Reply

Reply to Skublov et al. Comment on “Volodichev et al. Archean Zircons with Omphacite Inclusions from Eclogites of the Belomorian Province, Fennoscandian Shield: The First Finding. *Minerals* 2021, 11, 1029”

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Abstract: Early Precambrian retrogressed eclogites are abundant in the Archean Belomorian Province of the Fennoscandian Shield. Archean zircons with inclusions of omphacite have been found in these eclogites. Similar Archean zircons from the retrogressed eclogites also contain garnet inclusions. The Archean zircons display no negative Eu anomaly, which indicates their crystallization in plagioclase-free rock. Garnet, omphacite and clinopyroxene-plagioclase symplectite as a proxy of omphacite compose $\geq 75\%$ of the studied rocks, with garnet and omphacite being major constituents and associating with rutile and quartz. These data strongly suggest that the studied rock is eclogite. In the majority of petrogenetic grids, P - T parameters calculated for these rocks fall in the eclogite-facies field. Thus, these findings and data provide evidence that eclogite-facies metamorphism occurred in the Neoproterozoic.

Keywords: Archean; eclogite; zircon; omphacite; geochronology; geochemistry; mineral inclusion; Gridino eclogite-bearing mélange; Belomorian province

Citation: Volodichev, O.I.; Maksimov, O.A.; Kuzenko, T.I.; Slabunov, A.I. Reply to Skublov et al. Comment on “Volodichev et al. Archean Zircons with Omphacite Inclusions from Eclogites of the Belomorian Province, Fennoscandian Shield: The First Finding.

Minerals 2021, 11, 1029”. *Minerals* 2022, 12, 142. <https://doi.org/10.3390/min12020142>

Academic Editor: José Francisco Molina

Received: 20 December 2021

Accepted: 19 January 2022

Published: 25 January 2022

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Archean eclogite-facies rocks are scarce and used for studies of tectonic evolution of the Earth’s lithosphere [1,2]. Therefore, each metamorphic complex that contains eclogite attracts the attention of researchers [3], as indicated by comments on our paper published recently.

The Belomorian Province (BP) of the Fennoscandian Shield is undoubtedly of special interest because this contains abundant retrogressed eclogites. Furthermore, eclogite-facies metamorphism is assumed to have taken place in both Archean and Paleoproterozoic times in the BP ([1,4], and references therein). The continental crust of this province is argued to have been produced by Meso-Neoproterozoic (2.9–2.65 Ga) subduction-collision processes during the Belomorian orogeny and then became part of the Paleoproterozoic (2.0–1.85 Ga) Lapland-Kola collisional orogen [5]. Furthermore, in the period between these two orogenic events the BP’s earth crust was affected by mantle plumes, which have preserved as six generations of Paleoproterozoic dike swarms and intrusions [6]. The BP’s crustal evolution is too intricate to study mineral assemblages of early metamorphic events, because these have been largely destroyed by subsequent deformations and metamorphism. That is why, to decipher the early stages of long metamorphic evolution of the BP, multidisciplinary studies, such as geological mapping, structural geology, petrology, and geochronology, should be conducted. This approach is used to reveal relics of early structures and metamorphic mineral assemblages [7–9].

We believe that the interested reader can assess the validity of the available evidence for that eclogite-facies metamorphism occurred not only in the Paleoproterozoic but also in the Archean [4,9–12]. S.G. Skublov and his co-workers noted correctly that the finding of inclusions of omphacite in Archean zircon dated at 2683.1 ± 7.8 ($\pm 1 \sigma$) Ma is an important fact. However, this finding is the only one and should be confirmed by further research.

Our studies of the Belomorian eclogites are in progress, so in response to the comments we wish to draw attention only to several crucial aspects.

The authors of the comments do not think that the omphacite that we found as inclusions in Neoproterozoic zircon “... was derived under eclogite-facies conditions. The 25% Jd content of the omphacite is similar to the lower limit for omphacite [...]. Omphacite-hosting zircon has a $^{207}\text{Pb}/^{206}\text{Pb}$ -age of 2694.1 ± 8.1 Ma (... [...]). The age ~2.7 Ga, estimated from the zircon cores was interpreted by us as the timing of granulite-facies regional metamorphism in BMB [...]. The formation of omphacite under high-pressure granulite-facies metamorphic conditions has been repeatedly proved, for example, for the Bohemian Massif (up to 27% Jd, [...]) and the Western Sudetes (up to 32.6% Jd, [...]) granulites. The parameters of metamorphism for Gridino eclogites (14 kbar and 750°C [...]), calculated from omphacite inclusions in garnet with 23% Jd, are also consistent with high-pressure granulites, rather than eclogites ...”.

