GEOLOGICAL REVIEW

ARCHEAN-PALEOPROTEROZOIC CRUSTAL EVOLUTION OF THE BELOMORIAN PROVINCE (FENNOSCANDIAN SHIELD) AND THE TECTONIC POSITION OF ECLOGITES

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The Belomorian province, an Early Precambrian mobile belt, is located in the central part of the Archean core of the Fennoscandian shield and intervenes between the Archean Kola Province in the northeast and the Archean Karelian craton in the southwest (Figs. 1.1 and 1.2). This is believed to extend southeast at least 350 km beneath the sedimentary cover of the Russian platform (Bogdanova et al., 2005). The continental crust of the Belomorian Province was formed during the Meso- and Neoarchean Belomorian accretionary-collisional orogeny (Glebovitsky et al., 1996; Bibikova et al., 1999, 2004;

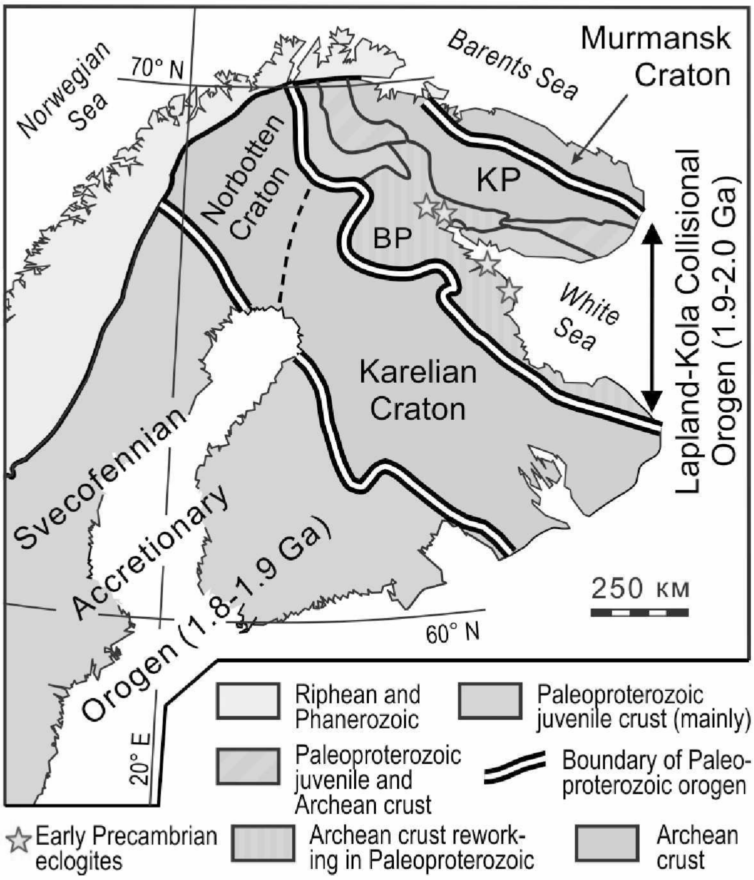

Fig. 1.1. Major tectonic units of the Fennoscandian shield (BP and KP, Belomorian and Kola provinces, respectively)

