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**Petrologic and thermodynamic constraints on the
petrogenesis of the Fiskenæsset Anorthosite Complex, SW
Greenland: An anhydrous model for Archean anorthosites**

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ABSTRACT

Here we present a new study of the petrology, geochemistry and thermodynamic modelling
of the ~2.97 Ga Mesoarchean Fiskenæsset Anorthosite Complex (FAC) in southern West
Greenland. Our results provide new constraints on the parental magma and the crystallization
history of the complex with implications for the petrogenesis and the geodynamic setting of
Archean anorthosites. Detailed logging, petrography, and mineral chemistry of an ~80-meter-

long drill-core intersecting anorthosite at Majorqap Qâva, shows that the rock is nearly monomineralic and has homogenous plagioclase compositions averaging $An_{87\pm1}$ throughout the drill-core. Based on textural relations,, the composition of mineral inclusions and thermodynamic modelling, we argue that the abundant amphiboles are solely metamorphic in origin and formed by the hydration and recrystallization of primary clinopyroxene. Thermodynamic modelling using Rhyolite-MELTS of various proposed parental magmas shows that the petrogenesis of the FAC rocks and similar high-An anorthosite can best be explained by crystallization of an anhydrous high-Al tholeiitic parental melt at shallow pressure (≤ 3 kbar), which results in early plagioclase saturation with a short interval of essentially plagioclase-only crystallization. Formation of such voluminous and homogenous anorthosites have further required frequent magma replenishment and physical sorting of the cumulates. Flotation of buoyant plagioclase is possible under anhydrous conditions only, and a process supported by previous studies of the FAC, the occurrence of snow-flake and megacrystic rocks (some with negative Eu-anomalies), and the large variation in $Mg\#$ of high-An anorthosites. The modelling results further demonstrate that the relatively evolved chromites ($Cr\#$ 46-67 and Cr/Fe^{2+} of 1-1.2) associated with the anorthosites cannot have co-crystallized with the high-An plagioclase. Instead, we propose that the anorthositic-chromitiferous rocks formed via either melt rock dissolution and replacement reactions in noritic-gabbro-noritic cumulates, the injection of chromitite slurries into anorthosite mush, or injection of an anorthosite slurry into chromitite. Alternatively the chromitite compositions of the FAC experienced significant modification during metamorphism. The combined results of this study provide a genetic link between the FAC and tholeiites of the spatially associated Bjørnesund Supracrustal Belt, representing a shallow, dry and open subvolcanic system. We propose a new petrogenetic model in which the high-Al parental magma of the FAC derived from a more primitive picritic precursor, which ponded and assimilated mafic Archean crust

in the lower to middle crust prior to final emplacement as plagioclase supersaturated melts in the upper crust. The emplacement of high-Al tholeiites resulted in massive anorthosite formation and feed the Bjørnesund Supracrustal Belt with melts. In contradiction with previous research, we argue against a hydrous subduction zone setting of the FAC and Fiskenæsset region around 3 Ga, suggesting simpler alternatively non-uniformitarian settings (e.g. ocean-plateau, rift, stagnant-lid). A similar model may apply for other Archean anorthosites, involving unique petrogenetic conditions of the Archean, facilitating high-degree melting of dry mantle, magmatic ponding, assimilation of mafic crust and generation of high-Al tholeiites.

Keywords: Achaeon, SW Greenland, Fiskenæsset Anorthosite Complex; High-Al tholeiite, Plagioclase fractionation.

1. INTRODUCTION

The petrogenesis of anorthosites and related rocks remains debated, despite having been highlighted more than a century ago by [Bowen \(1917\)](#). The majority of anorthosites formed during the Archean and Proterozoic Eons, occurring in Archean anorthosite complexes, Proterozoic massif anorthosite complexes and large layered intrusions (e.g. Bushveld and Stillwater Complex) ([Ashwal, 1993, 2010](#)). The temporality of Archean (~3.9 – 2.5 Ga) and the more voluminous Proterozoic (~2.5-0.5 Ga) anorthosites has thus been a major impetus for studies aimed at constraining petrogenetic and geodynamic processes operating in the early Earth ([Ashwal, 2010](#); [Ashwal & Bybee, 2017](#); [Sotiriou & Polat, 2023](#) and references therein). Both share the dominance of anorthositic lithologies (leucogabbro, leuconorite,

anorthosite) and lack of complementary ultramafic cumulates, in comparison to layered intrusions. Furthermore Archean anorthosites mainly associated with mafic supracrustal belts, whereas Proterozoic massifs with intermediate-felsic continental crust (Bybee et al., 2014; Ashwal & Bybee, 2017). Archean anorthosite complexes have more resemblance of layered intrusions, sharing many lithologically and geochemical similarities, including the occurrence of chromitites (Ashwal, 1993; Rollinson et al., 2010; Mohan et al., 2013; Rao et al., 2013; Barnes et al., 2022). However, the plagioclase of Archean anorthosites have distinctively calcic and uniform An-content averaging An₈₀₋₉₀, and are generally coarser grained with the characteristic occurrence of pseudo-hexagonal megacrysts (up to 30 cm in size) (Polat et al., 2009, 2018; Ashwal, 2010; Ashwal & Bybee, 2017). Proterozoic massifs are distinctly composite and massive in structure, and plagioclase is also relatively coarse grained, however far more sodic, averaging An₃₀₋₆₀ (Bybee et al., 2014, Ashwal & Bybee, 2017). Trace element and isotope systematics reflect significant crustal contamination in their petrogenesis (Charlier et al., 2010, 2015; Gleißner et al., 2011; Ashwal & Bybee, 2017). Proterozoic massifs lack chromitites, but have significant Fe-Ti oxide (magnetite, ilmenite, rutile) occurrences (Ashwal, 1993, 2010; Charlier et al., 2015).

Archean anorthosite complexes are abundant within Archean cratons such as the Superior Craton (Canada), North Atlantic Craton (Southwestern Greenland) and Dharwar craton (India) (Omens & Dymek, 1997; Windley & Garde, 2009; Ashwal & Bybee, 2017; Polat et al., 2018, Santosh & Li, 2018; Linnebjerg, 2021; Sotiriou & Polat, 2023). The Mesoarchean Fiskensæset Anorthosite Complex (FAC) of SW Greenland is one of the best exposed and preserved examples of Archean anorthosite complexes worldwide (Windley et al., 1973; Myers, 1985; Ashwal, 1993; Polat et al., 2009; Linnebjerg, 2021). The FAC is considered to contain key evidence for the operation of subduction and thus plate tectonics from around 3 billion years ago (Polat et al., 2009, 2018; Rollinson et al., 2010; Sotiriou & Polat 2020,

2023; Sotiriou et al., 2023). This is because the FAC, together with the majority of other Archean anorthosite complexes, is spatially associated with mafic supracrustal belts that share similar geochemical signatures characteristic of modern arc rocks (e.g. enrichment in LILE, Th and -LREE, and depletion in Nb, Ta and -Ti) (Henderson et al., 1976; Dilek & Polat 2008; Polat et al., 2008, 2011a; Ashwal, 2010; Hoffmann et al., 2012; Ashwal & Bybee, 2017). In addition, some of the anorthosites are spatially associated with calc-alkaline andesites (Dilek & Polat 2008; Polat et al., 2009; Windley & Garde, 2009; Szilas et al., 2012, 2018; Zhang et al., 2023 and references therein).

A key problem in understanding the origin of Archean anorthosites is that their parental magmas have not yet been successfully constrained, mainly due to high-grade metamorphism of the intrusions and lack of chilled margins that could represent liquid compositions (Ashwal, 1993, 2010; Polat et al., 2011b; Ashwal & Bybee, 2017; Linnebjerg, 2021).

Previous research based on field exposures, as well as petrological and geochemical data, suggested parent magmas ranging in composition from komatiites to picrites, high-Al tholeiites and andesites (Ashwal, 1993; Ashwal & Bybee, 2017; Sotiriou & Polat, 2020, 2023; Sotiriou et al., 2023 and references therein). The calcic plagioclase and abundant amphibole in the anorthosites have been considered to constitute strong evidence for an important role of water-rich magmas in anorthosite petrogenesis, consistent with a subduction zone origin (Takagi et al., 2005; Polat et al., 2009, 2012; Rollinson et al., 2010; Huang et al., 2014; Sotiriou & Polat, 2020, 2023; Linnebjerg, 2021).

In this study, we present new petrographic, mineral compositional and whole-rock geochemical data collected from samples of a drill-core and field outcrops from the Fiskenæsset Anorthosite Complex, SW Greenland. We conducted thermodynamic modelling using Rhyolite-MELTS to constrain the composition of the parental magma and the crystallization history for the FAC. Our study provides new constraints on the petrogenesis of

the FAC and Archean anorthosites in general, with implications for understanding the geodynamics that operated around 3 billion years ago.

2. GEOLOGICAL SETTING

The ~ 2.97 Ga Mesoarchean Fiskenæsset Anorthosite Complex (FAC) is located within the Fiskenæsset region of Southwest Greenland (**Fig. 1a**) (Polat et al., 2010; Linnebjerg, 2021). The FAC comprises ~2500 km² of well -exposed outcrops of mainly layered leucogabbro and anorthosite, with less abundant gabbro and ultramafic rocks (e.g. dunite, peridotite, pyroxenite, hornblendite) (Myers, 1985; Polat et al., 2009; Souders et al., 2013). The rocks occur as variably deformed and folded sheets and tectonic lenses within regional tonalite-trondhjemite-granodiorite (TTG) gneisses (Windley et al., 1973; Myers 1976a, 1985; Polat et al., 2009; Huang et al., 2013). The FAC is spatially associated with basaltic to andesitic amphibolites. The contact relations between the FAC and amphibolites have previously been interpreted as intrusive, suggesting emplacement of the anorthosites as multiple sill-like bodies into mafic Archean oceanic crust (Escher & Myers, 1975; Weaver et al., 1982; Polat et al., 2009, 2011b). The contemporaneous metavolcanic Bjørnesund Supracrustal Belt at the southern contact to the FAC (**Fig. 1a**) contains relict pillows structures and shares similar geochemical characteristics to the FAC, which led previous authors to propose it is cogenetic with the FAC (Weaver et al., 1981, 1982; Myers, 1985; Polat et al., 2009; Szilas et al., 2012). Diverse metasomatic Al-rich mineral assemblages, (e.g. garnet, corundum/ruby, kornetupine and sapphirine) are found at the contact between the amphibolites and anorthosites (Windley et al., 1973; Myers, 1985; Peck & Valley, 1996).

The FAC and associated amphibolites experienced deformation, break-up and polyphase metamorphism to amphibolite and granulite facies conditions subsequent to the emplacement of regional TTGs ~2.95 Ga. Further tectono-thermal events between ~2.94-2.65 Ga are

recorded in metamorphic zircon (Windley et al., 1973; Keulen et al., 2010; Polat et al., 2010; Huang et al., 2013; Sounders et al., 2013). Peak granulite facies metamorphism occurred ~2.82-2.8 Ga and ~2.75 Ga. The former event may be associated with emplacement of the Ilivertalik granitoid complex just north of Fiskenæsset (**Fig. 1a**) (Keulen et al., 2010; Polat et al., 2010; Næraa et al., 2018 and references therein). Peak metamorphic conditions have been suggested to be between ~6-9 kbar and ~700-850°C (Riciputi et al., 1990; Keulen et al., 2009, 2010). The Fiskenæsset region and much of the Tasiusarsuaq terrane experienced partial retrogression to amphibolite facies ~2.7 Ga (Nutman et al., 1889; Friend & Nutman, 2005, 2019; Windley & Garde, 2009; Keulen et al., 2009, 2010; Linnebjerg, 2021 and references therein).

Regional metamorphism and deformation have resulted in km-scale isoclinal folding, thrusting, faulting, and repetition of the stratigraphic layers within the FAC (Windley et al., 1973; Myers, 1985). However, the primary igneous stratigraphy and layering remain largely preserved across the region. Well-preserved features include megacrystic plagioclases up to 30 cm across, igneous minerals such as amphibole and chromitite, and a wide range of magmatic structures such as channel deposits, cross bedding and magmatic slumping (Windley et al., 1973; Myers, 1976b, 1985; Polat et al., 2009, 2011b; Huang et al., 2012, 2014). The most complete igneous stratigraphy is found in the central to eastern part of Fiskenæsset, at Majorqap Qâva, where metamorphism only reached amphibolite facies. Other well-preserved and exposed areas include Qeqertarssuatsiaq Island and Sinarsuk (**Fig. 1a**) (Windley et al., 1973; Myers, 1985; Polat et al., 2009, 2010, 2011b, 2012; Keulen et al., 2010; Rollinson et al., 2010; Huang et al., 2012, 2014). Based on mapping of these areas, Myers (1985) defined the igneous stratigraphy to contain seven major units. From the bottom to the top these are the lower gabbro (50 m), the ultramafic unit (40 m), lower leucogabbro (50 m), middle gabbro (40 m), upper leucogabbro (60 m), anorthosite (250 m) and upper

gabbro (50 m). In total, the intrusion displays a post-deformational thickness of approximately 540 m. However, there are significant local variations in thickness, and many smaller scale sills occur throughout the FAC ([Windley et al., 1973](#); [Myers, 1985](#); [Polat et al., 2011b](#)). Chromitites are found as centimetric to decametric layers in dunites and peridotites of the ultramafic unit, whereas abundant semi-massive layers up to >20 meters in thickness are found in the upper leucogabbro and anorthosite unit, representing some of the oldest anorthosite-hosted chromitite occurrences on Earth ([Ghisler & Windley, 1967](#); [Myers, 1985](#); [Rollinson et al., 2010, 2017](#); [Linnebjerg, 2021](#)).

3. ANALYTICAL METHODS

3.1 Whole rock major and trace elements

Whole rock major and trace element compositions were determined in the Geoanalytical Laboratory at Washington State University (WSU). Approximately 28 g of fresh rock chips from each sample was crushed to fine powder using an agate swing-mill. For XRF (major and minor elements) 3.5 g of sample powder were mixed with a pure di-lithium tetraborate flux ($\text{Li}_2\text{B}_4\text{O}_7$) in the ratio of (1:2). For ICP-MS analysis of trace elements 2 g of sample powder was used and the ratio of the sample powder to di-lithium tetraborate flux was 1:1. A single bead dilution-fusion technique was applied (incl. acid-dissolution step for ICP-MS), followed by XRF and ICP-MS (Agilent 4500) data acquisition. The XRF and ICP-MS methods measure trace elements accurately down to ~20 and <1 ppm, respectively. The reader is referred to WSU's webpage for full details on the analytical methods ([WSU, 2025](#)).

3.2 Electron Microprobe Analysis (EMPA)

The major element composition of the main mineral-phases in anorthosite and leucogabbro drill-core samples (Section 4), were analyzed using a JEOL JXA-8200 Electron Microprobe, at the Department of Geosciences and Natural Resource Management, University of Copenhagen. The EMP is equipped with five wavelength dispersive spectrometers (WDS) and one energy dispersive spectrometer (EDS). Carbon coated and polished 30 μm thin sections were analyzed with a 5 μm beam-size configuration at 15 kV accelerating voltage and an electron current of 15 nA. For FeO background counting time was set at 30s, and 20 s for all other major elements. Internal standards were used for calibration and monitoring accuracy. For full details about the EMPA setup, standardization, and measurement procedures, the reader is referred to [Waight & Tørnquist \(2018\)](#). Mineral endmember composition and classification were calculated and plotted using the Matlab-based MinPlot software. For a detailed description of the software the reader is referred to [Walters \(2022\)](#).

