting of the metasomatized mantle caused the second stage of metasomatism (Halla *et al.* 2009), which was more alkaline in character. In addition to the ‘sanukitoid signature’, mafic magmatic enclaves are common in sanukitoids and Closepet-type granitoids, giving further evidence of the mantle contribution in their petrogenesis (Ramiz & Mondal 2016).

Mantle metasomatism is a complicated process, in which the composition of peridotite changes at high temperatures by the infiltration of carbonate or silicate melts and by CO₂-rich and water-rich fluids. Subduction-related H₂O-fluids may carry LIL elements, whereas melts are responsible for the transportation of high field strength (HFS) elements,

such as Ti, Zr, Hf, Nb and Ta. A commonly suggested source for Ba and Sr is a slab-melt or fluid metasomatized mantle wedge. A study of Mogarovskii *et al.* (2007) highlights the possibility that Ba and Sr can accumulate in the upper mantle as a consequence of mantle metasomatism and melting in the metasomatized mantle. It is possible that the upper-mantle source of sanukitoids was enriched in Ba and Sr as a final point at the time of formation of sanukitoid magmas.

Geochemical signatures that support pure crustal melting are high SiO₂, low MgO and lower Ba–Sr compared with enriched mantle-derived rocks (the HSLM group of Joshi *et al.* 2016). These rocks are very common worldwide, but there are differences in their abundance and temporal occurrence in different Archaean cratons. The explanation for the formation of this group of granitoids is partial melting in the continental crust, triggered by a flux of heat and metasomatic fluids/melts from the mantle. The geochemical differences within this group, such as differences in Eu (plagioclase-controlled) and HREE content (garnet-controlled) are due to differences in the source composition and mineralogy, as well as the depth of formation.

Temporal constraints

The sudden emergence of sanukitoid magmatism with a high K–Mg–Ba–Sr–P signature (Fig. 3a), indicative of an enriched mantle source, between 3.0 and 2.5 Ga (Fig. 3b), has invoked the debate on the onset of modern plate tectonics, since the enrichment of the subcontinental lithospheric mantle with incompatible elements requires the recycling of crustal material into the mantle, which, in turn, is a process generally attributed to subduction.

An example of the age relationships of TTGs and the best-known sanukitoids (Fig. 3b) from different cratons shows variable time gaps between the rock types up to 150 Ma, indicating that the TTGs and sanukitoid granitoids are not temporally related. This can be best observed in the Bundelkhand Craton, where TTG rafts up to 3.2 kyr old are embedded within abundant 2.5 Ga granitoids without any sign of a transitional change from sodic to calc-alkaline high-K magmatism in-between.

Sanukitoids appeared in the Archaean rock record at around 3.0 Ga and continued to form progressively from craton to craton until the end of the Archaean. Sanukitoids were intruded after the latest phase of local TTG magmatism, with variable time gaps, and were followed by, or were coeval with, purely crust-derived potassic magmatism. The oldest, Mesoarchaean sanukitoids, were formed in the Pilbara (west Australia) and Amazonian (Carajás Province, South America) cratons. It seems that in the Neoarchaean, the formation of sanukitoids was

a spatially and temporally progressive process that started in the Murchison Province of the western Yilgarn Craton (west Australia) at 2.76 Ga, continuing in the eastern part of the Karelian Craton at 2.74 Ga and advancing to West Karelia at 2.72 Ga, northern Superior at 2.70 Ga, southern Superior at 2.68 Ga and eastern Yilgarn Craton at 2.66 Ga. In each area, the period of sanukitoid magmatism was very limited. The latest sanukitoids were formed between 2.6 and 2.5 Ga in central India and north China. The geochronological picture of sanukitoid magmatism remains to be refined in the future, but, based on current knowledge, the formation of sanukitoids was a temporally restricted and spatially and temporally progressive event signifying an emergence of new geodynamic processes that advanced 'in order' from craton to craton.