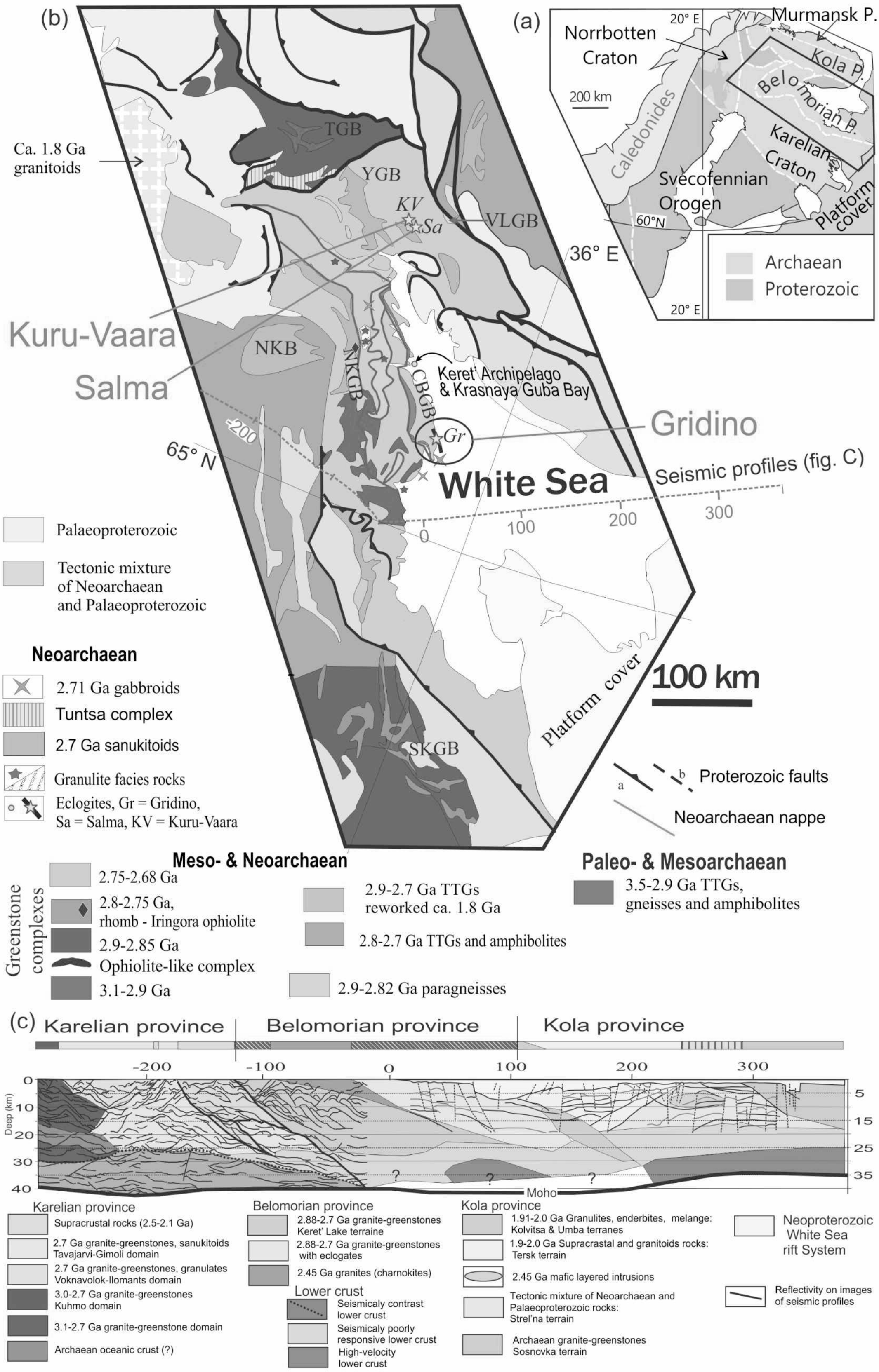

Fig. 1.2. (a) Location of the geological scheme shown in (b); (b) Geological scheme of the Belomorian province, Fennoscandian Shield (modify after Slabunov, 2008). **Paragneiss belt:** ChPB = Chupa; **Greenstone belt:** KGB = Keret'; NKGB = North Karelian; YGB = Yona greenstone belt; VLGB = Voche-Lambino greenstone belt; **Constituent part (structure) of geenstone belt**: Kh = Khizovaara; Ke = Keretozero; Ki = Kichany; Ka = Kolikorva; Ch = Chelozero; **Eclogite-bearing complex:** Gr = Gridino; Sa = Salma. (c) Geological deep section along seismic profiles DSS–CDP Kalevala–Kem'–White Sea (Sharov et al., 2010)

Slabunov, 2008; Mints et al., 2015). The Belomorian province was under the influence of a 2.40–2.45 Ga superplume (Bogdanova, 1996; Kulikov et al., 2010; Stepanova, Stepanov, 2010) and a *ca.* 2.1 Ga continental rifting (Stepanova et al., 2014). Then the Belomorian Province was the southwestern foreland of the Paleoproterozoic Lapland-Kola collisional orogen and was reworked during the Lapland-Kola orogeny (Daly et al., 2001, 2006; Balagansky, 2002). Hence, the Belomorian province is a deep Archean crust considerably exhumed shortly after the peak of the Paleoproterozoic collision (<1.90–1.92 Ga).