3.3 Micro-XRF and AMICS mineral mapping

Element and mineral mapping of representative drill-core samples were carried out using a Bruker M4 Tornado Plus micro-XRF at the Department of Geosciences and Natural Resource Management, University of Copenhagen. The instrument is equipped with a Rh tube with polycapillary lenses and collimator to focus X-rays onto flat sample surfaces and detects X-ray fluorescence with two XFlash silicon drift detectors with 130 eV resolution. Representative core samples (**Figs. 4-5**), were measured at 2 mbar vacuum, 50 kV voltage, and 60 μA current to avoid Ar adsorption and effectively detect lighter elements. The measurements were done at 20 μm beam size, 20 μm step size, and an acquisition time of 20 ms pr. pixel and a stage speed of 1000 $\mu\text{m/s}$ ([Flude et al., 2017](#); [Christiansen, 2023](#)). The Bruker software package AMICS (Automated Mineral Identification and Classification

Software) was used to create mineral maps from the scanned core samples. The software compares the measured X-ray fluorescence spectra of each pixel with a database of known minerals and solid solutions at a pre-defined threshold. The threshold or priority used was 10%, to effectively classify pixels despite overlapping spectra. Due to information arriving from various depths within the samples, some spectra are mixed, therefore mineral mixes were created with different standards to cover the unknowns. The classification was quality checked with detailed understanding of the sample mineralogy from petrography, pXRD, and mineral data (Section 5) (Christiansen, 2023).

3.4 Powder X-ray Diffraction (pXRD)

Representative samples across the drill-core were crushed into fine powder using an agate mill. The powders were loaded in a horizontal metal disc and analyzed with a Bruker Advance D8 powder-XRD at the Department of Geosciences and Natural Resource Management, University of Copenhagen. The samples were analyzed with monochromatic X-rays from a Cu (1.5406 Å) source and recorded by a LynxEYE detector. The sample rotates at an angle of θ , and the detector at 2θ . 2θ -angles were measured between 5-90 degrees. Diffraction spectra were treated with the TOPAS software packages for qualitative and quantitative phase-analysis, identifying the main mineral components (Christiansen, 2023).

4. SAMPLES AND PETROGRAPHY

4.1 Qeqertarsuatsiaq Island

Samples were collected from across the central and eastern Qeqertarssuatsiaq Island in the western Fiskenæsset region during field work in 2022 (**Fig. 1, Supplementary materials 1**). In this study we report whole-rock major and trace element data for 31 of the samples. Based on field appearance and mineral assemblages, the samples were divided into the following lithological groups: anorthosite (10), leucogabbro (14), gabbro (2), hornblendite (3), and amphibolite (2) (**Fig. 1b**). For representative field-photos see **Supplementary materials 1**.

4.2 Drill core 21 (Majorqap Qâva)

We additionally report detailed observations on the petrography, mineral chemistry, and whole-rock major and trace element geochemistry for samples (n=13) from a drill core intersecting the anorthosite unit at Majorqap Qâva (**Fig 1a**). The drill core, referred to as drill core 21, was provided for this study by Greenland Anorthosite Mining (GAM). The anorthosites from the Majorqap Qâva area are the least deformed and most pristine of the Fiskenæsset Anorthosite Complex ([Myers, 1985](#); [Huang et al., 2012](#)). GAM has done extensive drilling and core-logging across Majorqap Qâva to commercialize the calcic anorthosites ([GAM, 2025](#)). Detailed logging of drill core 21 shows that it comprises mainly anorthosite with centimeter- to meter-sized layers of leucogabbro. Across the entire drill core there are abundant cross-cutting felsic veins and layers of mainly tonalite and granitoids (**Fig. 2, Supplementary materials 2**). We further report the average plagioclase composition of >4000 analyses from 23 samples of anorthosite and leucogabbro across the drill core (**Fig. 2**).

The anorthosites in drill core 21 are mainly comprised (~93-97 vol.%) of unzoned medium- to coarse-grained plagioclase. The rocks tend to show well-equilibrated polygonal textures with triple junctions consistent with high-grade metamorphism (**Figs. 3a-b, 4a**). On average, plagioclase from these anorthosites have very homogeneous compositions across the

entire drill core, averaging $An_{87\pm1}$ (**Fig. 2, Supplementary materials 3 - Tables S2**). Mafic phases constitute up to 10 vol.% of the rock (average ≤ 5 vol.%), comprising mainly amphibole and minor biotite, whereas pyroxenes are rare. Metamorphic quartz is common, and accessory phases include sillimanite, dark green spinel, titanite, sulfides (pyrite, chalcopyrite), garnet, and apatite (**Figs. 3a-b, 4a**). Subhedral to euhedral amphibole and rounded quartz inclusions are common in plagioclase (**Figs. 3a-b**). Within the average medium-grained rock, rare coarser grained plagioclase (up to ~2 cm) occurs throughout the core (**Fig. 2, Supplementary materials 2**).

Alteration predominantly occurs associated with either brittle fractures or along the boundary between anorthosite and leucogabbroic or felsic layers. In the former case, plagioclase and amphibole are variably to nearly completely replaced by a fine-grained matrix of epidote-zoisite group minerals, sericite, chlorite, quartz, calcite, and clay-minerals, giving a brecciated texture (**Figs. 3c-d, 4b**). These phases are confirmed with micro-XRF and qualitative powder XRD-analysis (**Fig. 4b, Supplementary materials 4**). The An-content of plagioclase is only slightly disturbed in these alteration zones, with an average of $An_{85\pm1}$ (**Fig. 2, Supplementary materials 3 - Table S2**).

Another style of alteration occurs at the boundary between anorthosite to leucogabbroic or felsic layers (**Figs. 4b-c, 5**). Here, biotite is the dominant mafic phase and plagioclase is commonly slightly zoned. Amphibole and biotite show cross cutting relations, indicating a late-stage metasomatic origin (**Figs. 3e-f**). The An-content of plagioclase in these areas is, on average, $An_{83\pm10}$ and can be as low as $An_{73\pm12}$ (**Fig. 2, Supplementary materials 3 - Table S2**).

Leucogabbroic layers and bands show relatively sharp contacts with anorthosite (**Figs. 2, 4c-d**). The leucogabbros comprise on average around ~60-80 vol.% plagioclase and

~20-40 vol.% mafic minerals, mainly amphibole and biotite. Plagioclase is unzoned but less polygonal than in anorthosite, whereas amphiboles and biotite commonly show foliation (**Figs. 3g-h, 4c-d**). Plagioclase commonly contains inclusions of euhedral amphibole, biotite and rounded quartz, similar to the anorthosites. Biotite is significantly more abundant than in anorthosites and shows cross-cutting relations to amphiboles indicating late-stage fluid-activity and potassic metasomatism (**Figs. 3h, 4d**). Accessory phases include quartz, epidote-zoisite group minerals, spinel, Fe-Ti oxides, garnet, and sulfides (pyrite, chalcopyrite) (**Figs. 4c-d**). The An-content of plagioclase varies, but is overall higher than in the anorthosite, with an average of $An_{90\pm3}$ (**Fig. 2, Supplementary materials 3 -Table S2**). The transitional domains between anorthosite and leucogabbro typically show relatively sudden (on a centimeter scale) increases towards more calcic plagioclase, however the majority of the transitional domains measured have on average lower anorthite content (average $An_{84\pm5}$) (**Figs. 2, 4b, Supplementary materials 3 - Table S2**).

The drill core contains abundant felsic intrusives, forming millimeter and -centimeter -sized veins, and meter-sized layers (**Fig. 2, Supplementary materials 2**). The felsic intrusives consist of variable amounts of plagioclase, alkali feldspar, and quartz, with minor biotite, muscovite, amphibole, and garnet. Accessory phases include corundum (incl. Ruby), apatite, Fe-Ti oxides, and sulfides (pyrite, chalcopyrite) (**Figs. 3i-l, 5**). Based on the proportion of alkali feldspar and quartz, most of these rocks are tonalites (**Fig. 5a**) and felsic granitoids (**Figs. 5b-c**). They are found as relatively undeformed coarse-grained, gneissic, and pegmatitic varieties (**Figs. 3i-l, 5a-c**). Anorthosites are commonly found as rounded inclusions within these granitoids, having rims of relatively low anorthite content that contain abundant biotite (**Fig. 5d**). The late-stage tonalites and felsic granitoids commonly cause alteration of adjacent anorthosite, resulting in a lighter color and lower An-content (**Figs. 2, 3e-f, 4b**).

317

318 **5. ANALYTICAL RESULTS**

319 **5.1 Major and trace element geochemistry**

320 In the following section, we present the main geochemical features of the FAC based on
321 whole-rock major and trace element data from 31 samples collected in the field at
322 Qeqertarsuatsiaq Island (**Fig. 1b**) and 13 samples from drill core 21 (**Fig. 1, Supplementary**
323 **materials 3 - Tables S3-4**). Samples with LOI>3% or containing significant chromite,
324 metamorphic garnet, biotite, calc-silicates, and carbonates have not been included in the
325 dataset. Major element concentrations reported are normalized to 100 wt. % volatile free
326 basis (**Supplementary materials 3 - Table S4**).

327 The amphibolites (n=2) are compositionally similar to regional basaltic intrusives
328 associated with the FAC (**Fig. 6**), having a relatively evolved composition with high Al₂O₃
329 (8.9-15.4 wt.%), and FeO_T (14.5-15.4 wt.%) while Mg# range from 56-58, Cr from 163-297
330 ppm, and Ni from 125-188 ppm. REE patterns are relatively flat with slight LREE-
331 enrichment at above 10 times chondritic abundances, and relatively uniform HFSE-patterns.
332 However, one sample that displays a uniform REE-pattern, shows strongly enriched LILE
333 approaching 100 times primitive mantle abundance (e.g. Ba, Rb, K) and a positive Pb-
334 anomaly (**Fig. 7a-b**).

335 Similar to previously published data, the hornblendites (n=3) show a significant
336 compositional range (**Fig. 6**), with Mg# ranging from 46-77, SiO₂ from 42.1-47.4 wt.% and
337 Al₂O₃ from 10-19.1 wt.%. Cr ranges from 41-823 ppm, and Ni from 145-666 ppm. The
338 samples show broadly similar compositions to basalts, gabbros and pyroxenites within the
339 complex, but with one sample having relatively high FeO_T (20.4 wt.%) and TiO₂ (3.9 wt.%)
340 indicative of abundant Fe-Ti oxides. A similar compositional heterogeneity is observed in

their REE-patterns, ranging from relatively flat to slightly enriched in LREE and/or depleted HREE, at between one and more than 10 times chondritic abundance (**Fig. 7a**). Two samples show pronounced negative or positive Eu anomalies. All samples display significant scatter on a multielement diagram at 1-10 times primitive mantle abundance, especially in terms of LILE (**Fig. 7b**). One sample shows strong positive K, Pb, Sr and Ti anomalies, but with a negative Nb anomaly. The other samples show less spiky patterns, but with pronounced negative P, Sr, U and Th anomalies.

The gabbros (n=2) are compositionally similar to previously published data, having relatively high Mg# ranging from 73-78 with moderate to low Cr (117-581ppm) and Ni (231-541ppm) (**Fig. 6**). The gabbros show relatively flat to slightly concave REE patterns, with between near chondritic to 10 times chondritic abundances (**Fig. 7c**) and, in one case, a strong positive Eu anomaly. On multielement diagrams the gabbros show relatively flat patterns, but with minor negative Zr and Ti anomalies, pronounced negative Nb and positive K, Pb and Sr anomalies (**Fig. 7d**).

The leucogabbros (n=18) show moderate compositional variation within the range of previously published data (**Fig. 6**), with relatively high Al₂O₃ (23-30.6 wt.%), CaO (13.6-16.7 wt.%) and low TiO₂ (0.03-0.4 wt.%). Larger variation is observed in Mg# ranging from 56-78, Cr from 12-1069 ppm, and Ni from 44-329 ppm. Leucogabbro samples from drill core 21 (n=4) are compositionally far more restricted at higher CaO and Al₂O₃ than the Qeqertarsuatsiaq samples. However, they are more enriched in K₂O (0.6-0.9 wt.%) reflecting abundant biotite. With the exception of two samples with snow-flake and megacrystic texture (**Supplementary materials 1**), the leucogabbros show relatively flat to slightly LREE-enriched REE patterns with strong positive Eu anomalies and sub-chondritic to nearly 10 times chondritic abundances of the other REE (**Fig. 7c**). The drill core samples show chondritic to sub-chondritic REE abundances. On multielement diagram the

leucogabbros show broadly similar patterns, but some drill core samples are highly enriched in LILE (e.g. Rb, Cs, K), up to more than 1000 times primitive mantle values (**Fig. 7d**). The majority of the samples have variably negative Ti, Zr, Th, and Nb anomalies, and positive Sr, Pb, and K anomalies.

Similar to the leucogabbros the anorthosites (n=19) show high Al_2O_3 (30.6-33.8 wt.%), CaO (14.3-17.8 wt.%), and low TiO_2 (0.02-0.5 wt.%) (**Fig. 6**). There is considerable variation in Mg#, ranging from 42-62, and the rock have very low contents of Cr (7-198ppm) and Ni (9-58ppm). Samples from drill core 21 (n=9) are more homogenous, except for a few samples with elevated SiO_2 (48.2-51.2 wt.%), Na_2O (1.7-2.9 wt.%), and K_2O (0.1-0.5 wt.%), attributed to alteration. The anorthosite samples from Qeqertarsuatsiaq and drill core 21 show broadly similar REE patterns, ranging from relatively flat to significantly LREE enriched, whereas a few samples display HREE depletion (**Fig. 7e**). However, the majority of the drill-core samples have chondritic REE abundances and significantly larger positive Eu-anomalies than the Qeqertarsuatsiaq samples. On the multielement diagram, the vast majority of the anorthosites show variably negative Ti and Zr anomalies, pronounced negative Nb and positive Pb, K and Sr anomalies (**Fig. 7f**). The LILE show variable abundances, with some samples having >100 times primitive mantle abundance, while HFSE patterns remain relatively flat (**Fig. 7f**).

5.2 Mineral chemistry

In the following section we report the main results of electron microprobe analysis of minerals across drill core 21. The EMPA data are presented in **Supplementary materials 3 - Tables S1-2 and S6-8**.

Plagioclase was analyzed in 23 samples across the drill core 21, on average in every 4-meter interval ($n = 4184$) (**Supplementary materials 3 - Table S1-2**). The analysis included pure anorthosites, altered anorthosites and leucogabbros along with the transitional domains between rock types (**Figs. 3a-h, 4**). The median values are reported in **Figure 2** and **Supplementary materials 3 Table S2**. The plagioclase grains in the anorthosite samples display no zoning, and a relatively minor compositional range, at An_{80-93} . The mean value of the entire unaltered population is $An_{87\pm1}$. Altered anorthosite is mainly associated with intrusive granitoid veins and sheets (e.g. samples 214519 and 214200) analyzed at 42, 45.19, 57, and 57.32 meters depth (**Figs. 2, 3e-f, 5d**). The altered anorthosite shows significantly lower average An-content than unaltered anorthosite, along with larger compositional range of An_{54-93} . There is significant compositional variation around the mean value ($An_{83\pm10}$), which we interpret to result from potassic alteration related to adjacent granitoid sheets and veins. At a depth of 17m and 19.42 m we observe zoisite-sericite rich alteration, which has caused some scatter in the An-content (An_{77-90}) and resulted in a slightly lower mean composition of $An_{85\pm1}$ (**Figs. 2, 3b-c, 4b**).