We think, however, that in analyzing these comments the reader should take into account the following:

1. A rock is identified as eclogite primarily on the basis of the definition accepted by the geological community. We follow the definition of eclogite as “plagioclase-free metamorphic rock composed of $\geq 75\%$ omphacite and garnet, both of which are present as major constituents” ([13], p. 32). Almost all of the Archean Gridino eclogites are intensively retrogressed. Omphacite in these rocks is almost completely replaced by plagioclase clinopyroxene-symplectites [12], whereas garnet is well-preserved. The percentage of the symplectites, which are interpreted as a proxy of initial omphacite, is much higher than 5%, and the total percentage of symplectites and garnet is at least 75%, which is sufficient for identifying the studied rock as eclogite. This conclusion is supported by the presence of quartz and rutile. We do not think that the rock studied can be defined as omphacite-bearing granulite similar to those from the Bohemian Massif [14] or the Western Sudetes [15]. The point is that the omphacite in granulites of the Bohemian massif is not equilibrium with metamorphic minerals of granulite facies and represents a relic of an older mineral assemblage of eclogite facies [16,17].

2. According to [13], for a rock to be identified as eclogite, the presence of omphacite, rather than the jadeite content of omphacite is crucial. According to [18], omphacite is clinopyroxene solid solution of jadeite, augite, and aegirine, with jadeite concentration of at least 20%. Two clinopyroxenes from inclusions in Archean zircons contain 23.0% and 25.4% jadeite [11] and can be identified as omphacite. Thus, the above requirement is met.

3. It should be stressed once more that Archean metamorphic zircons from the eclogites studied by us display no negative Eu anomaly, which indicates their crystallization in plagioclase-free metamorphic rock. Thus, another requirement for identifying the studied rock as eclogite (the lack of plagioclase) is met. Moreover, Archean zircons of the same age, 2689 ± 5 Ma, from the same rocks contain garnet inclusions [19]. Thus, 2.69 Ga zircon formed in association with omphacite and garnet in plagioclase-free metamorphic rock, which indicates that the discussed eclogite-facies metamorphic event took place in the Neoproterozoic.

4. Finally, P - T parameters of the formation of the studied eclogites were calculated based on relic eclogite-facies mineral assemblages. These display minor variations and do not seem to be consistent with the peak eclogite-facies parameters [20]. These parameters ($P = 1.0$ – 18.5 kbars and $T = 700$ – 800°C [11,19], fall in the eclogite-facies field in some diagrams [21,22], on the boundary between granulite- and eclogite-facies fields in others [23], and in the eclogite high-pressure granulite-facies field, which is part of eclogite facies, in which plagioclase remains stable in some bulk compositions [24]. On the petrogenetic grid in [25] referred to in the comments, 80% of the P - T parameters lies in the eclogite-facies field and 20% in the high-pressure granulite-facies field. As for amphibole, it is present in the mineral parageneses of the lowest stage of eclogite facies [21,22,24].

In conclusion, we again wish to thank the authors of the comments for critical assessment of our work and useful discussion.

Author Contributions: Conceptualization, O.I.V., O.A.M. and A.I.S.; methodology, O.I.V.; validation, O.I.V., O.A.M. and A.I.S.; investigation, O.I.V., O.A.M.; resources, O.I.V.; data curation, T.I.K., O.A.M.; writing—original draft preparation, O.I.V., O.A.M. and A.I.S.; writing—review and editing, O.I.V., O.A.M. and A.I.S.; supervision, A.I.S.; project administration, O.A.M. and A.I.S.; funding acquisition, O.I.V., O.A.M. and A.I.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by state assignment to Institute of Geology Karelian Research Centre RAS AAAA-A18-118020290085-4.

Conflicts of Interest: The authors declare no conflict of interest.

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