The Belomorian province is a tectonic collage consisting of several thrust-bounded sheets (nappes) as shown by geological mapping (Miller, Milkevich, 1995) and deep seismic profiles (Fig. 1.2 b-c) (Sharov et al., 2010). Neoarchean (*ca.* 2.7 Ga) nappes were probably responsible for the province structure (Miller, Milkevich, 1995; Glebovitsky et al., 1996) and Paleoproterozoic Lapland-Kola collision made this structure much more intricate (Glebovitsky, 2005; Daly et al., 2006; Mints et al., 2010b; Mudruk et al., 2013).

The Belomorian province consists of dominantly of Meso- and Neoarchean TTG rocks and subordinate amphibolites and paragneisses of the same age (2.90–2.65 Ga). The most ancient rocks are represented by ≥2.9 Ga dismembered remnants of a supra-subduction zone (SSZ) ophiolite (Fig. 1.2), a constituent part of the Late Mesoarchean Seryak mafite-ultramafite complex (Slabunov et al., 2019). Multiply foliated and migmatized TTG gneisses have developed from igneous protoliths from 2.88 Ga to 2.72 Ga, while their Sm-Nd model ages (t_{DM}) range from 2.93 to 2.72 Ga, indicating a lack of older crustal sources (Slabunov et al., 2006a, b; Slabunov, 2008). Archean high-grade amphibolite and paragneiss belts make up *ca.* 15–20 % of the province area (Fig. 1.2b) and consist of rocks geochemically close to island-arc volcanics, fore-arc basin sediments, and dismembered SSZ ophiolites, as well as molassa-type rocks. Five generations of greenstone complexes were formed at 2.88–2.82 Ga, 2.8–2.78 Ga, *ca.* 2.75 Ga, *ca.* 2.72 Ga and not later than 2.66 Ga, and two paragneiss complexes at 2.89–2.82 and 2.78 Ga ago.

The most prominent characteristic feature of the Belomorian province is the occurrence of eclogites (Fig. 1.2b) mentioned in papers already in the first half of the 20th centure (Eskola, 1921; Sudovikov, 1939). A modern stage of studying eclogites has been started after the discovery of these rocks first in the Gridino area (Volodichev et al., 2004) and in the Kuru-Vaara and Salma area, southwestern Kola Peninsula (Mints et al., 2010b), and then on islands of the Keret Archipelago and the Krasnaya Guba Bay (Figs. 1.1 and 1.2b). Two distinct types in age of eclogites have been reported from the Belomorian province, Meso- to Neoarchean (Volodichev et al., 2003, 2004; Slabunov et al., 2006a, b; Mints et al., 2010a, b; 2015; Li et al., 2015; Dokukina, Konilov, 2011; Konilov et al., 2011; Dokukina et al., 2014; Shchipansky et al., 2012a, b) and Paleoproterozoic (Volodichev et al., 2004, 2008; Travin, Kozlova, 2005, 2009; Kozlovsky, Aranovich, 2008, 2010; Skublov et al., 2011a, b, 2012, 2016; Berezin et al., 2012, 2013; Mel'nik, 2015; Travin, 2015; Imayama et al., 2017; Yu et al., 2017, 2019a, b).

Meso- and Neoarchean (2.88–2.82 Ga and ≥2.72 Ga) eclogites occur as remnant mineral assemblages preserved in intensely disintegrated amphibolites embedded in a TTG matrix which has been interpreted as the tectonic mélange in the Gridino area or as the eclogite-TTG mélange in the Kuru-Vaara and Salma areas (Fig. 1.2b; Volodichev et al., 2004; Slabunov et al., 2006a, b; Mints et al., 2010b; 2015; Konilov et al., 2004, 2005, 2011; Shchipansky et al., 2012a; Balagansky et al., 2015). Meso- and Neoarchean (2.82–2.8 Ga, 2.78–2.74 Ga and 2.72 Ga) medium-pressure (MP) granulites have also been reported from mélange zones. Minor 2.7 Ga S-type collisional leucogranites are also noteworthy; in addition, 2.67 Ga late- and postkinematic granites are common.

