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Comment on Bybee et al. (2014): Pyroxene megacrysts in Proterozoic anorthosites: Implications for tectonic setting, magma source and magmatic processes at the Moho

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In their recent paper, Bybee et al. (2014) present new isotopic and geochronological data on High-Alumina Orthopyroxene Megacrysts (HAOM) sampled in three different Proterozoic massif-type anorthosites, namely, the Mealy Mountains Intrusive Suite (MMIS), the Nain Plutonic Suite (NPS) and the Rogaland Anorthosite Province (RAP). The Sm–Nd isochron ages obtained on HAOM from these three provinces indicate that the most alumina-rich samples, i.e. those that crystallized at the highest pressure, are 80–120 Ma older than their host anorthosites. Moreover, Sm–Nd isochrons between plagioclase lamellae, host orthopyroxene and whole-rock from the NPS and RAP have decompressed at ages that correspond to the crystallization ages of the host anorthosites at mid crustal level, as recorded by zircon U–Pb data (i.e. Emslie, 1990; Myers et al., 2008; Schärer et al., 1996). There is thus a 70–100 Ma gap between the crystallization of the HAOM at the base of the crust, on the one hand, and their decompression and anorthosite crystallization in the rising diapirs (or crystal mush), on the other hand. The authors interpret these geochronological data by proposing that HAOM crystallized from mantle derived magmas ponded at the base of the crust some 100 Ma before the crystallization and emplacement of the anorthosite and that the 100 Ma time interval was spent partly in a convecting and recharging lower crustal magma chamber and partly in the ascent of the anorthosite. As the diapiric rise of the RAP anorthosites was modelled to last for about 2.5 Ma (Barnichon et al., 1999), most of the

100 Ma timespan is left in this case for the lifetime of the lower crustal magma chamber.

These new geochronological data bring very important constraints on the petrogenesis of Proterozoic massif anorthosites (2.12–0.92 Ga: Hamilton et al., 1998; Ryan et al., 1999; Vander Auwera et al., 2011). We agree with the authors that several lines of evidence support that their isochrons record crystallization of the HAOM. These evidences include the consistent ca. 100 Ma timespan between HAOM crystallization and anorthosite emplacement obtained in three different anorthositic provinces. However, we think that there is an alternative explanation to this 100 Ma timespan that has not been explored by the authors. We will discuss this alternative below with a focus on the RAP for which extensive data have been presented on the regional geology, isotopic measurements for the anorthosite massif and the surrounding rocks, completed by extensive experimental study for phase equilibria.

There is an ongoing debate about the mantle or lower crustal source of the anorthosite parent magma. Experimental data acquired on a high-Al basalt (HLCA), parent magma of Proterozoic anorthosites provide a strong constraint as they indicate that, at the lower crustal pressures (10–13 kbar) necessary to produce the characteristic HAOM, this high-Al basalt lies on a thermal divide of the plagioclase + pyroxene liquidus surface requiring that it was produced by partial melting of a gabbro-noritic lower crustal source (Duchesne et al., 1999; Longhi et al., 1999). Vander Auwera et al. (2011) identified several possible precursor mafic magmatic events in the Sveconorwegian orogen that could potentially have provided the lower crustal source of the younger RAP (0.93 Ga): the 1.05 Ga Feda suite mafic facies, the volcanic

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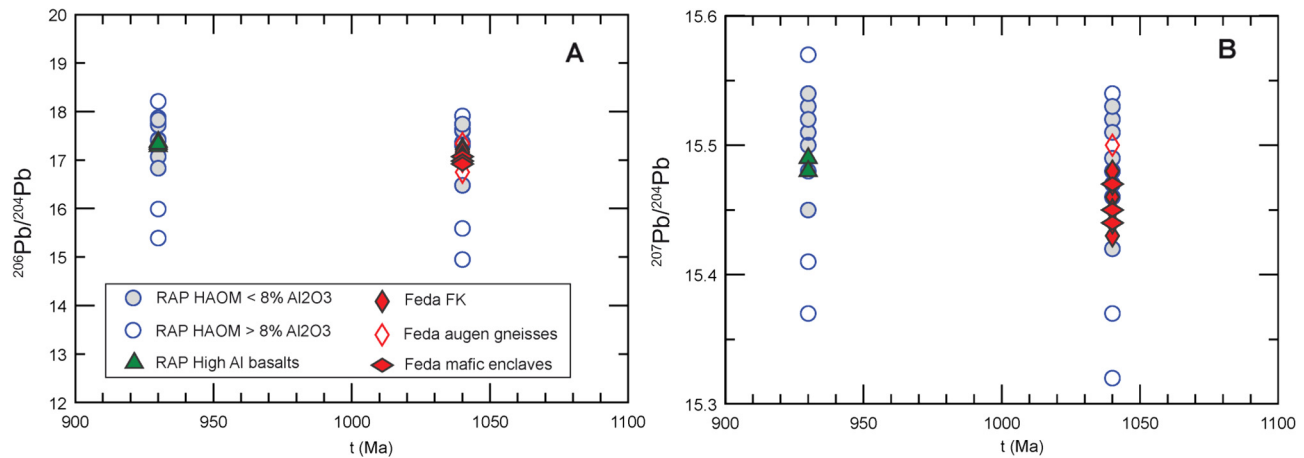