Leucogabbroic samples display, on average, higher An-content of plagioclase than the anorthosites (mean of $An_{90\pm3}$) despite a similar range (An_{73-95}). An exception is the sample located at 25.5 meters depth (212550), having a composition similar to the average anorthosite ($An_{87\pm7}$) (**Figs. 2, 4d**).

Transitional domains between anorthosite and leucogabbro show An-values that are intermediate between the two lithologies with An_{71-96} , however only the sample analyzed at 55.24 meters depth shows a sharp increase across the contact, whereas the other samples (i.e. 28.11 and 55.24 meters depth) show values lower than, or similar to altered anorthosite, at around An_{83-84} , with a mean value of $An_{84\pm5}$ (**Figs. 2, 4c**).

We analyzed interstitial amphibole and amphibole inclusions within plagioclase across the drill core (n=437). The amphiboles are classified mainly as Mg-hornblende to pargasite, with some grains having compositions towards tschermakite and tremolite-actinolite solid solution (**Supplementary materials 3 - Table S6**).

Amphiboles in anorthosites (n=94) have Mg# ranging from 44-68 (except one grain with Mg# of 72 and low 4.2 wt.% Al₂O₃), whereas leucogabbro (n=110), on average, have slightly higher Mg# ranging from 65-83. The anorthosite-hosted amphiboles have overall higher TiO₂ (0.3-1.5 wt.%), whereas leucogabbro hosted amphiboles have similar to slightly higher CaO (9.4-13.1 wt.%) and Al₂O₃ (10.9-16.4 wt.%). Amphiboles in transitional domains (n=164) have Mg# ranging from 48-74, i.e. intermediate compositions between amphiboles in anorthosite and leucogabbro. Amphibole inclusions measured in plagioclase from multiple samples (n=69) have similar composition as interstitial amphiboles, however, inclusions from sample 215524 show more restricted composition (Mg# 63-72) similar to the leucogabbroic part of the sample, compared to interstitial (Mg# 48-74) reflecting the entire transition (**Supplementary materials 3, Table S6**).

Pyroxene is a rare phase in the drill core. Only a single clinopyroxene grain was analyzed and classifies as a calcic diopside (clinopyroxene) with 51.4% SiO₂, 22.5% CaO, 2% Al₂O₃, and Mg# of 69 (**Supplementary materials 3 - Table S7**).

Biotite (n=134) is abundant in the leucogabbroic parts of the drill-core (**Figs. 3g-h, 4c-d**). Most grains falls within the compositional field of phlogopite (**Supplementary materials 3 - Table S8**). In anorthosite, biotite has Mg# ranging between 44 to 69 (mainly < 60), compared to biotite in leucogabbro which has Mg# ranging from 74 to 81. Transitional domains show intermediate values (Mg# 65-75). Two biotite grains analyzed in an anorthosite inclusion in

granitoid (sample 215700, 57 m depth, **Figs. 2, 5d**) show higher Al_2O_3 of 19.5-19.8 wt.% and lower Mg# (44-45) than in the other anorthosite samples.

6. DISCUSSION

6.1 Whole rock geochemistry

The whole-rock major and trace element data of samples collected at Qeqertarsuatsiaq Island and across drill core 21, fall compositionally within the range of previously published data from the FAC (**Fig. 6**) (e.g. [Polat et al. 2009, 2011a-b, 2012](#); [Huang et al., 2012](#)). We suggest similarly that most of the rocks of the FAC have preserved their primary magmatic composition, despite multiple metamorphic events. However, some anorthosites and all leucogabbros from drill core 21 show variably elevated SiO_2 , Na_2O , and K_2O along with LILE enrichment at >100 times primitive mantle abundance (**Figs. 6, 7c-f**). This is interpreted to reflect fluid-related alteration associated with metamorphism and cross-cutting granitoids, resulting in the formation of zoisite-sericite rich alteration assemblages and abundant metasomatic biotite observed petrographically in these samples (**Figs. 3c-h, 4, 5**). Alteration also affected the mineral composition of these samples significantly as discussed in **Section 6.2**.

The observed major element variation trends are consistent with control by the relative proportions/modes of the cumulus minerals. The divergence between anorthositic, gabbroic and basaltic rocks at <10 wt.% MgO reflects variable mineral modes and, to some degree, magmatic differentiation (**Fig. 6**). As previously inferred, the REE-patterns of e.g., anorthosite and leucogabbro are consistent with variable degrees and depth of partial source

melting and or magmatic differentiation, along with source heterogeneity (Polat et al., 2009, 2011b, 2012; Huang et al., 2012, 2014).

Two leucogabbroic samples collected adjacent to anorthosite from Qeqertarsuatsiaq Island have snowflake- and megacrystic textures (**Supplementary materials 1**), and show LREE enriched REE-patterns with negative Eu-anomalies, indicating substantial plagioclase fractionation prior to their formation (**Fig. 7c**). Snowflake and -megacrystic textures have previously been reported from the FAC and other Archean anorthosites, and considered characteristic features (**Section 1-2**), normally thought to result from plagioclase flotation, high nucleation and crystal growth (Windley et al., 1973; Myers, 1985; Ashwal, 1993; Ashwal & Bybee, 2017; Polat et al., 2009, 2018; Sotiriou & Polat, 2023 and references therein).

The hornblendites occur as layers and veins in the ultramafic portion of the FAC, but also as cross-cutting dikes (Huang et al., 2012; Polat et al., 2012, **Supplementary materials 1**). They show a large range in major and trace element compositions (**Figs. 6, 7a-b**). Some of these rocks were interpreted to have crystallized from late-stage volatile-rich residual magmas veining the FAC ultramafic rocks, and or as recrystallized ultramafic cumulates (Polat et al., 2012; Huang et al., 2012, present study).

The vast majority of the FAC rocks show negative Nb, positive K and Pb anomalies along with LREE and LILE enrichment (**Fig. 7**), consistent with an arc-like signature or, alternatively, crustal contamination (e.g. Li et al., 2015; Bédard, 2018; Barnes et al., 2021 and references therein). Previous studies found no evidence of significant crustal contamination (e.g. Polat et al., 2010; Polat & Longstaffe, 2014), except for Souders et al. (2013) who suggested that $\epsilon(\text{HF})$ isotopic signature in zircon and Pb-isotopic composition of plagioclase were consistent with assimilation of old mafic Eoarchean crust in the precursor to the FAC

parental magma. The intrusive amphibolites have similar trace element patterns to basaltic supracrustals of the region, showing both arc and non-arc-like patterns (**Supplementary materials 1**) (Polat et al., 2009, 2011a; Szilas et al., 2012). Polat et al. (2009, 2011a), interpreted this to reflect a progressive transition from a MORB to an Island arc geodynamic setting for the Fiskenæsset region.

6.2 Metamorphic recrystallization

The drill core 21 provides a unique opportunity to study the mineralogy of the most pristine section of the FAC at Majorqap Qâva (**Fig. 1a**). Mineralogically and texturally the samples analyzed in detail show evidence of equilibration and recrystallization at high grade metamorphism (**Section 4**). The presence of sillimanite, garnet, biotite and corundum (incl. Ruby) further support both equilibration at high P-T metamorphic conditions and metasomatic reactions with cross-cutting intrusive TTGs (**Figs. 2-5**). By excluding variously altered anorthosite samples and transition areas, the plagioclase composition across the drill-core is relatively homogenous. We interpret the population mean of $An_{87\pm1}$ as the best estimate of the average igneous composition of the pristine anorthosites at Majorqap Qâva (**Section 5, Supplementary materials 3 – Table S2**), which has important implications for the thermodynamic modelling presented in **Section 7**. The variably lower An-content and elevated SiO_2 , Na_2O , and K_2O observed in altered anorthosites, are related to fluids from younger felsic granitoids and/ -or metamorphic fluids. The higher An-content of leucogabbros ($An_{90\pm3}$) (except sample 212550), has also previously been reported from gabbros and leucogabbros of the FAC, interpreted to reflect earlier crystallization of the leucogabbros from a more primitive magma (Polat et al., 2009, 2011b, 2012, 2018; Rollinson et al., 2010; Huang et al., 2012, 2014). Similar is reflected in the overall higher Mg# of the leucogabbros and their interstitial mafic phases (**Section 5**).

The abundant amphiboles of the FAC, occurring as an abundant interstitial phase in all lithologies and as inclusions in silicate-phases and chromite, have long been considered at least partly of magmatic origin (Windley et al., 1973; Myers, 1985; Polat et al., 2009, 2011b, 2012, 2018; Rollinson et al., 2010; Ashwal & Bybee, 2017; Sotiriou & Polat, 2020, 2023). Based largely on their high abundance, their composition and textural observations, these authors argued that the amphiboles could constitute key petrogenetic evidence of hydrous parental magmas of the FAC, analogous to amphiboles occurring in modern subduction zone derived magmas. In contrast, we interpret all amphiboles in our samples to be purely metamorphic, based on both textural observations (e.g. the presence of abundant amphibole inclusions in recrystallized plagioclase (**Fig. 3a-h**) and the identical compositions between inclusions and the interstitial amphiboles (**Section 5, Supplementary materials 3 – Table S6**). This indicates that the inclusions formed during recrystallization and metamorphic growth. The presence of metamorphic quartz and biotite inclusions in the same grains further support a metamorphic origin of the amphiboles in these rocks (**Fig. 3a-h**). Amphibole-rich layers in leucogabbros often show foliation along with biotite (**Figs. 4c-d**), and therefore do not necessarily represent primary igneous layering. Similar metamorphic banding and foliation is commonly observed in outcrops (**Supplementary materials 1**). Preferred orientation of some inclusions may similarly be a metamorphic feature, however, inclusions are mainly randomly oriented within the same grain (**Figs. 3c, 3g-h**).

The hydrous recrystallization of high-CaO clinopyroxene (diopside) to amphiboles (hornblende) would add significant CaO to plagioclase and take up Na₂O. This mechanism could explain the relatively high An-content observed in some gabbros and leucogabbros where amphibole is abundant (Polat et al., 2009, 2011b; Rollinson et al., 2010; Huang et al., 2012; 2014). Given the abundant amphibole and biotite of metamorphic and metasomatic origin in these rocks, and the rarity of interstitial pyroxenes, we consider the slightly higher

An_{90±3} of leucogabbros a metamorphic signature (**Fig. 2, Section 5.2**). Pseudo-section modelling using Perple_X thermodynamic software on leucogabbro sample 210390 from drill core 21, is consistent with the metamorphic formation of abundant amphibole from hydration of clinopyroxene under a large P-T range (**Supplementary materials 5**) ([Conolly, 2005, 2009](#)). However, the overall difference in Mg# between amphibole and biotite in anorthosite and leucogabbro indicates that the mafic layers may have crystallized from a relatively more primitive, MgO-rich magma or alternatively represents mixing between different magmatic systems (e.g. [Huang et al., 2012, 2014](#); [Polat et al., 2012](#)) (**Section 5, Supplementary materials 3 – Tables S6, S8**).

7. Thermodynamic MODELLING

Previous research including study of field relations, petrology and geochemistry has considered Archean anorthosites, including the Fiskenæsset Anorthosite Complex, to have formed through mainly fractional crystallization of mafic-ultramafic magmas, including komatiites, picrites, basalts, tholeiites and boninites ([Weaver et al., 1982](#); [Ashwal, 1993](#); [2010](#); [Polat et al., 2009](#); [Ashwal & Bybee, 2017](#); [Sotiriou & Polat 2020, 2023](#); [Sotiriou et al., 2023](#) and references therein). The combination of large volumes of high-Ca plagioclase, aluminous chromite and abundant amphibole led most previous authors to interpret the parent magma as being aluminous, evolved, and hydrous, compatible with experimental data (e.g., [Takagi et al., 2005](#); [Polat et al., 2009, 2012](#); [Rollinson et al., 2010](#)). In order to constrain the nature of the parent magma(s) and the magmatic processes that gave rise to the FAC and its high-An anorthosites, we conducted modelling using the thermodynamic software rhyolite-MELTS v.1.2.0 ([Gualda et al., 2012](#); [Ghiorso & Gualda, 2015](#)). MELTS modelling has previously been used to constrain the petrogenesis of anorthosites, including those in

Proterozoic massifs, layered intrusions, and on the Moon (e.g., [Arai & Maruyama, 2017](#); [Latypov et al., 2020](#); [Shellnutt & Prasanth, 2021](#); [Fred et al., 2022](#); [Maier & Barnes, 2024](#)), and to establish a petrogenetic link between supracrustal metavolcanics and spatially associated ultramafic cumulates (e.g. in SW Greenland) ([Zhang et al., 2023](#); [Zhang & Szilas, 2024](#)).

7.1 Model conditions and parental magmas

We modelled a variety of magma compositions using previously published major element data of volcanic rocks considered to be parental and or genetically related to the FAC and Archean anorthosites in general (**Table 1**).

This included the most primitive high Al-tholeiite and high-Mg andesite from the adjacent coeval pillow-bearing Bjørnesund Supracrustal Belt (BSB) (**Fig. 1a**) ([Szilas et al., 2012](#)).

Many anorthosites in SW Greenland are associated with tholeiitic basaltic to calc-alkaline andesitic volcanic rocks in adjacent supracrustal belts ([Owens & Dymek, 1997](#); [Polat et al., 2008, 2011a](#); [Windley & Garde, 2009](#); [Hoffman et al., 2012](#)), and the BSB have previously been considered genetic related to the FAC, representing its volcanic derivatives ([Esher & Myers, 1975](#); [Peck & Valley, 1996](#); [Polat et al., 2009, 2011b](#); [Szilas et al., 2012](#); [Szilas, 2018](#)).

More MgO-rich magmas such as komatiites and picrites have also been considered parent magmas or at least primitive precursors of the melts forming the FAC and Archean anorthosite complexes. Particularly komatiites share a similar temporal restriction as Archean anorthosites, which have suggested similar unique petrogenetic conditions ([Phinney et al. 1988](#); [Ashwal, 1993](#); [Polat et al., 2011b](#); [Ashwal & Bybee, 2017](#); [Sotiriou & Polat, 2020, 2023](#); [Sotiriou et al., 2023](#) and references therein). Due to the absence of spatially associated

komatiites and Archean picrites in SW Greenland (Windley & Garde, 2009; Szilas et al., 2012, 2015, 2018; Klausen et al., 2017; Szilas, 2018), a primitive aluminum undepleted komatiite with spinifex-texture from the ~2.7 Ga Bellingwe komatiite formation were modelled (Table 1) (Sossi et al., 2016), and a picritic melt composition estimated from the high-Al tholeiite parental using the PRIMELT3 software by Herzberg & Asimow (2008, 2015).