There are several models proposed for the tectonic evolution of the Belomorian province in the Meso- and Neoarchean. According to (Bibikova et al, 1999, 2004; Shchipansky et al., 2004, 2012a, b; Slabunov, 2008; Slabunov et al., 2006a, b, 2019; Hölttä et al., 2008, 2012, 2014), main stages of the Archean crustal evolution of the Belomorian province are as follows:

- *ca.* 2.9 Ga – initiation of subduction and the formation of the Seryak ophiolite-like sequence;
- *ca.* 2.88–2.82 Ga – the first subduction-accretion event recorded by island-arc volcanics of the Keret greenstone belt, fore-arc meta-graywacke of the Chupa paragneiss belt and the Salma eclogites;
- 2.81–2.78 Ga – the second subduction-accretion event marked by island-arc volcanics and supra-subduction ophiolite in the Iringora area, and metagraywackes and granulites in the Norozero area;
- 2.75 Ga – the third subduction event marked by island-arc volcanics in the Chelozero area;
- 2.73–2.72 Ga – the fourth subduction-accretion event marked by island-arc volcanics, granulites and the Gridino older eclogites (Balagansky et al., 2019 and this guidebook);
- *ca.* 2.7–2.66 Ga – collisional event marked by collisional S-granites, kyanite-type metamorphic rocks, molassa-type rocks, subalkaline granitoids and leucogabbro.

Another tectonic model (Mints et al., 2010b, 2015; Mints, Eriksson, 2016; Dokukina, Mints, 2019) suggests a leading role of subductional, accretionary and collisional processes during the growth of the Belomorian continental crust at 2.9–2.78 Ga and its reworking due to an impingement of mantle plumes at 2.78–2.74 Ga. Paleoproterozoic basic dikes in the Gridino area (Stepanov, Stepanova, 2005; Stepanova, Stepanov, 2010) have been re-interpreted as being Archean in age (Dokukina, Konilov, 2011; Dokukina et al., 2014) and their emplacement are thought to be related to subduction of a mid-ocean slow-spreading ridge beneath the Kola continental plate (Mints et al., 2010b; Konilov et al., 2011; Mints et al., 2014; Dokukina, Mints, 2019). According to this model, the Meso- and Neoarchean eclogite-facies overprint that occurred in these dikes is ascribed to the Archean collision; plume-related metamorphic changes are also suggested. The Archean age of the dikes is strongly disputable and needs more convincing evidence.

In the Early Paleoproterozoic (2.5–2.34 Ga) the Belomorian continental crust was subjected to a thermal influence by a mantle superplume impingement. Located beneath the eastern Fennoscandian Shield, this superplume was responsible for the formation of NW-trending rift-belts (Fig. 1.3) parallel to major Archean tectonic boundaries (Daly at al., 2006; Lahtinen et al., 2008; Stepanova et al., 2010, 2014; Kulikov et al., 2010, 2017; Egorova, 2017). Abundant small, commonly coronitic gabbroid intrusions and dikes (Fig. 1.3), as well as potassic granites were intruded under conditions of oblique crustal extension (Stepanov, 1981; Balagansky et al., 1998; Krivolutskaya et al., 2010; Stepanova et al., 2010; Slabunov et al., 2011; Kulikov et al., 2017). Specific plutonic rocks of this period are 2.44–2.39 Ga lherzolite-gabbronorite (Bibikova et al., 2004; Krivolutskaya et al., 2010; Stepanova, Stepanov, 2010; Slabunov et al., 2011; Volodichev et al., 2012), 2.44 Ga enderbite and charnockite (Korsakova et al., 2011) and rare gabbro-anorthosite of 2.5 Ga (Skublov et al., 2016; Stepanova et al., 2017).