Fig. 1. A. $(^{206}\text{Pb}/^{204}\text{Pb})$ of RAP HAOM versus time (Ma). B. $(^{207}\text{Pb}/^{204}\text{Pb})$ of RAP HAOM versus time (Ma) same symbols as in A. Data from Bingen et al. (1993), Bybee et al. (2014) and Weis (1986).

sequences of Gjuve–Morgedal (1.16 Ga), Valldal (1.26 Ga) and Vemork (1.50 Ga). Vander Auwera et al. (2011) favoured the Feda suite because the Nd and Pb isotopic composition of the mafic facies of this suite is very close to the isotopic composition of the high-Al gabbros of the RAP. The 1.04 Ga age obtained by Bybee et al. (2014) for the crystallization of the RAP HAOM with the highest Al_2O_3 content (>8 wt.%) corresponds within error to the age of the Feda suite of southern Norway (1.05 Ga; Bingen and van Breemen, 1998). Moreover, the Pb isotopic composition of the RAP HAOM recalculated back at 1.05 Ga (supplementary data of Bybee et al., 2014) ($^{206}\text{Pb}/^{204}\text{Pb}_{1.05\text{ Ga}} = 14.91\text{--}17.88$; $^{207}\text{Pb}/^{204}\text{Pb}_{1.05\text{ Ga}} = 15.32\text{--}15.53$) perfectly overlaps the initial Pb isotopic composition of the Feda suite ($^{206}\text{Pb}/^{204}\text{Pb}_{1.05\text{ Ga}} = 16.92\text{--}17.32$; $^{207}\text{Pb}/^{204}\text{Pb}_{1.05\text{ Ga}} = 15.43\text{--}15.50$) (Bingen et al., 1993; Vander Auwera et al., 2011) (Fig. 1). This is also clear when average compositions are compared: Feda (30 samples) ($^{206}\text{Pb}/^{204}\text{Pb}_{1.05\text{ Ga}} = 17.06$; $^{207}\text{Pb}/^{204}\text{Pb}_{1.05\text{ Ga}} = 15.46$), HAOM (13 samples) ($^{206}\text{Pb}/^{204}\text{Pb}_{1.05\text{ Ga}} = 17.03$; $^{207}\text{Pb}/^{204}\text{Pb}_{1.05\text{ Ga}} = 15.47$). The ranges of $\epsilon_{\text{Nd},1.05\text{ Ga}}$ displayed by the RAP HAOM (-0.9 to $+3.4$) (Bybee et al., 2014) and the Feda suite (-0.7 to $+3.8$) (Bingen et al., 1993; Vander Auwera et al., 2011) perfectly overlap too. The RAP HAOM with the highest Al_2O_3 content (>8 wt.%) thus crystallized at the same time as the Feda suite and from a magma that had the same isotopic composition than the Feda suite. Moreover, available isotopic data on the high-Al gabbros (3 samples) of the RAP (Vander Auwera et al., 2011; Weis, 1986) recalculated back at 0.93 Ga display an isotopic composition ($^{206}\text{Pb}/^{204}\text{Pb}_{0.93\text{ Ga}} = 17.28\text{--}17.37$; $^{207}\text{Pb}/^{204}\text{Pb}_{0.93\text{ Ga}} = 15.48\text{--}15.49$) that is in the range of the Pb isotopic composition of the RAP HAOM also calculated back at 0.93 Ga ($^{206}\text{Pb}/^{204}\text{Pb}_{0.93\text{ Ga}} = 15.39\text{--}18.21$; $^{207}\text{Pb}/^{204}\text{Pb}_{0.93\text{ Ga}} = 15.37\text{--}15.57$) (Bybee et al., 2014) (Fig. 1). At 0.93 Ga, the RAP HAOM were thus in chemical, as shown by the experimental data (Fram and Longhi, 1992; Longhi et al., 1999), and isotopic equilibrium with the high-Al basalts (Fig. 1).