In order to assess the effect of H₂O on crystallization sequence as well as parent melt and mineral compositions, initial H₂O contents used in the modelling were 0, 0.25, 2 and 4 wt.%. The low and high values correspond to H₂O contents of magmas in modern MORB and island arc basalts, respectively (Takagi et al., 2005; Kelly & Cottrell, 2009; Kelly et al., 2019; Li et al., 2017; Zhang et al., 2023). The dQFM ± 1 oxygen buffer was applied in all models, to assess the effect of redox conditions and because oxidation state of the 3 Ga Archean mantle beneath SW Greenland is considered to be within QFM ± 0.5 (Gao et al., 2022; Zhang et al., 2023). Lithostatic pressure was modelled at 1-4, 6, 8 and 10 kbar corresponding to the depths of upper, middle, and lower crust, respectively. All models were run using isothermal fractionation mode and -1°C increments, between the liquidus temperature to 800°C unless the model reached equilibrium. Below in Section 7.2-7.3 we summarize and discuss the findings of 336 MELTS-simulations and evaluate whether they can explain the petrogenesis of the FAC. The output data of the models are compared with field, petrological, mineral and -whole-rock geochemical data constrained from drill core 21, outcrop samples and previously published data.

7.2 Modelling results

All parental magmas modeled, except for the high-Mg andesite, can yield plagioclase with high-An content around $An_{87\pm1}$, overlapping with the igneous composition of plagioclase in drill core 21 (**Section 4-5, Table 2**). The initial An-content of the model plagioclase increases with H_2O content of the parent magma and decreases with increasing lithostatic pressure, constraining a depth of crystallization of ≤ 3 kbar and ≤ 6 kbar for H_2O -poor and hydrous conditions, respectively. The komatiitic parent magma crystallizes slightly more calcic plagioclase at pressures as high as 8 kbar at dQFM+1, however at 8-10 kbar plagioclase is mainly replaced by garnet (**Supplementary materials 6**). Furthermore, there is no field or geochemical evidence suggesting the FAC was emplaced into lower crust. Instead, its spatial association with the pillow-basalt bearing supracrustals in the Fiskenæsset-Bjørnesund region suggest an upper crustal emplacement level ([Esher & Myers, 1975](#); [Peck & Valley, 1996](#); [Polat et al., 2009, 2011a](#); [Szilas et al., 2012](#) and references therein). **Table 3** gives a graphical overview of the modelling results presented here and in **Section 7.3**, and a comparison between the simulated parental magmas regarding the petrogenesis of the FAC.

Any successful petrogenetic model must be consistent with the occurrence of abundant chromitite within the anorthosites, and the aluminous composition of the chromite. **Figure 8** shows a comparison of the crystallizing Cr-spinel trends of the models at shallow to mid-crustal conditions (1-6 kbar), with observed chromite compositions. The high-Al tholeiite and picrite parent magma overlap and or approaches the lower compositional trend at ≤ 3 kbar for H_2O -poor models only (0-0.25%) and at moderate to reducing conditions (dQFM to dQFM-1). In contrast, models with higher H_2O (2-4%), higher pressure and oxidizing conditions (dQFM+1) all yield too low Cr# (**Fig. 8**). Models of the komatiitic parent magma shows more continuous trends from high to low Mg# and Cr#, and can reproduce similar chromite compositions up to moderate H_2O (2%) at shallow pressure ≤ 3 kbar.

However, as noted by [Drage & Brennan \(2023\)](#), MELTS does not handle chromite properly at mid to high crustal pressures, since Cr is not partitioned into pyroxenes. Chromite data of [Rollinson et al. \(2010, 2017\)](#) (**Fig. 8**), also clearly shows a metamorphic enrichment trend towards higher Cr# and lower Mg# (Fe-Al rich), however, the lower part of the trend reflects a more reasonable igneous composition. [Barnes et al. \(2022, 2025\)](#) also recently documented that even massive chromite layers/seams in Bushveld Complex had to some degree equilibrated with interstitial liquid or silicates, similarly, causing secondary enrichment of Fe-Al. Therefore, the chromite compositions of the FAC and MELTS should be used carefully and not as a main proxy of the parental. However, the results are consistent with formation of similar aluminous chromite at shallow crystallization of ≤ 3 kbar and likely low to intermediate $\leq 2\%$ H₂O content of the FAC parental magma (**Table 3**).

We further compare the whole-rock data generated in this study and from previous publications with the estimated incremental bulk-cumulate trends produced by the models (**Fig. 9, Supplementary materials 6**). The high Al-tholeiite, picrite and komatiite reproduce the main trend of the FAC gabbros, primitive leucogabbros and evolved hornblendites as well as associated basaltic amphibolites for the majority of major elements at a variety of modelled pressures and H₂O contents. However, the composition of the ultramafic rocks and primitive hornblendites are difficult to reproduce by the evolved tholeiite, and also the picrite, despite some overlap. The ultramafic rocks are best explained to have crystallized the komatiite, but none of the modelled parent magmas provides a good fit for the majority of the anorthositic rocks in e.g. Al₂O₃, FeO_T and TiO₂ (**Fig. 9, Supplementary materials 6**). The overlap in CaO with anorthositic rocks at relatively hydrous conditions is due to the combined contribution of cumulus calcic plagioclase and clinopyroxene. Furthermore, the increased bulk Al₂O₃ for models run at relatively high lithostatic pressure towards 6 kbar reflects mainly increasing modal garnet (**Fig. 9, Supplementary materials 6**). Hydrous

models can broadly simulate TiO_2 contents of some anorthositic rocks at lower Mg#, but the fit with the observed compositions is relatively poor.

In contrast to the other parent magmas and model conditions, simulations of H_2O -poor tholeiites (0-0.25 wt.%) do result in crystallization of plagioclase as the essentially sole liquidus phase only at shallower pressures <6 kbar (**Fig. 9, Supplementary materials 6**). Isobaric fractional crystallization of either picrite or komatiite parent magma, does not result in plagioclase as sole liquidus phase and thus requires additional phase-sorting processes. Variation in redox shows that oxidizing conditions of dQFM+1 results in generally more fragmented and inconsistent cumulate trends, whereas at dQFM 0 to -1 for the tholeiitic and picritic parent magmas results in relatively smooth fractionation trends (**Fig. 9, Supplementary materials 6**). We therefore conclude that crystallization conditions in the FAC were broadly at moderate oxidizing to slightly reducing conditions (dQFM to dQFM-1) (**Table 3**). We also note that the relatively hydrous models (2-4% H_2O) show more fragmented and less continuous trends, although there is more overlap in terms of CaO with anorthositic rocks across a higher range in Mg# (**Fig. 9, Supplementary materials 6**). At last, the whole-rock NiO and Cr_2O_3 trends of the FAC are difficult to reproduce, given the relatively low Cr concentration of the tholeiite and picrite, which may likely reflects olivine, pyroxene and chromite fractionation prior to final emplacement. The komatiite model generally shows the best fit with Ni and Cr contents at the modelled conditions (**Table 1, Supplementary materials 6**).

7.3 Petrogenesis of the FAC

The modelling presented in the **Section 7.2** indicates that it is difficult to form anorthosites solely by in situ fractional crystallization of basaltic to komatiitic magmas. Of the magmas considered in this study, the high-Al tholeiite from the Bjørnesund Supracrustal Belt (BSB)

677 is the only one that reaches early saturation of calcic plagioclase without significant co-
 678 crystallization of ferromagnesian silicates or oxides, as long as the magma is relative H₂O-
 679 poor (e.g. 0.25%) and lithostatic pressure is low (≤ 3 kbar) (**Fig. 9, Table 3**).
 680 The early sequence of essential chromite only followed by anorthosite (**Supplementary**
 681 **materials 6**), may likely be associated with depressurization of the magma and
 682 oversaturation of Ca-Al causing the magma to leave the plagioclase-olivine cotectic, similar
 683 to the models of Bushveld anorthosites and chromitites by [Latypov et al. \(2017, 2020\)](#). The
 684 high-Al tholeiite also reproduces the high An-content of plagioclase to the drill core 21 from
 685 Majorqap Qâva, as well as aluminous chromite and it explain many of the cumulate trends
 686 presented in **Fig. 9**. Furthermore, the high-Al tholeiite provides a direct link between the
 687 spatially associated FAC cumulates and volcanics of the BSB. Crystallization at low H₂O-
 688 poor (e.g. 0.25%), moderate to reducing conditions (dQFM to dQFM-1) and low lithostatic
 689 pressure (≤ 6 kbar) reproduce best the tholeiitic trend of the BSB, whereas hydrous (2-4 %
 690 H₂O) and oxidized (dQFM+1) conditions reproduces more a calc-alkaline trend (**Fig. 10a**,
 691 **Supplementary materials 6**).
 692 Fractionation of primitive picrites and komatiites may also explain some of the features of the
 693 FAC, however, these magmas never have calcic plagioclase as sole liquidus phase and are not
 694 spatially associated with the FAC ([Windley & Garde, 2009](#); [Szilas et al., 2012](#); [Szilas, 2018](#)).
 695 Furthermore such high-MgO magmas produce olivine $\pm$ pyroxene dominated intrusions
 696 (**Supplementary materials 6, Table 3**). In contrast, the crystallization of the high-Al
 697 tholeiite produces predominantly felspathic cumulates such as gabbro, leucogabbro and
 698 anorthosite, consistent with the paucity of significant of complementary ultramafic rocks in
 699 the FAC and Archean anorthosites in general (**Supplementary materials 6, Table 3**).
 700 The MELTS modelling further demonstrate that the calcic plagioclase of the FAC
 701 anorthosites and the relative evolved chromite (Cr# 46-67 and Cr/Fe²⁺ of 1-1.2) of the

associated chromite layers cannot have formed simultaneously and/or from the same high-Al tholeiitic magma (**Fig. 10b**). Similar problem has been discussed for the Bushveld chromitites (Latypov et al., 2024a; Maier & Barnes, 2024 and references therein). We therefore suggest four possible models (i) The chromitites in the FAC formed by settling of chromite into an anorthosite mush, (ii) Anorthosite buoyantly intruded into chromitite rich intervals, analogues to the model of Maier & Barnes (2024) for the Bushveld anorthosite. (iii) The composition of the chromite could have been altered by metamorphism and or melt/silicate equilibration (iv) The chromites could have formed during melt-rock reactions by dissolution and replacement of pyroxene in e.g. melanorites or gabbro-norites, similar to models suggested for chromitites of the Bushveld and Rum intrusion (O'Driscoll et al., 2009; Marsh et al., 2021; Barnes et al., 2022; Maier & Barnes, 2024; Boudreau, 2025 and references therein).

For petrogenesis of the FAC anorthosites, it should be noted that the crystallization interval of plagioclase being essentially the sole liquidus phase, is relatively small in the anhydrous tholeiite simulations ($\leq 18^\circ\text{C}$ interval, $< 8\%$ crystallization). This suggests that fractional crystallization on its own is unlikely to result in such massive and homogeneous anorthosites, and will require frequent magma replenishment and phase-sorting cumulate processes (**Fig. 9, Supplementary materials 6**). Plagioclase is buoyant in H_2O -poor magmas only, whereas it settles in hydrous magmas, thereby enabling flotation accumulation (**Fig. 10c**). Evidence of flotation and plagioclase-rich mushes have been reported across the FAC in this study, Windley et al. (1973), Myers (1976b, 1985), Polat et al. (2009, 2011b, 2018) and in Huang et al. (2012, 2014), by the occurrence of snow-flake and megacrystic rocks adjacent to anorthosite (some with negative Eu-anomalies), anorthositic dikes, disrupted chromite layers in anorthosite, and the large range in whole-rock and mineral Mg# and trace elements systematics in high-An anorthosites, leucogabbros and gabbros (**Supplementary materials**

1, Figs. 6-7). The cumulate rocks of the FAC (incl. hornblendites) can additionally be formed by accumulation of various proportions of olivine, clinopyroxene and plagioclase (**Fig. 11**). The abundant amphiboles in the FAC rocks, are best explained by metamorphism of primary clinopyroxene as argued in **Section 6.2**, and by identical FeO_T vs MgO trends between clinopyroxene in anhydrous models compared to the amphiboles analyzed from drill core 21 (**Fig. 11, Supplementary materials 6**).

These results further contradict a hydrous parental of the FAC as previously suggested (e.g. [Polat et al., 2009, 2011b, 2012](#); [Rollinson et al., 2010](#); [Huang et al., 2012, 2014](#)). We therefore conclude that the petrogenesis of the FAC lithologies, including the voluminous calcic anorthosites can be reproduced by mainly fractional crystallization of plagioclase, clinopyroxene, chromite and minor olivine, from an anhydrous high-Al tholeiite parent emplaced into shallow upper crust (**Fig. 12**). Crystal settling and sorting of dense mafic phases relative to plagioclase formed ultramafic cumulates, whereas flotation of buoyant plagioclase formed anorthosite, as previously suggested in studies of layered intrusions, the FAC and by thermodynamic modelling (e.g. [Ghisler & Windley 1967](#); [Raedeke & McCallum, 1980](#); [Myers, 1985](#); [Eales et al., 1986](#); [Scoates, 2000](#); [Polat et al., 2011b](#); [Arai & Maruyama, 2017](#); [Latypov et al., 2020, 2024b](#); [Shellnutt & Prasanth, 2021](#); [Krättli & Schmidt, 2021](#); [Fred et al., 2022](#); [Maier & Barnes, 2024](#)). Additional cumulate processes such as granular flow of crystal slurries may have aided flotation in the efficient phase separation, resulting in anorthosite and chromitite formation ([Maier et al., 2013, 2016, 2021](#)) (**Fig. 12**).