In the western Karelia Province, sanukitoids and crust-derived high-K granitoids were intruded subsequently during a longer period (2.74–2.66 Ga), whereas the different types of Bundelkhand granitoids formed within a narrow time span (2.57–2.54 Ga). The anatectic melting was more widespread in Bundelkhand than in the Karelia Province. Also, the proportion of TTGs and high-K calc-alkaline granitoids is different: the Karelia Province consists mostly of TTGs; whereas, in the Bundelkhand Craton, the TTGs occur as scarce rafts within abundant high-K granitoids. In other words, the Karelia Province shows longer crust-enriched mantle interactions (80 Ma) than the Bundelkhand Craton (30 Ma). In the eastern Dharwar Craton, the high-K granitoids were formed within 10 myr (2.53–2.52 Ga). These time differences might reflect different processes (e.g. slab breakoff v. delamination) or the cratons may just represent different fragments of a large supercontinent. Subsequent slab breakoffs would produce a Karelia-like age patterns, whereas delamination might fit with the shorter timescale of magmatism in the Bundelkhand. However, the suggested tectonic environment for both cratons is a convergent continental margin.

Metamorphic constraints

The paper of Hölttä *et al.* (2016) brings metamorphic evidence on the tectonic setting of high-K granitoids from the Ilomantsi greenstone belt in the central Karelia Province by identifying metamorphic zonation that can be explained by regional heat advection in a collisional setting associated with late orogenic high-K magmatism. The Ilomantsi belt differs from tholeiitic greenstone belts in its restricted age (2.75–2.73 Ga), the mainly felsic and intermediate compositions of the volcanic rocks and the scantiness of basalts and ultramafic rocks, and their arc-type geochemistry and association with abundant coeval

sanukitoids. The belt is surrounded by TTG gneisses and is intruded by sanukitoids. In the Karelia Province, evidence points to a long-lasting high-grade metamorphism and melting that produced migmatites and potassic granites, granodiorites, and monzogranites from 2.71 to 2.64 Ga. The suggested tectonic setting is an active continental margin with simultaneous sedimentation, volcanism and plutonism (Hölttä *et al.* 2014). The Karelia Province was assembled during a Neoproterozoic collision event at around 2.7 Ga, which could have been related to the assembly of the possible Kenorland supercontinent at 2.7–2.6 Ga.

The results also indicate Palaeoproterozoic overprinting, which should be taken account when studying deformed Archaean granitoids. By studying Pb isotopes and the geochemistry of well-preserved, as well as retrogressed and deformed, sanukitoid granodiorites, Halla & Heilimo (2009) showed that retrograde metamorphism at temperatures of 400–500°C does not affect the geochemistry of granitoids, but may cause Pb-isotope exchange between K-feldspar and whole rock.

Tectonic scenario

The crust-forming igneous magmatism began with volcanic activity on the Hadean Earth at around 4 Ga and was followed by a long, but episodic, period of TTG formation from basaltic sources resulting in Eoarchaean–Mesoarchaean microcontinents.

The Mesoarchaean–Neoproterozoic geochemical diversification of granitoids that occurred in a time span between 3.0 and 2.5 Ga signifies an important change in plate tectonics. Melting in oceanic basaltic sources ended and a new environment for melting emerged: an enriched mantle wedge and continental crust. The latter sources indicate the formation of large-scale convergent continental margins. Contributions and interactions of melts and fluids from different sources in heterogeneously enriched mantle and pre-existing crust promoted the diversification of granitoid magmatism that account for the wide geochemical range of high-K calc-alkaline granitoids.

The source of mantle-derived granitoids probably underwent more than one phase of metasomatism. In the first subduction-related stage, water and incompatible LILEs (K, Rb, Ba, Sr and Pb) were introduced into the mantle with fluids, and HFSEs (Zr, Hf, Nb and Ta) with melts originated from the slab/sediments. In the second stage, the enriched mantle was partially melted and further metasomatized by carbonatite melts or CO₂ fluids highly enriched in incompatible elements such as Ba and Sr.