The new isotopic data of Bybee et al. (2014) combined with the experimental constraints (Fram and Longhi, 1992; Longhi et al., 1999) thus support a two-step model for the origin of the RAP Proterozoic anorthosites. During the first step, the HAOM (>8 wt.% Al_2O_3) crystallized at 1.05 Ga at the base of a thickened crust most probably from the parent magma of the Feda suite. 120 Ma later, during a second step, the lower crustal gabbro-noritic cumulates including the HAOM were partially melted to produce the high-Al basalts. According to this model, the HAOM could be restitic minerals of the lower crustal source. This would suggest that the HAOM displaying the highest Al_2O_3 content (and also possibly the mega-plagioclase that locally display ophitic textures with the

HAOM) observed and sampled in the RAP are representative fragments of the source, unmelted either because they were crystals too large (up to 1 m) to melt or they were originally incorporated in monomineralic layers. The Feda suite has been interpreted as resulting from the crystallization of a mantle-derived magma of calc-alkaline affinity mixed with crustal melts produced during the lower crustal underplating of the basalts (Bingen et al., 1993). Experimental data (Müntener et al., 2001) and field observations (Hermann et al., 2001) indicate that this type of magma produces significant amounts of gabbro-noritic cumulates when crystallizing at the base of the crust. As noted by Bybee et al. (2014), the major element composition of the HAOM is generally similar to the composition of the experimentally obtained orthopyroxenes with, however, significant differences in their Mg#s and FeO concentrations, Mg#s (0.49–0.66; Bybee et al., 2014) and FeO concentrations (11.65–19.6 wt.%; Bybee et al., 2014) of the HAOM are respectively lower and higher than the Mg#s (0.88–0.77) and FeO (7.7–13.7 wt.%) concentrations of the experimental orthopyroxenes (Müntener et al., 2001). This difference cannot be explained by the early crystallization of olivine as this mineral is notably absent in the experimental high pressure cumulates (Müntener et al., 2001) due to the shrinking of the olivine stability field with increasing pressure. In agreement with what was initially proposed by Longhi et al. (1999), we suggest that HAOM were part of the more evolved cumulates, containing more ferroan pyroxenes together with Fe–Ti oxides and phosphate, that were preferentially foundered or down-thrust because of their higher density.

As previously mentioned by Longhi et al. (1999) and recalled by Bybee et al. (2014), the above model requires extensive melting of the lower crust at high temperature. The recent work of Drüppel et al. (2013) on the petrology of sapphirine-bearing gneisses occurring just north of the RAP supports this interpretation. Indeed, zircon U–Pb geochronology, phase modelling and geothermobarometry indicate that the sapphirine granulites record ultra-high temperature metamorphic conditions of about 1000 °C and ca. 0.75 GPa at 1.01 Ga, i.e. after intrusion of the Feda suite and before emplacement of the RAP, followed by near isothermal decompression at 0.55 GPa. These results thus indicate that at that time, the temperature in the lower crust was well above c. 1000 °C. Considering a lower crustal pressure of 1.25 GPa (Charlier et al., 2010; Longhi et al., 1999) and a conservative geothermal gradient of 20 °C/km, the temperature at the base of the crust can be estimated at 1390 °C. Clearly, improved geochronology of regional metamorphism is required to link pressure–temperature paths in the crust to magmatic events and possible heat sources.

In conclusion, we think that the high-Al basalts, parent magmas of massif-type anorthosites are product of melting of a dry lower crustal protolith, in accordance with available experimental data. The data of Bybee et al. (2014) can be interpreted to support crystallization of a gabbro-noritic lower crust followed ca. 100 Ma later by remelting and production of the anorthosite parent magma. In terms of secular evolution of the earth, it may mean that the Proterozoic was a time where temperature and convection of the mantle was favourable for the remelting of freshly crystallized crustal underplates.