7.4 Geodynamic implications

The petrogenesis of the FAC can be best explained by crystallization of a relative anhydrous high-Al tholeiite emplaced into shallow crust as concluded in **Section 7.3**. The high-Al

751 magma was likely derived from a more primitive picritic precursor ponding at the middle to
752 lower crust, as [Phinney et al. \(1988\)](#) initially suggested ([Ashwal, 1993](#)). This is supported by
753 the simulation of the PRIMELT3 derived picritic parent composition (**Table 1**), which can
754 reproduce the composition of the high-Al tholeiite parent at 6-10kbar by fractionation of
755 olivine-rich ultramafic cumulates (**Fig. 13**). Based on the combined petrological, geochemical
756 and thermodynamic modelling results presented in this study, a hydrous subduction
757 geodynamic setting for the FAC can be ruled out, given that such specific setting is not
758 necessary to explain the observed field, lithological, mineralogical and geochemical
759 characteristics. Furthermore, the MELTS-modelling results is inconsistent with previous
760 claims of hydrous parental melt(s) (**Section 7.2-7.3**) and the abundant amphiboles are likely
761 not magmatic, but of metamorphic origin (**Section 6.2**). The observed variable crustal,
762 MORB and arc-like trace element signatures (e.g. enriched LILE, LREE, Th, negative Nb-Ti)
763 (**Section 6.1**), are considered relatively non-discriminative of the tectonic setting of magmas,
764 since they can be explained by various processes such as crustal contamination, Ti-oxide
765 fractionation, metamorphism or as previously suggested subduction ([Li et al., 2015](#); [Barnes et](#)
766 [al., 2021](#)). [Polat et al. \(2010\)](#) and [Polat & Longstaffe \(2014\)](#) argued that Nd, Pb, Sr and O-
767 isotope systematics of the FAC show derivation from a relatively uncontaminated long-term
768 depleted mantle. However, [Sauders et al. \(2013\)](#) interpreted Hf and Pb isotopic data from
769 zircon and plagioclase by contamination with old Eoarchean mafic crust. Therefore our
770 proposed new petrogenetic-model for the FAC, suggest simpler alternatively non-
771 uniformitarian settings for the Fiskenæsset region at 3 Ga (e.g. ocean-plateau, rift, stagnant-
772 lid). The petrogenesis of the FAC occurred likely in two steps, i) Large degree anhydrous
773 melts (picritic or alternatively komatiitic) ponds at lower to middle crust, fractionating
774 ultramafic cumulates and assimilating mafic crust, resulting in generation of the high-Al
775 tholeiite parental, ii) The high-Al tholeiitic parental, likely containing dissolved plagioclase

phenocryst, ascents to lower crustal levels. The decompression and emplacement causes formation of massive calcic anorthosites through mainly plagioclase-only crystallization and flotation in sill-like magma chambers, feeding the Bjørnesund Supracrustal Belt with melts (**Fig. 12**). This two-stage model is similar to that of Proterozoic massif anorthosites, except that contamination is lesser and involve old mafic crust rather than felsic continental (Phinney et al., 1988; Bybee et al., 2014; Charlier et al., 2010, 2015; Ashwal & Bybee, 2017). Furthermore it involves unique petrogenetic conditions of the hotter Archean Earth, facilitating high-degree and anhydrous mantle melts, and slow cooling limiting crystallization during ascent and facilitating megacrysts formation (Herzberg et al., 2010; Polat et al., 2011b, 2018; Ashwal & Bybee, 2017; Palin et al., 2020; Bédard, 2018, 2024 and references therein). Similar petrogenetic model and geodynamic implications may apply for other Archean anorthosites, given the many lithological, petrological and geochemical similarities (Ashwal, 1993; Ashwal & Bybee, 2017; Sotiriou & Polat, 2023, Sotiriou et al., 2023).

8. CONCLUSION

In the present paper we provide new insight into the petrogenesis of the Mesoarchean Fiskenæsset Anorthosite Complex, based on petrological and geochemical data, and thermodynamic simulations. Detailed petrographic and mineralogical study of a drill-core from Majorqap Qâva shows that the anorthosites have high-grade metamorphic textures and homogenous compositions, with unaltered plagioclase having a mean composition of $An_{87\pm1}$. Leucogabbros have slightly higher An-contents, resulting from recrystallization of calcic clinopyroxene to amphiboles. Mineral data and thermodynamic modelling results indicate that the abundant amphiboles are of metamorphic origin, rather than magmatic as previously considered. MELTS simulations show that crystallization of high-Al tholeiite from the Bjørnesund Supracrustal Belt can successfully explain the cumulate rocks of the FAC,

801 assuming an emplacement at low lithostatic pressure ≤ 3 kbar, relative anhydrous, and
802 moderate to reducing conditions. H₂O-poor melts facilitates more efficiently the early
803 formation of calcic anorthosites and enables flotation accumulation, which along with
804 cumulate-processes and frequent magma replenishment formed the massive anorthosites and
805 associated chromitites. Based on the combined results of this study, we present a new
806 anhydrous petrogenetic model of the FAC, involving decompression and emplacement of
807 plagioclase supersaturated high-Al tholeiites in the upper crust which feed the Bjørnesund
808 Supracrustal Belt with magmas. The high-Al tholeiite parental, derived from a more primitive
809 picritic precursor that ponded and fractionated ultramafic cumulates in the lower to middle
810 crust and assimilated old mafic crust, explaining the variable crustal trace element signature
811 of the rocks and anorthositic bulk of the complex. We therefore argue against the need of a
812 hydrous subduction zone setting of the FAC and Fiskeneset region around 3 Ga, and
813 propose simpler alternatively non-uniformitarian settings (e.g. ocean-plateau, rift, stagnant-
814 lid). A similar petrogenetic model may apply for other Archean anorthosites, involving unique
815 petrogenetic conditions of the Archean, facilitating high-degree melting of dry mantle,
816 magmatic ponding, assimilation of mafic crust and generation of high-Al tholeiites.

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DECLARATIONS OF COMPETING INTEREST

Authors have no known competing interest that could have influenced the work reported in this paper.

DATA AVAILABILITY

Research data underlying this study is available in its online supplementary material, and all raw geochemical data generated is available from <https://doi.org/10.60520/IEDA/113405>. Raw data files for pXRD, Perple_X and MELTS can be made available upon request.

APPENDIX A - SUPPLEMENTARY MATERIALS

Supplementary materials are available in the online version at Journal of Petrology.

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Figure & Table captions:

Figure 1: (a) Geological map of the Fiskenæsset region in SW Greenland. The red box on the Greenland outline highlights the study region. The large red box and star marks the location of collected outcrop samples and drill core 21, respectively. (b) Geological map of Qeqertarssuatsiaq Island showing sample locations and lithologies reported in this study. Map is modified from mapping and compilation by the Geological Survey of Denmark and Greenland (Keulen et al., 2010).

Figure 2: Simplified lithological log of drill core 21 (1:200), for more detailed scale-log see Supplementary materials 2. The log shows the measured mean An-content (molar %) $\pm 2\sigma$ of plagioclase in anorthosite, altered anorthosite and leucogabbro layers across the drill core. The composition of both anorthosite and leucogabbro parts are shown for transitional domains. For mineral data see Supplementary materials 3 - Tables S1-2 and Section 5.2.

Figure 3: Representative microphotographs and back scattered electron images of lithologies observed in drill core 21 from Majorqap Qâva. Modified from Christiansen (2023). (a-b) Anorthosite, (c-d) Zoisite-sericite altered anorthosite, (e-f) Potassic altered anorthosite, (g-h) Leucogabbro, (i-j) granitoid gneiss, (k) granitoid, (l) Tonalitic pegmatite. The following mineral abbreviation is used; plagioclase (Pl), alkali-feldspar (Kfsp), amphibole (Amp), biotite (Bt), Muscovite (Ms), quartz (Qz), garnet (Grt), sillimanite (Sil), clinozoisite (Clz). Alteration matrix covers over a fine grained assemblage of clinozoisite, sericite, chlorite, prehnite, illite and calcite. For pXRD data, see supplementary materials 4.

Figure 4: AMICS Mineral maps based on micro-XRF scanning of representative drill core samples. Modified from Christiansen (2023). (a) Anorthosite, (b) Altered anorthosite, (c) Transition between anorthosite and leucogabbro, (d) Leucogabbro. Alteration phases include mainly epidote-zoisite group minerals, and minor andesine-albite, orthoclase, chlorite, muscovite, prehnite, montmorillonite, sepiolite, illite and calcite. Accessory phases include mainly garnet, apatite, zircon, and minor clinopyroxene, titanite, Fe-Ti oxides, pyrite and chalcopyrite. For pXRD data, see supplementary materials 4.

Figure 5: AMICS Mineral maps based on micro-XRF scanning of representative drill core samples. Modified from [Christiansen \(2023\)](#). (a) Tonalitic pegmatite, (b) Granitoid, (c) Granitoid gneiss, (d) Anorthosite inclusion in granitoid. Alteration phases include mainly epidote-zoisite group minerals, and minor andesine-albite, orthoclase, chlorite, muscovite, prehnite, montmorillonite, sepiolite, illite and calcite. Accessory phases include mainly garnet, apatite, zircon, and minor clinopyroxene, titanite, Fe-Ti oxides, pyrite and chalcopyrite. For pXRD data, see supplementary materials 4.

Figure 6: Whole-rock major element variation diagrams for the FAC data presented in this study, compared with data compiled from previous studies (Supplementary materials 3 - Tables S3-5). Data presented is normalized to 100% volatile-free basis. Modified from [Linnebjerg \(2021\)](#).

Figure 7: Trace-element variation diagrams of FAC samples presented in this study, respectively chondrite normalized rare earth diagrams ([McDonough & Sun, 1995](#)) and primitive mantle multi-element diagrams ([Sun & McDonough, 1989](#)). (a-b) amphibolite and hornblendite (c-d) gabbro and leucogabbro (e-f) anorthosite. Circles are samples collected at Qeqertarsuatsiaq Island and diamond points are from drill core 21 samples (**Fig. 1**) (Supplementary materials 3 - Table S3). Diagrams were created using Gcdkit v.6.0 ([Janoušek et al., 2006](#)).

Table 1: Major element compositions (wt%) of parental magmas modelled in this study using rhyolite-MELTS v.1.2.0.

Foot Notes:

¹Source for parental compositions can be found in Supplementary materials 6.

²Picrite estimated with PRIMELTS based on High-Al tholeiite parental, following procedure for basalts of [Herzberg & Asimow \(2008, 2015\)](#).

³Mg# number is defined as molar $\text{Mg}/(\text{Mg}+\text{Fe}^{2+}) \times 100$, Fe^{2+} is assumed to be 90% of total FeO unless Fe^{3+} has been estimated.

⁴Initial H_2O contents in wt. %, compositions normalized to 100% in modelling.

Table 2: Overview of initial liquidus plagioclase composition in molar An % for each MELTS-model presented in this study at various initial water content, lithostatic pressure and redox condition. Missing value is either due to instability of MELTS at high water contents at low pressure (1-2kbar) or the replacement of plagioclase with garnet at high pressure (≥ 6 kbar).

Table 3: Graphical summary table of modelling results discussed in Section 7.2-3 for simulated parent magmas at QFM. For summary tables of models at $\text{QFM} \pm 1$ see Supplementary materials 6.

Figure 8: Spinel-trends for each modelled parental magma at 1, 3 and 6 kbar, 0-4% H₂O, and QFM±1, compared with chromite data for anorthosite-hosted chromitites by [Rollinson et al. \(2010, 2017\)](#) (black diamonds, Supplementary materials 6).

Figure 9: Compositional evolution of cumulates formed by pure fractional crystallization for selected MELTS models at 3kbar and QFM-1, compared with whole-rock data presented in this study and from literature. For more compositional plots see Supplementary materials 6.

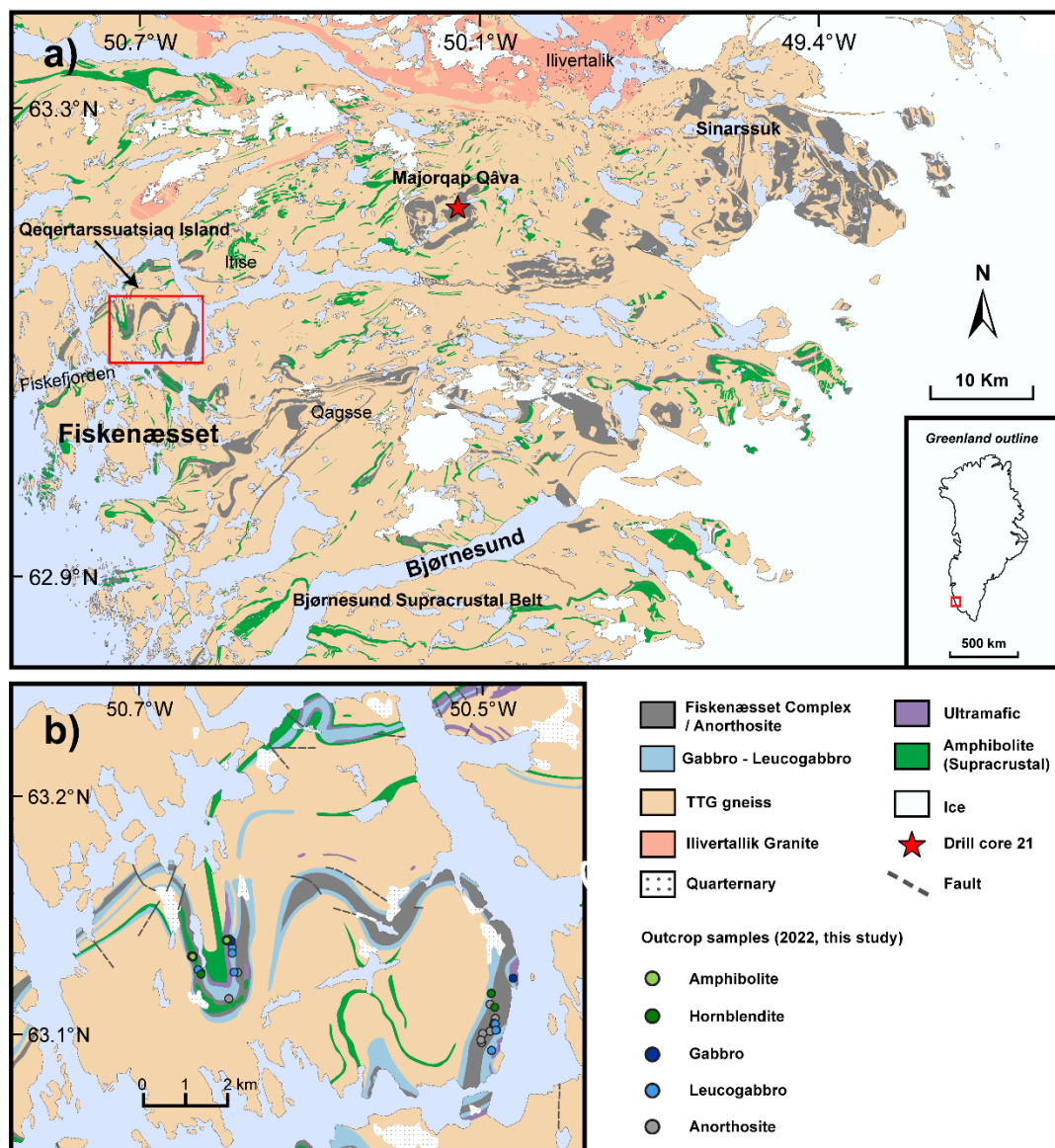
Figure 10: (a) TiO₂ vs Mg# evolution of liquid line of descent (LLD) for high-Al tholeiite parental models (3kbar, QFM-1) compared with whole-rock data from Bjørnesund Supracrustal Belt ([Szilas et al., 2012](#)) (Supplementary materials 6). (b) Cr-spinel vs plagioclase compositional trends during crystallization of the high-Al tholeiite at anhydrous conditions (0 and 0.25% H₂O), 1kbar and QFM-1. FAC chromite compositional field based on data from [Rollinson et al. \(2010, 2017\)](#) presented in Fig. 8. The diagram illustrates that the region in which anorthosites form with similar composition to the FAC, the co-crystallizing chromite do not match the observed trend of the FAC until after significant crystallization. (c) Melt (LLD) and plagioclase (Plg) density vs temperature during crystallization of high-Al tholeiite at 3kbar, QFM-1 and various H₂O contents. Plagioclase in anhydrous models (<2% H₂O) show largely positive buoyancy relative to melt across magmatic evolution facilitating flotation, whereas plagioclase fractionating in hydrous models (2 and 4% H₂O) show negative buoyancy facilitating settling.