The continental crust of the entire Fennoscandian Shield began to breakdown at 2.1–2.0 Ga ago as evidenced, first of all, by the rift-type ophiolite of Jormua (Peltonen, Kontinen, 2004), as well as by numerous Belomorian Fe-tholeiitic dikes (Fig.1.3) of that age (Stepanova et al., 2014). The Kola Ocean was opened at *ca.* 2.0 Ga along the boundary between the Belomorian and Kola provinces and its closure led to the Lapland-Kola collisional orogeny (Berthelsen, Marker, 1986; Daly et al., 2001, 2006; Balagansky, 2002; Lahtinen et al., 2008; Lahtinen, Huhma, 2019). The juvenile continental crust that composes the core of the Lapland-Kola collisional orogen (first of all, the Lapland granulite belt and the Umba granulite terrane) was formed during NE- or SW-directed subduction of the Lapland-Kola oceanic crust at 1.98–1.94 Ga in the Kola region and approximately 20–30 Ma later in northern parts of Finland and Norway (Daly et al., 2001, 2006; Mints et al., 2007; Mudruk et al., 2013; Lahtinen, Huhma, 2019). The latest studies that used a large body of geophysical data suggest a SW-directed subduction (Mudruk et al., 2013; Lahtinen, Huhma, 2019). Tuisku and Makkonen (1999) reported on a metamorphic rock that was formed under P–T conditions transitional between amphibolite- to eclogite facies (11–12 kbar and 670 °C) at 1.90–1.88 Ga. This rock developed from an olivine cumulate in a gabbroid intrusion in the Tanaelv collisional mélange that intervenes between the Archean Belomorian rocks and the overlying Paleoproterozoic Lapland granulite belt (Daly et al., 2001). Its igneous protolith can hardly be coeval to that of extended layers of the Meso- to Neoarchean Belomorian amphibolites containing remnants of eclogite-facies assemblages because these amphibolites originated from basalts of oceanic affinity (Slabunov, 2008; Shchipansky et al., 2012a, b; Mints et al., 2010b, 2014, 2015). The peak of the collision and high-P amphibolite- to granulite-facies metamorphism occurred in the Belomorian province and the Russian part of the overlying Lapland granulite belt at 1.925 Ga (Volodichev, 1990; Glebovitsky, 2005; Daly et al., 2006) and 20–30 Ma later in Finnish Lapland (Lahtinen, Huhma, 2019). Paleoproterozoic gabbroid intrusions and dikes were metamorphosed, and coronitic textures were largely developed (Fedorov, 1896; Stepanov, 1981; Larikova, 2000; Egorova, 2017).

For the first time, Paleoproterozoic eclogite-facies overprint expressed by patches of eclogite-facies mineral assemblages in the igneous matrix was discovered in Paleoproterozoic mafic dikes (Volodichev, 1990; Volodichev et al., 2004). Later the Paleoproterozoic eclogitic assemblages were reported both from Paleoproterozoic basic and gabbro-anorthosite dikes and massifs (Travin, Kozlova, 2005, 2009; Kozlovsky, Aranovich, 2008, 2010; Berezin et al., 2012, 2013; Volodichev et al., 2012; Travin, 2015; Skublov et al., 2016) and from Archean amphibolites (Skublov et al., 2010, 2011a,b; 2012; Herwartz et al., 2012; Mel'nik et al., 2013; Imayama et al., 2017; Yu et al., 2017, 2019a, b). It should be pointed out that these amphibolites are the same rocks in which relics of Archean eclogite were described. Furthermore, ultra-high pressure (UHP) eclogite-facies mineral assemblages were found in some meta-mafic rocks (Morgunova, Perchuk, 2012, Perchuk, Morgunova, 2014). At last, diamond-bearing eclogites that univocally evidence UHP metamorphism have been recently established in the Kuru-Vaara area but an Archean age is argued for these UHP rocks (Shchipansky et al., 2019 and this guidebook).