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References

- Barnichon, J.-D., Havenith, H.B., Hoffer, B., Charlier, R., Jongmans, D., Duchesne, J.C., 1999. The deformation of the Egersund-Ogna massif, South Norway: finite element modelling of diapirism. *Tectonophysics* 303, 109–130.
- Bingen, B., van Breemen, O., 1998. Tectonic regimes and terrane boundaries in the high-grade Sveconorwegian belt of SW Norway, inferred from U–Pb zircon geochronology and geochemical signature of augen gneiss suites. *J. Geol. Soc. (Lond.)* 155, 143–154.
- Bingen, B., Demaiffe, D., Hertogen, J., Weis, D., Michot, J., 1993. K-rich calc-alkaline augen gneisses of Grenvillian age in SW Norway: mingling of mantle-derived and crustal components. *J. Geol.* 101, 763–778.
- Bybee, G.M., Ashwal, L.D., Shirey, S.B., Horan, M., Mock, T., Andersen, T.B., 2014. Pyroxene megacrysts in Proterozoic anorthosites: implications for tectonic setting, magma source and magmatic processes at the Moho. *Earth Planet. Sci. Lett.* 389, 74–85.
- Charlier, B., Duchesne, J.C., Vander Auwera, J., Storme, J., Maquil, R., Longhi, J., 2010. Polybaric fractional crystallization of high-alumina basalt parental magmas in the Egersund-Ogna massif-type anorthosite (Rogaland, SW Norway) constrained by plagioclase and high-alumina orthopyroxene megacrysts. *J. Petrol.* 51, 2515–2546.
- Drüppel, K., Elsäber, L., Brandt, S., Gerdes, A., 2013. Sveconorwegian mid-crustal ultrahigh-temperature metamorphism in Rogaland, Norway: U–Pb LA-ICP-MS geochronology and pseudosections of sapphirine granulites and associated paragneisses. *J. Petrol.* 54, 305–350.
- Duchesne, J.C., Liégeois, J.P., Vander Auwera, J., Longhi, J., 1999. The crustal tongue melting model and the origin of massive anorthosites. *Terra Nova* 11, 100–105.
- Emslie, R.F., 1990. Ages and petrogenetic significance of igneous mangerite-charnockite suites associated with massif anorthosites, Grenville Province. *J. Geol.* 98, 213–231.
- Fram, M., Longhi, J., 1992. Phase equilibria of dikes associated with Proterozoic anorthosite complexes. *Am. J. Sci.* 77, 605–616.
- Hamilton, M., Ryan, A., Emslie, R., Ernanovics, I., 1998. Identification of Paleoproterozoic anorthositic and monzonitic rocks in the vicinity of the Mesoproterozoic Nain Plutonic Suite, Labrador: U–Pb evidence. *Radiogenic Age and Isotopic Studies. Geological Survey of Canada, Report 11, current research 1998-F*, pp. 23–40.
- Hermann, J., Müntener, O., Günther, D., 2001. Differentiation of mafic magma in a continental crust-to-mantle transition zone. *J. Petrol.* 42, 189–206.
- Longhi, J., Vander Auwera, J., Fram, M., Duchesne, J.C., 1999. Some phase equilibrium constraints on the origin of Proterozoic (massif) anorthosites and related rocks. *J. Petrol.* 40, 339–362.
- Müntener, O., Kelemen, P., Grove, T., 2001. The role of H₂O during crystallization of primitive arc magmas under uppermost mantle conditions and genesis of igneous pyroxenites: an experimental study. *Contrib. Mineral. Petrol.* 141, 643–658.
- Myers, J., Voordouw, R., Tettelaar, T., 2008. Proterozoic anorthosite-granite Nain batholith: structure and intrusion processes in an active lithosphere-scale fault zone, northern Labrador. *Can. J. Earth Sci.* 45, 909–934.
- Ryan, B., Hamilton, M., Emslie, R., Connelly, J., 1999. Paleoproterozoic and Mesoproterozoic anorthositic and granitic plutons in the Nain-Okak region, Labrador: repetitive anorogenic magmatism. *Eos*, S366.
- Schärer, U., Wilmart, E., Duchesne, J.C., 1996. The short duration and anorogenic character of anorthosite magmatism: U–Pb dating of the Rogaland complex, Norway. *Earth Planet. Sci. Lett.* 139, 335–350.
- Vander Auwera, J., Bolle, O., Bingen, B., Liégeois, J.-P., Bogaerts, B., Duchesne, J.C., De Waele, B., Longhi, J., 2011. Sveconorwegian massif-type anorthosites and related granulites result from post-collisional melting of a continental arc root. *Earth-Sci. Rev.* 107, 375–397.
- Weis, D., 1986. Genetic implications of Pb isotope geochemistry in the Rogaland anorthositic complex (southwest Norway). *Chem. Geol.* 57, 181–199.