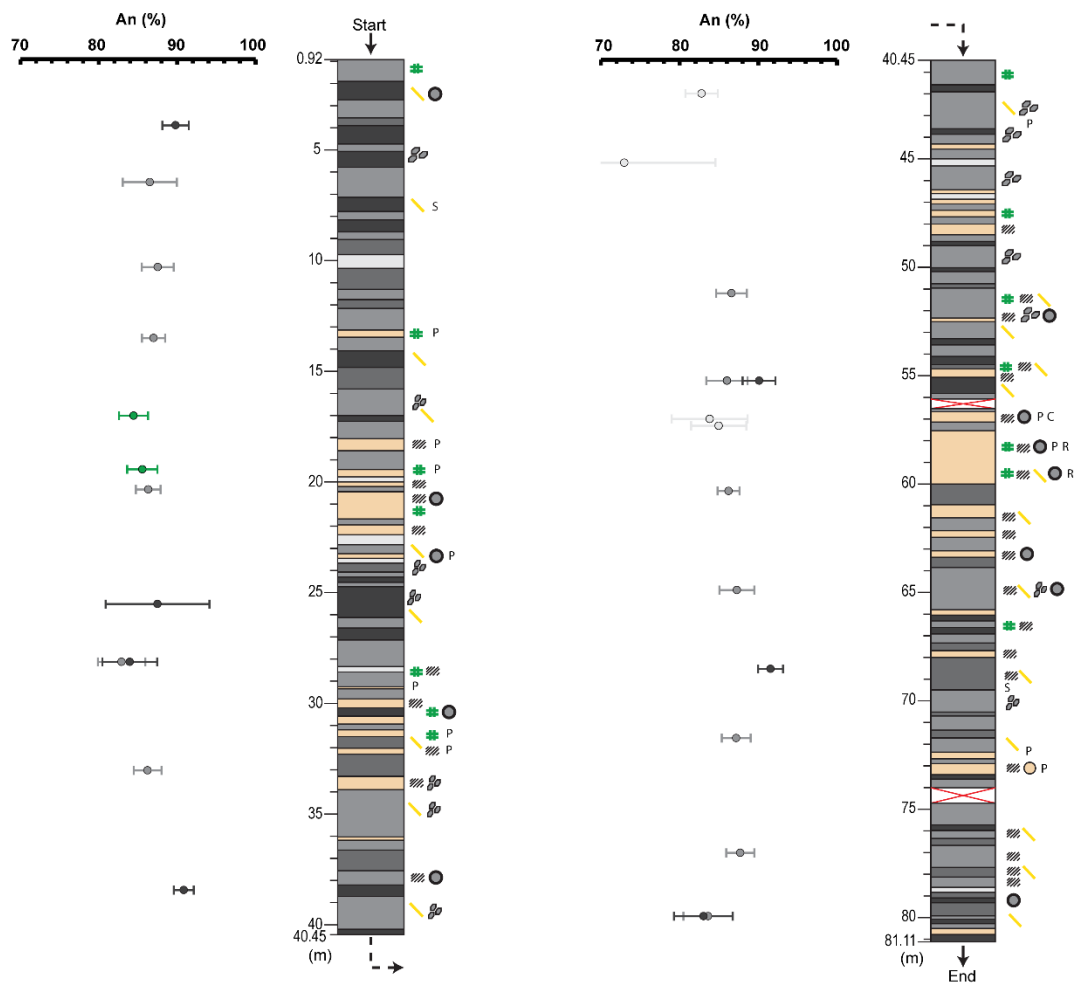
Figure 11: Major element variation of main mineral phases crystallization from high-Al tholeiite parental at 0.25% H₂O, 1kbar and QFM-1, compared with whole-rock data from FAC rocks, plagioclase, amphibole and cpx data from drill-core 21 (Supplementary materials 3+6, lithological legend as Fig. 6). The arrows indicate that the FAC rocks can largely be reproduced by accumulation of olivine, clinopyroxene and plagioclase, based on the modelled mineral trends. Clinopyroxene for the model shown reproduces identical FeO_T vs MgO trend of measured amphiboles in drill core 21.

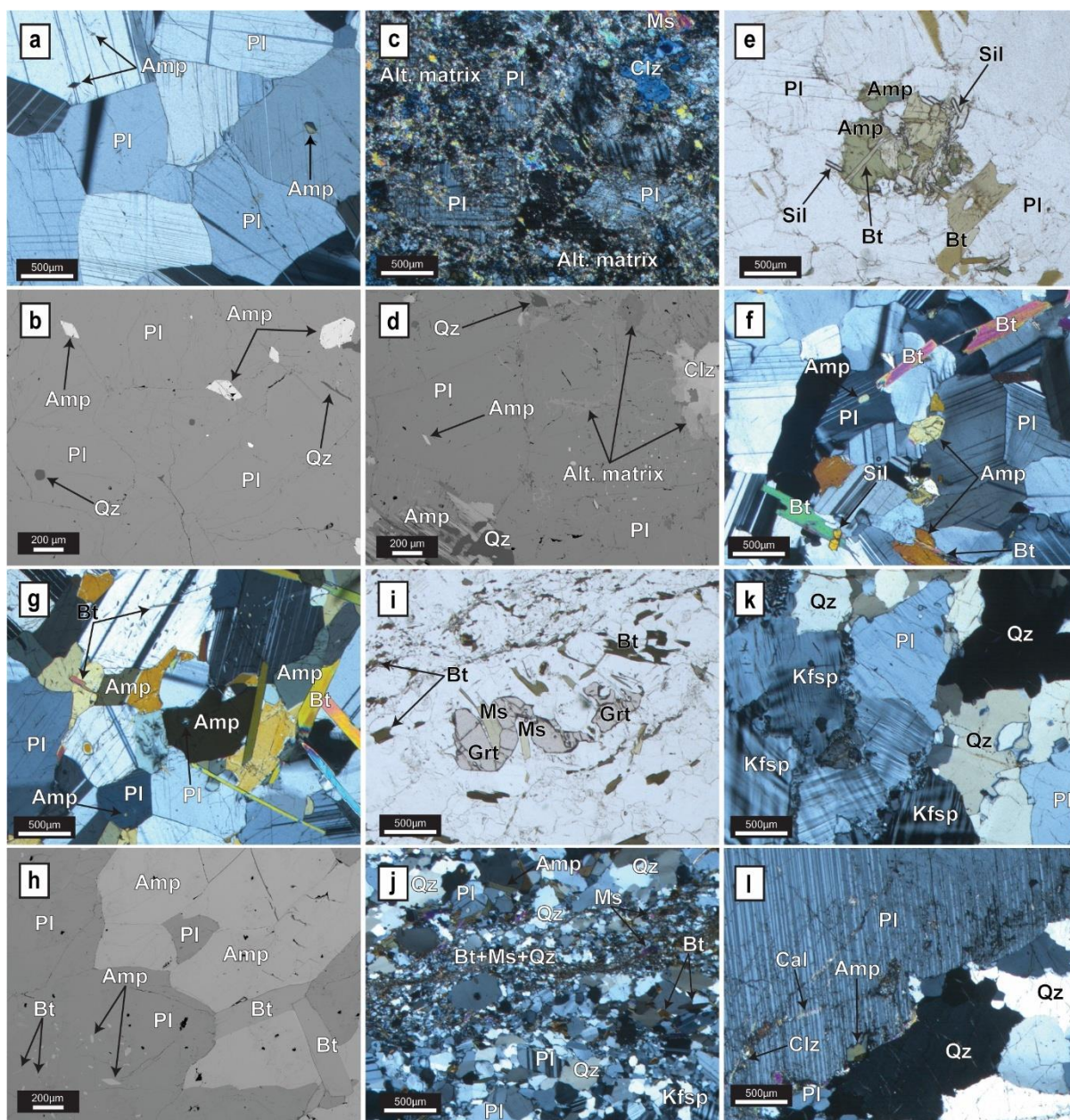
Figure 12: Petrogenetic model schematic for the Fiskensæset Anorthosite Complex (inspired by [Fred et al., 2022](#)). (i) Anhydrous mantle-derived primitive picritic melts ponds at lower to middle crust, evolving into a high-Al tholeiite by crystallizing early ultramafic cumulates and assimilating older mafic crust. (ii) The high-Al tholeiite ascends into the upper shallow crust, dissolving any early formed plagioclase phenocryst. Emplacement into multiple sill-like bodies, the decompressed plagioclase supersaturated melt formed anorthosites by plagioclase only crystallization and flotation, accompanied by other phase-sorting

processes e.g. crystal slurries. The shallow open subvolcanic system was frequently replenished, resulting in massive and homogenous calcic anorthosites, chromitites and minor ultramafic rocks, supplying the Bjørnesund Supracrustal Belt with melts.

Figure 13: Al_2O_3 vs Mg# liquid line of descent (LLD) for picrite and komatiite parental models (1-10 kbar, 0.25% H_2O and QFM-1), compared with tholeiite data of the Bjørnesund Supracrustal Belt ([Szilas et al., 2012](#)). The diagram illustrates that the picrite can well reproduce the high-Al tholeiite parental of the FAC after some crystallization, at conditions up to 10kbar, whereas the remaining tholeiite trend requires crystallization at lower lithostatic pressure.

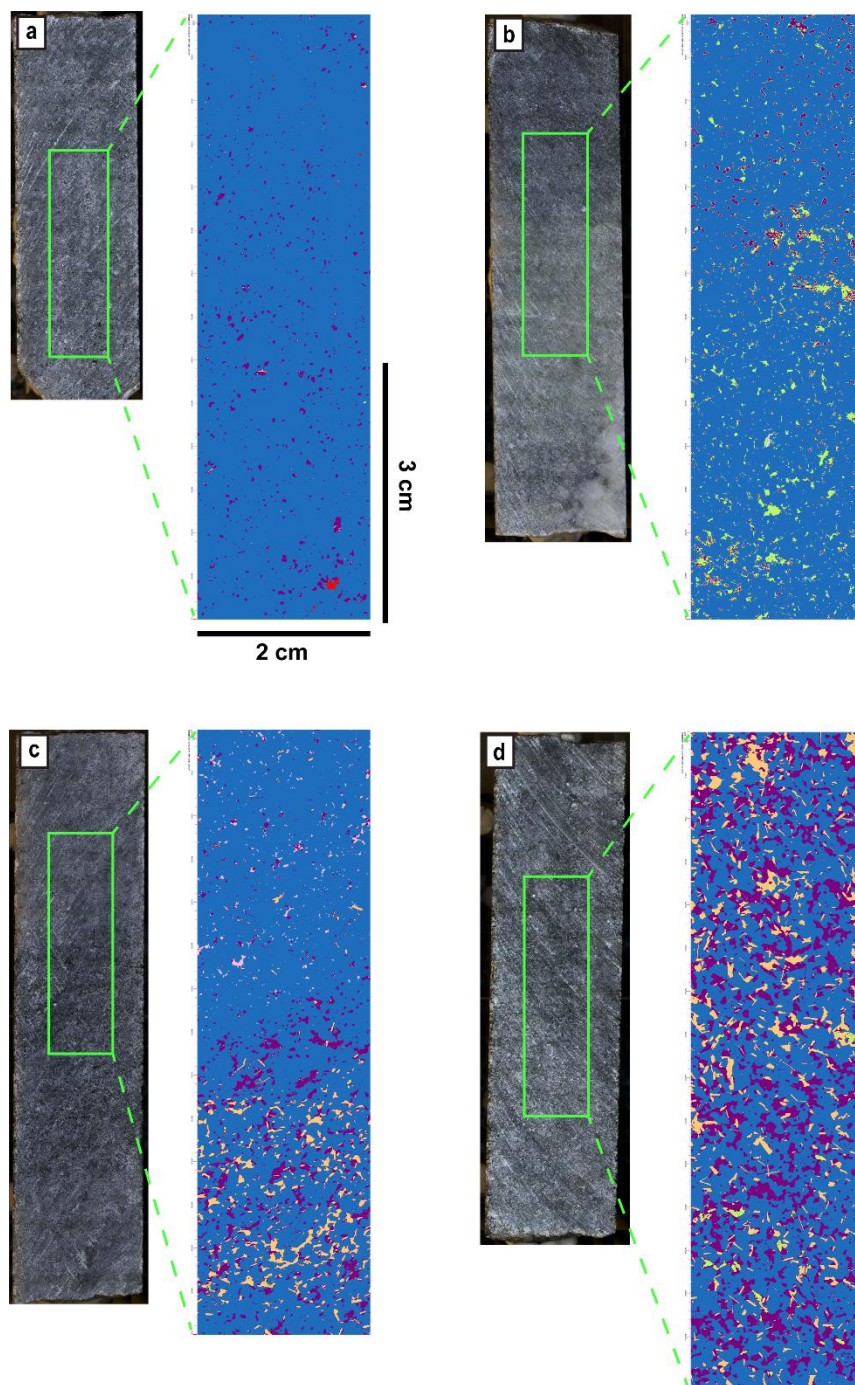






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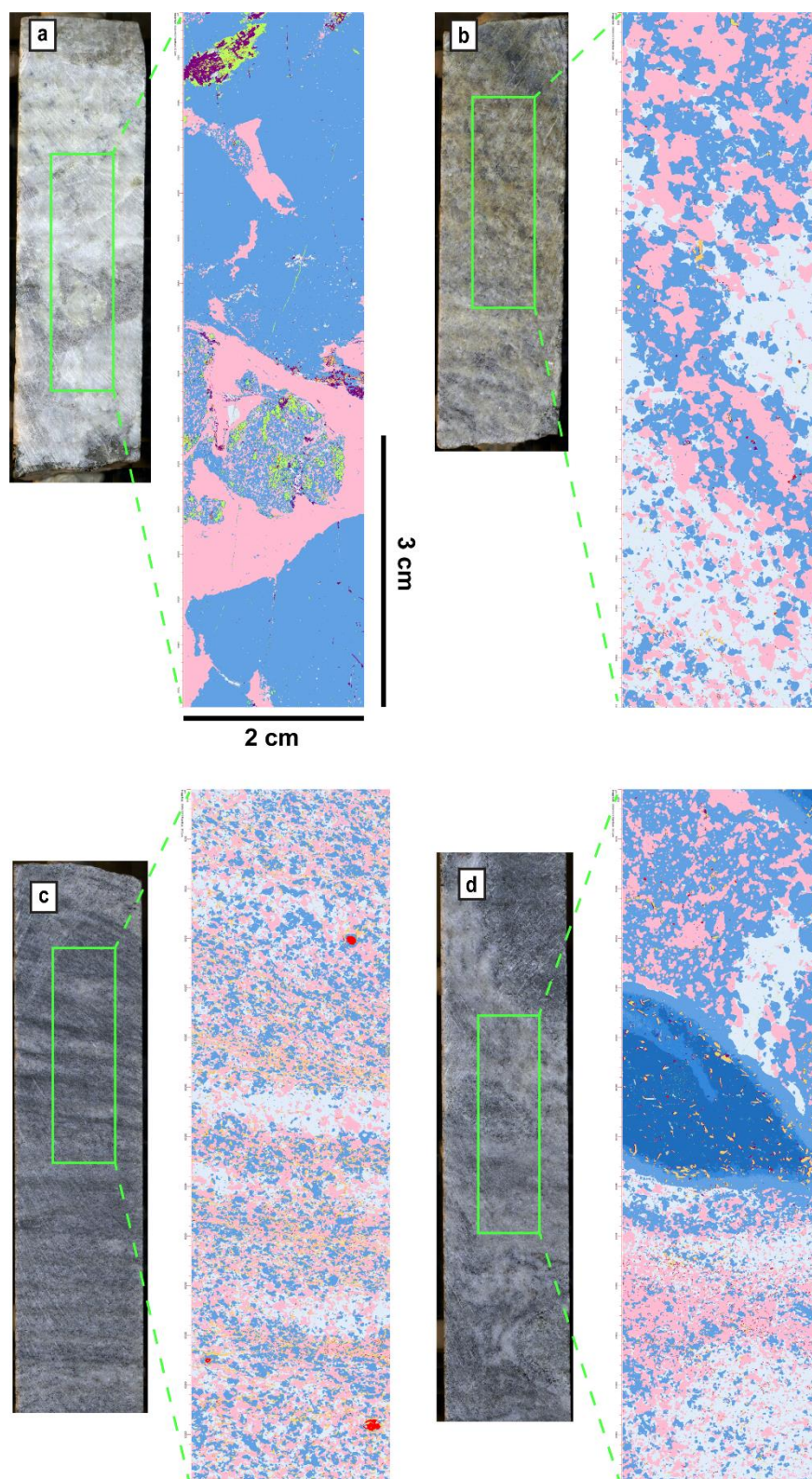
Legend