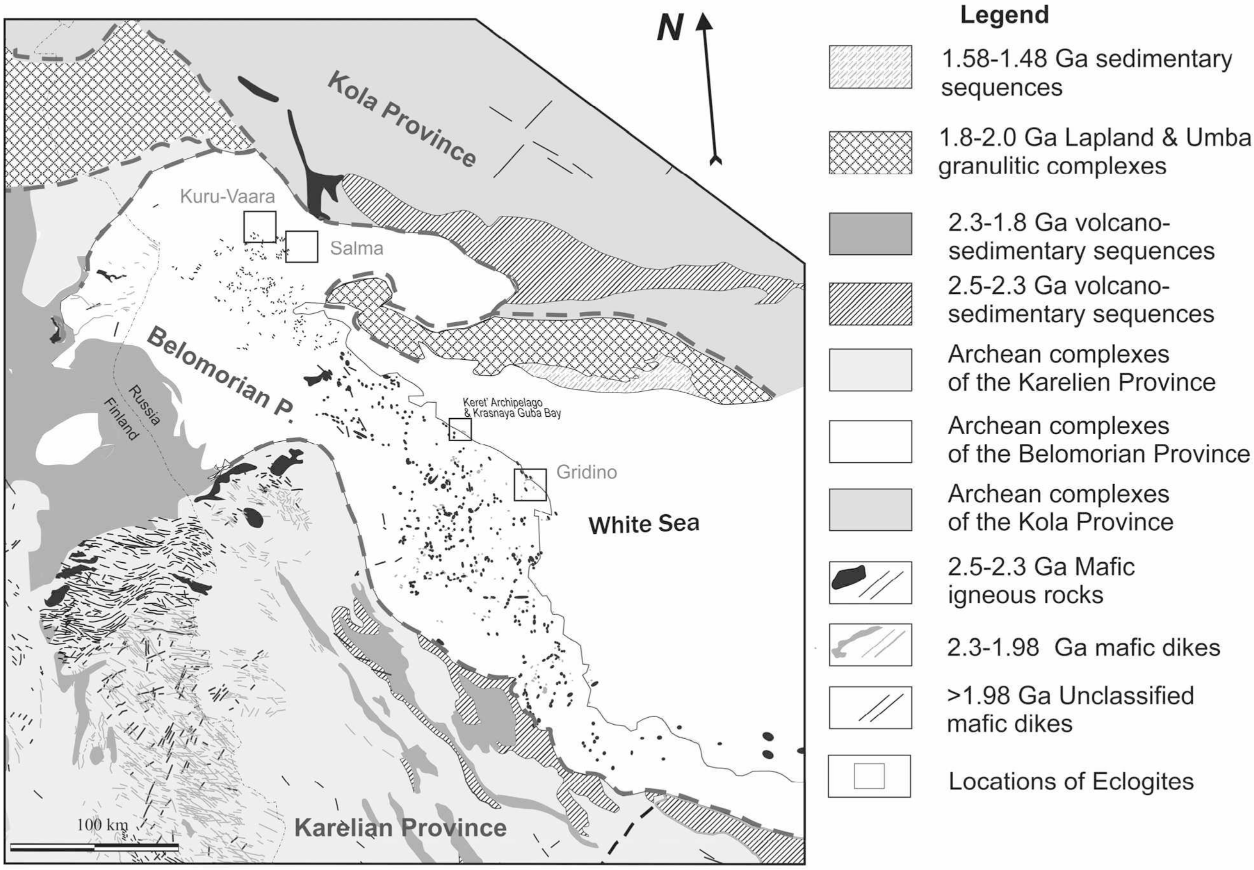

Fig. 1.3. Geological sketch map of the eastern Fennoscandian Shield showing the distribution of Paleoproterozoic mafic rocks (modified after Stepanova et al., 2014) and the location of eclogites in the Belomorian province