The mantle metasomatism and melting may have occurred as a consequence of a post-collisional

mantle upwelling triggered by a slab breakoff or delamination of the lower part of the crust. A slab breakoff has been suggested as the trigger of sanukitoid magmatism by, for example, Calvert *et al.* (2004), Whalen *et al.* (2004), Lobach-Zhuchenko *et al.* (2008) and Halla *et al.* (2009), and delamination is favoured by Gao *et al.* (2004). Slab breakoff is thought to follow attempted subduction of buoyant continental lithosphere during continental collision (Wortel & Spakman 2000; van Hunen & van den Berg 2008). Oceanic lithosphere detaches from continental lithosphere, and hot asthenosphere upwells into the tearing slab causing melting and metasomatism in the overriding mantle lithosphere (Davies & von Blanckenburg 1995). Mantle melting may also have acted as the trigger for intracrustal melting.

One aspect of economic importance is that most of the orogenic gold deposits found in Archaean cratons are spatially and temporally associated with igneous intrusions, especially sanukitoids, which have been thought to generate the fluids and melts for gold mineralization. Recently, sanukitoids have been identified as a potential gold indicator (Kwelwa *et al.* 2013; Lin & Beakhouse 2013; Kirkland *et al.* 2015); an observed peak in gold production at around 2.70 Ga correlates with the peak of sanukitoid formation. According to Lin & Beakhouse (2013), accretionary collision led to the cessation of subduction, slab breakoff and the influx of asthenospheric mantle into the sub-arc mantle wedge. This led to the generation of sanukitoid magmas and associated hydrothermal fluids. Slab breakoff, related magmas and hydrothermal fluids, late granitoid magmatism, and possible gold mineralization were all linked to a range of processes associated with the accretionary growth and stabilization of the craton.

The compositional diversification of magmas as a result of the contributions from lithospheric mantle and reworked continental crust indicates the emergence of thick continents and subcontinental lithospheric keels: that is, the components of modern-type continental margins. However, geochemical differences still exist at the Archaean–Proterozoic boundary. The most important feature that needs further explanation is the worldwide occurrence of high K–Mg–Ba–Sr–P signatures in totally or partly mantle-derived rocks regardless of their SiO₂ content. This must be linked to processes in the mantle that have affected most of the Archaean cratons. Processes such as slab breakoff and delamination offer an explanation for the strong heat flux and mantle metasomatism after subduction. It is possible that the plates behaved differently because of their different properties (thickness, temperature and buoyancy) due to the different physical conditions of the early Earth. Subduction might

have ended in breaking buoyant slabs before deep subduction. A challenging question is how to explain the abrupt change in Earth's geodynamics by slow progressive cooling of the Earth, which has previously been suggested as the trigger for large tectonic changes. Perhaps the formation of the first supercontinent has also had a profound effect on the change in the style of plate tectonics.

Based on the results on this special publication, we provide the following conclusions on Archaean mantle–crust interactions and granitoid diversification:

- Minor mantle–crust interactions have occurred since the Eoarchaean, as evidenced by the geochemical and isotope composition and U–Pb ages obtained for tholeiitic–andesitic greenstone belts and their metamorphic equivalents from West Greenland, the Ukrainian Shield and central India.
- Strong crust–mantle interactions and diversification of granitoids occurred in the Karelia (2.74–2.66 Ga), Bundelkhand (2.57–2.54 Ga) and eastern Dharwar (2.53–2.52 Ga) cratons, as well as in other cratons between 3.0 and 2.5 Ga, although the time and duration varies from craton to craton.
- Metamorphic studies from the Karelia Province support the view that high-grade metamorphism and partial melting in a collisional setting produced migmatites and high-K calc-alkaline granites that intruded the TTG–greenstone terrains.
- The increase in mantle–crust interactions, probably as a consequence of frequent slab breakoffs or delamination at convergent continental margins, caused multisource magmatism by triggering melting, metasomatism and hydrothermal activity in the mantle and crust, reflecting possibly an assembling supercontinent towards the end of the Archaean.

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