 Plagioclase An10-50	 Alkali feldspar	 Alteration phases
 Plagioclase An50-70	 Amphibole	 Accessory phases
 Plagioclase An70-90	 Biotite	 Unidentified pixels
 Plagioclase An90-100	 Quartz	

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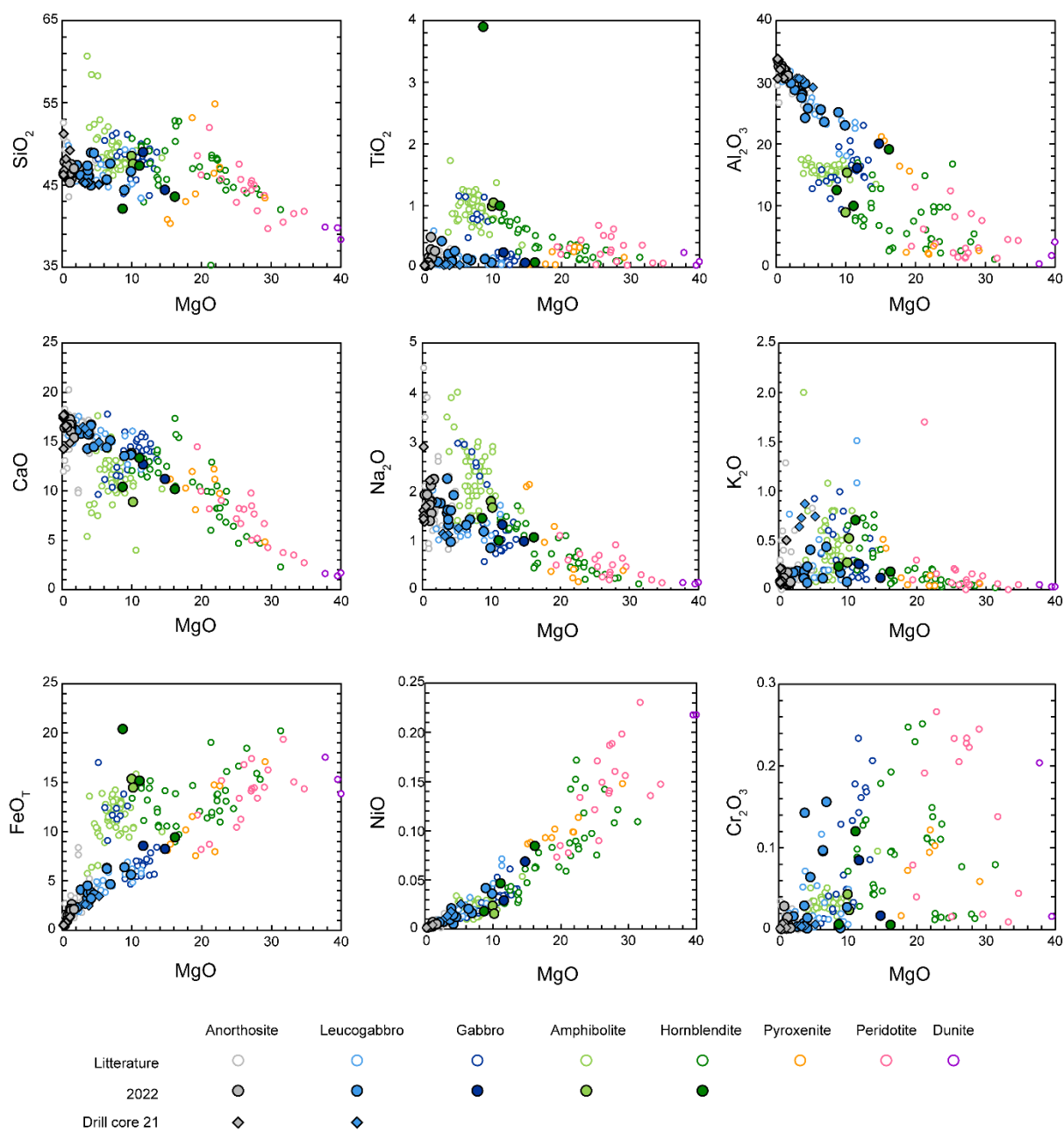
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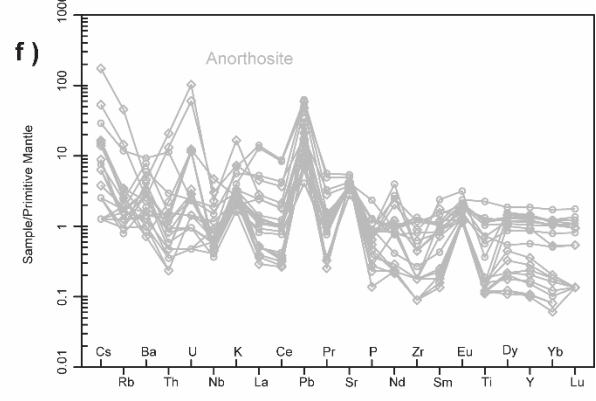
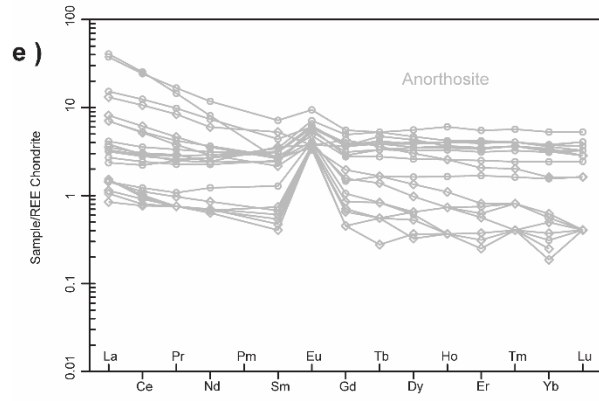
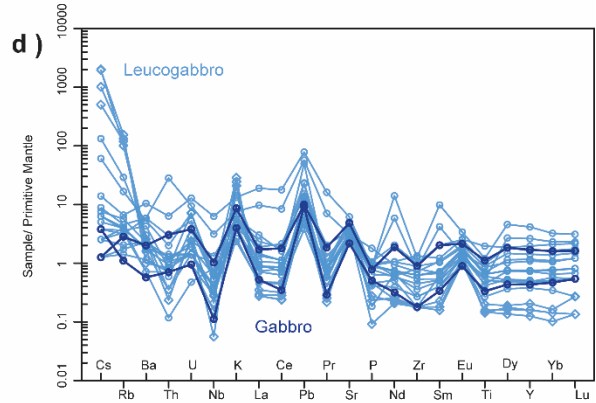
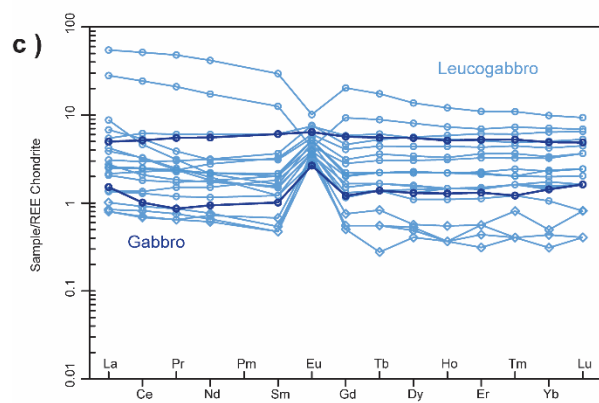
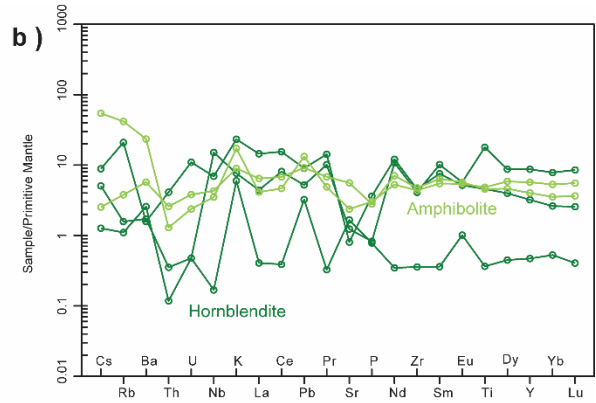
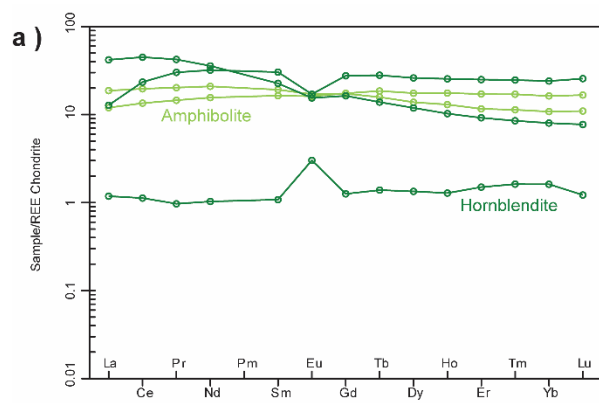
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Legend

Plagioclase An10-50	Alkali feldspar	Alteration phases
Plagioclase An50-70	Amphibole	Accessory phases
Plagioclase An70-90	Biotite	Unidentified pixels
Plagioclase An90-100	Quartz	





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1304 **Table 1:**

Parental magmas				
Rock/Melt type ¹	Amphibolite (High-Al tholeiite)	Leucoamphibolite (High-Mg andesite)	Picrite ²	Komatiite ³
SiO ₂ (wt%)	47.71	52.27	46.16	46.61
TiO ₂	0.51	1.3	0.41	0.29
Al ₂ O ₃	17.63	15.42	13.95	11.94
FeOt	9.81	9.4	10.02	-
Fe ₂ O _{3t}	-	-	-	11.94
MnO	0.17	0.15	0.17	0.23
MgO	9.36	6.94	17.45	28.06
CaO	12.96	10.65	10.30	5.79
Na ₂ O	1.64	2.91	1.29	0.22
K ₂ O	0.14	0.51	0.11	0.45
P ₂ O ₅	0.06	0.44	0.05	0.02
Cr ₂ O ₃	0.06	0.05	0.06	0.352
NiO	0.002	0.003	0.01	0.17
Mg# ³	65	59	76	84
H ₂ O ⁴	0, 0.25, 2, 4	0, 0.25, 2, 4	0, 0.25, 2, 4	0, 0.25, 2, 4

1316 Foot Notes:

1317 ¹Source for parental compositions can be found in Supplementary materials 6.

1318 ²Picrite estimated with PRIMELT3 based on High-Al tholeiite parental, following procedure for basalts of [Herzberg and Asimow \(2008,](#)
1319 [2015\)](#).

1320 ³Mg# number is defined as molar Mg/(Mg+Fe²⁺)*100, Fe²⁺ is assumed to be 90% of total FeO unless Fe³⁺ has been estimated.

1321 ⁴Initial H₂O contents in wt. %, compositions normalized to 100% in modelling.