The Paleoproterozoic eclogite-facies overprint occurred at *ca.* 1.90 Ga as evidenced by 1.90–1.87 Ga zircon rims containing rare inclusions of omphacite, garnet and kyanite (Imayama et al., 2017; Yu et al., 2017, 2019a, b). These unambiguous Paleoproterozoic eclogites are considered as the younger eclogites in the Gridino area (Balagansky et al., 2019 and this guidebook). All dates obtained for the Paleoproterozoic eclogites fall in the period of the Lapland-Kola collision which started at 1.925 Ga in the Kola part of the Lapland-Kola orogen (Daly et al., 2006) and terminated at 1.88 Ga in the Finnish Lapland part (Lahtinen, Huhma, 2019). During this period, a collage of nappes was developed and resulted in thrusting Belomorian rocks onto the Karelian Craton in the southwestern Belomorian province and, thus, in exhumating its deep crustal levels. The exhumation is consistent with a spatial distribution of U-Pb titanite and rutile ages throughout the Belomorian province: the titanite ages decrease from 1.94 Ga to 1.82 Ga and the rutile ages from 1.81 Ga to 1.74 Ga southwestwards (Bibikova et al., 2001; Nesterova et al., 2011). In turn, the Lapland granulite belt, the Umba granulite terrane and the Tersk terrane were thrust onto the northern and northeastern Belomorian province. Thus, the Lapland-Kola collision resulted in the formation of the Belomorian crustal tectonic stacking so giving rise to the high-P metamorphism. It is the Lapland-Kola collisional orogeny that is considered to be responsible for the Paleoproterozoic eclogite-facies overprint (Balagansky et al., 2015; Lahtinen, Huhma, 2019).

An alternative tectonic model has been recently argued for the evolution of the Belomorian province in the Late Paleoproterozoic (Mints et al., 2015; Mints, Eriksson, 2016). The foundation stone of this model is the Lapland–Mid-Russia–South Baltia intracontinental orogen that originated and evolved due to an influence of mantle plumes. This geodynamic concept excludes the formation of eclogite at that time.

So, the Belomorian province drastically differs from other Archean tectonic units of the Fennoscandian shield in its tectono-metamorphic history (cf. Slabunov et al., 2006a, b). First, the Belomorian rocks underwent regional high-*P* (kyanite-type) amphibolite-facies and granulite-facies metamorphic events in the both Archean and Paleoproterozoic (Volodichev, 1977, 1990; Glebovitsky at al., 1986, 1996; Slabunov et al., 2016, 2017). Second, ultra-high-temperature metamorphic rocks have been reported from several localities of the Belomorian province (Azimov et al., 2017). Finally, vestigial UHP mineral assemblages in the eclogitic remnants (Morgunova, Perchuk, 2012; Perchuk, Morgunova, 2014; Shchipansky et al., 2019 and this guidebook), and phengite-bearing zoisitites (Volodichev et al., 2014; Slabunov et al., 2015) have been also documented. It is obvious that the Belomorian eclogites are of the prime interest for Early Precambrian geodynamics. It comes as no surprise that their provenance and age remain much disputable. According to the review given above there are three points of view on the age of the Belomorian eclogites:

1. Archean and Paleoproterozoic eclogites (Volodichev et al., 2004, 2012; Slabunov et al., 2011; Balagansky et al., 2015; Li et al., 2015; Babarina et al., 2017; Maksimov, 2019);
2. solely Mesoarchean eclogites (Konilov et al., 2004; 2011; Mints et al., 2010a, b; 2015; Dokukina, Konilov, 2011; Dokukina et al., 2014; Shchipansky et al., 2012a, b; Dokukina, Mints, 2019; Mints, Dokukina, 2019);
3. solely Paleoproterozoic eclogite (Kozlovsky, Aranovich, 2008, 2010; Skublov et al., 2010, 2011a, 2012, 2016; Berezin et al., 2012, 2013; Morgunova, Perchuk, 2012, Mel'nik et al., 2013; Perchuk, Morgunova, 2014; Travin, 2015; Imayama et al., 2017; Li et al., 2017; Yu et al., 2017, 2019a, b; Brown, Johnson, 2018).

The planned geological excursions provide a good opportunity for the reader to exanimate these contradicting points of view immediately on perfect outcrops on islands of the White Sea, on the benches of the Kuru-Vaara quarry and in the walls of road pits in the Salma area.

Good luck, the reader!

Acknowledgements

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