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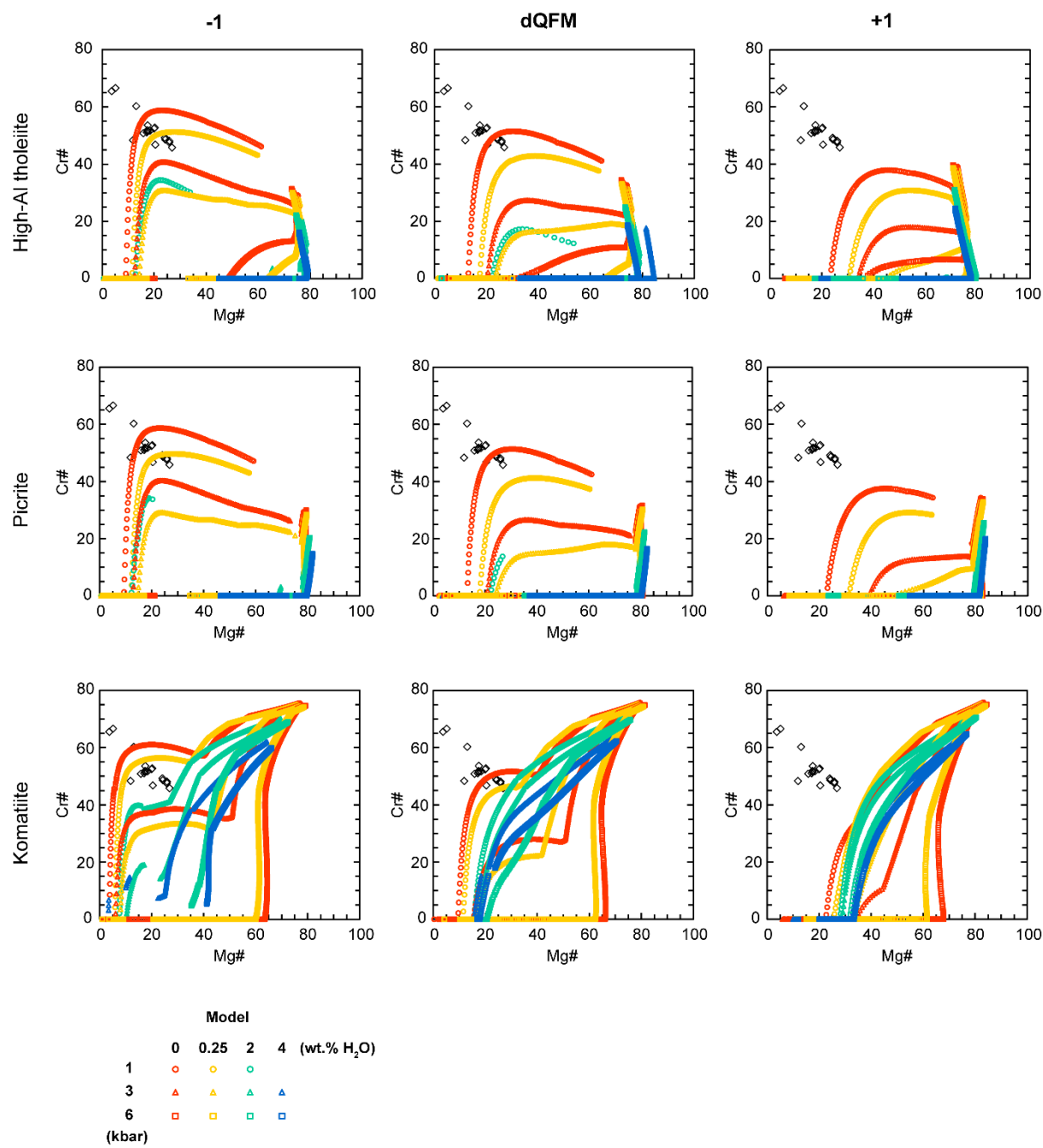
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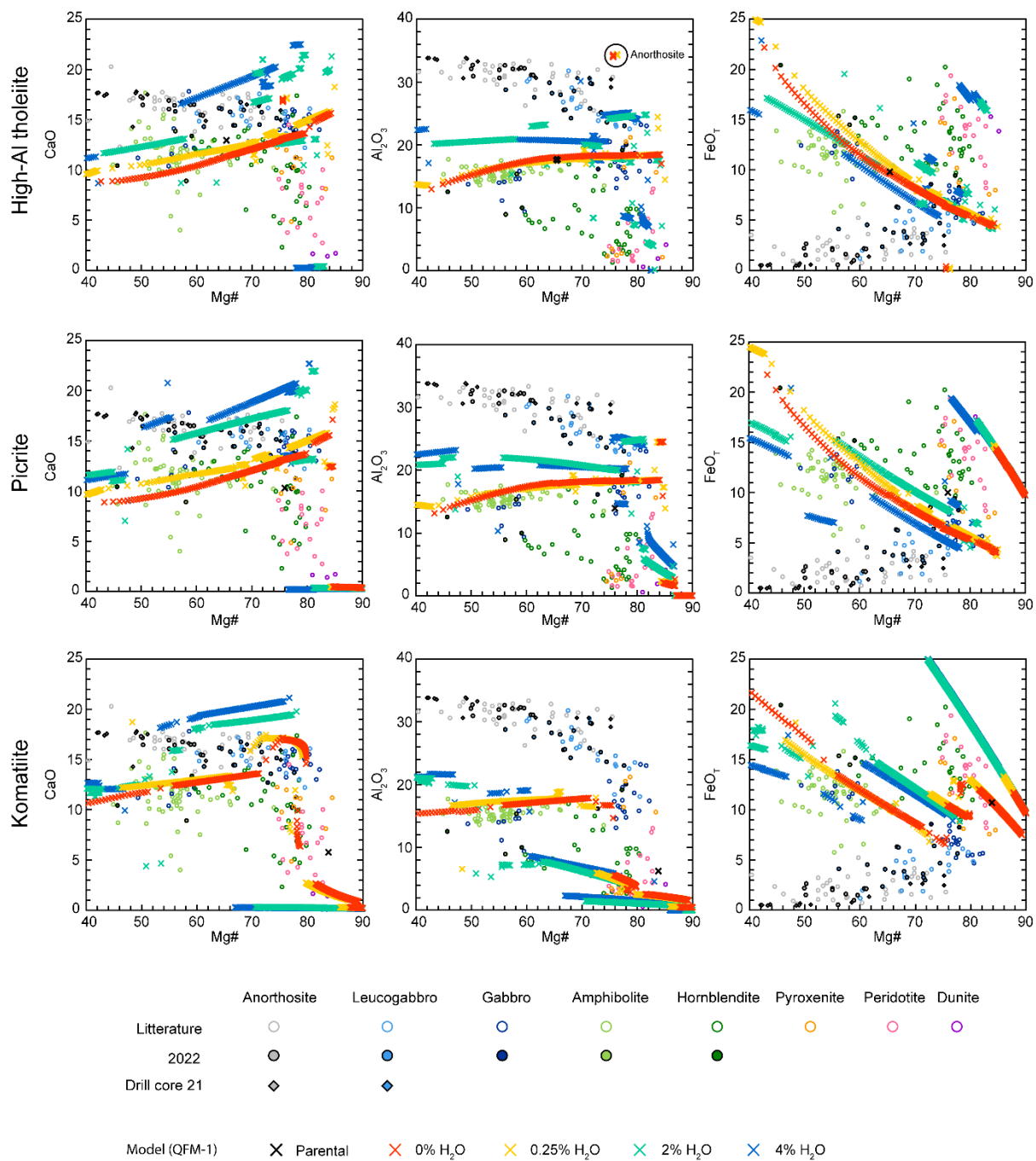
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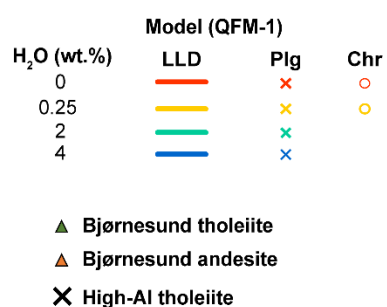
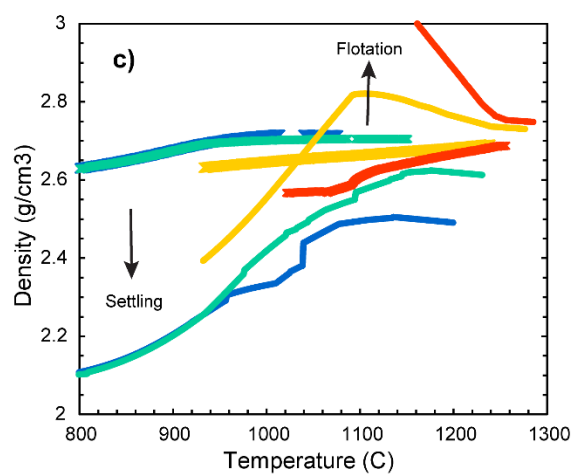
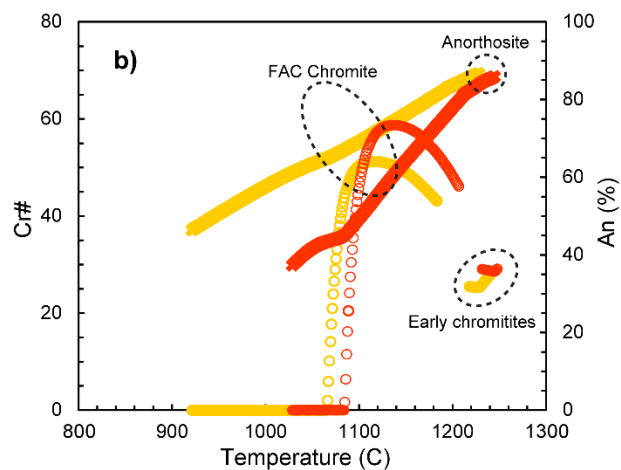
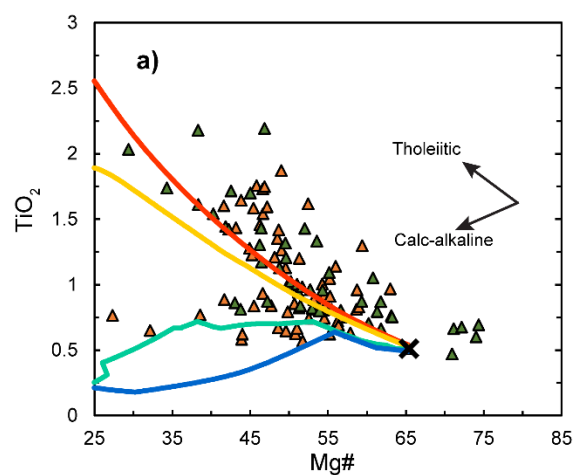
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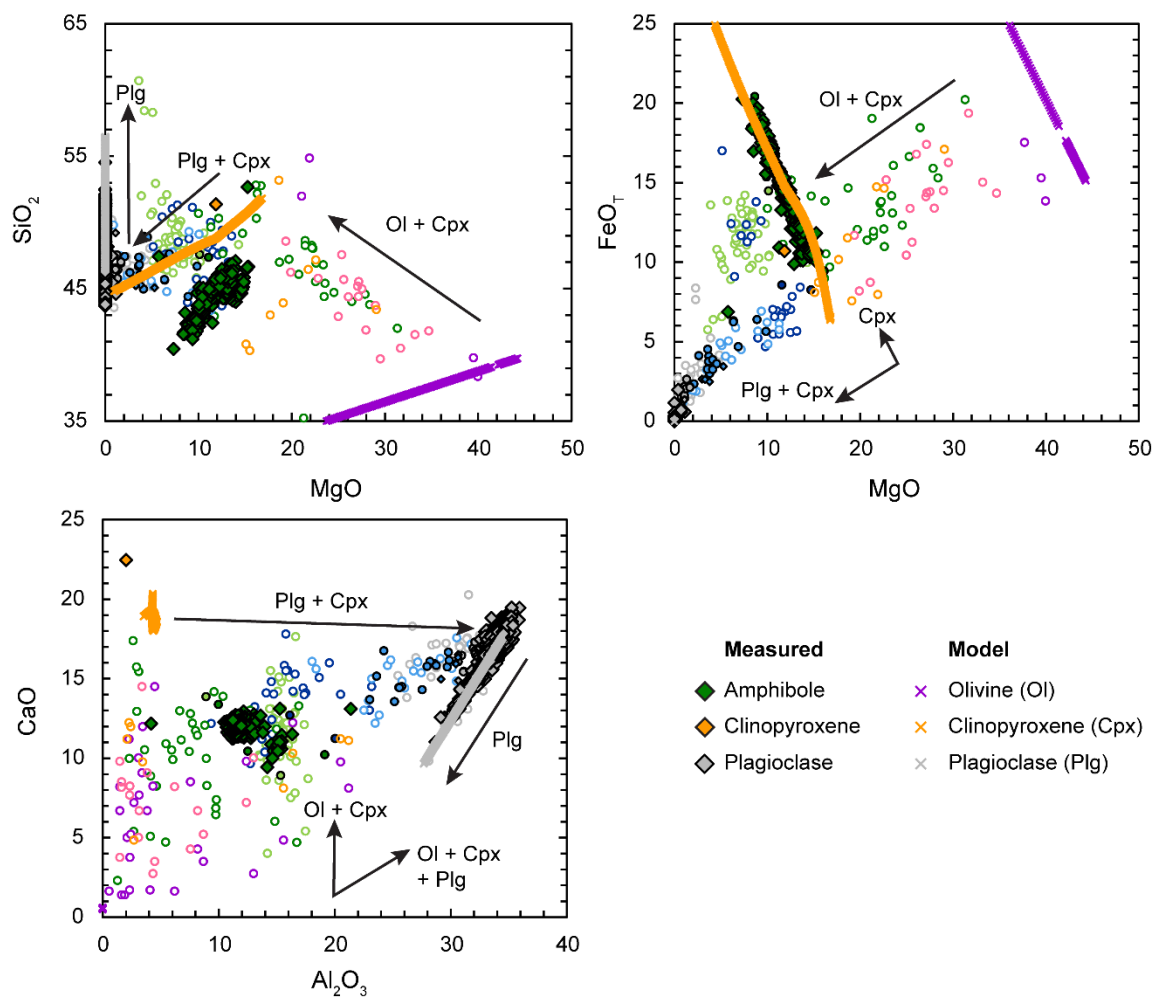
1336 **Table 3:**
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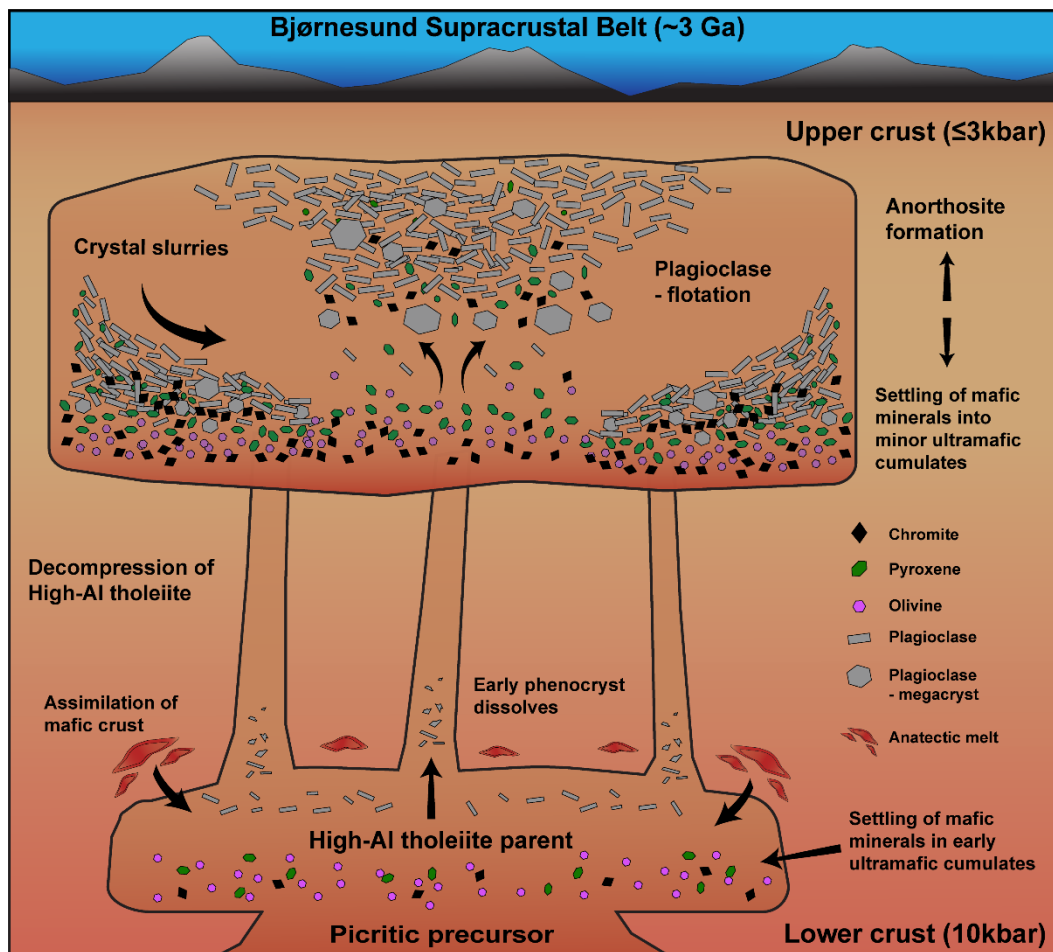
QFM	High-Al tholeiite				High-Mg andesite				Picrite				Komatiite			
H ₂ O(wt.%)	0	0.25	2	4	0	0.25	2	4	0	0.25	2	4	0	0.25	2	4
Field association with the FAC																
	Yes				Yes				No				No			
Reproduces similar high-An content of plagioclase in anorthosites, constrained from drill-core 21 (An _{87±1})																
1(kbar)																
2																
3																
4																
6																
8																
10																
Reproduces similar aluminous chromite as the anorthosite-hosted chromitites of the FAC																
1(kbar)																
3																
6																
Forms anorthosites with similar composition to the FAC by fractional crystallization																
1(kbar)																
3																
6																
Crystallization sequence dominated by plagioclase and pyroxene (i.e. minor ultramafic cumulates)																
1(kbar)																
3																
6																
Yes / Identical				Similar / Intermediate				No / Not similar				Model/ Plagioclase unstable				





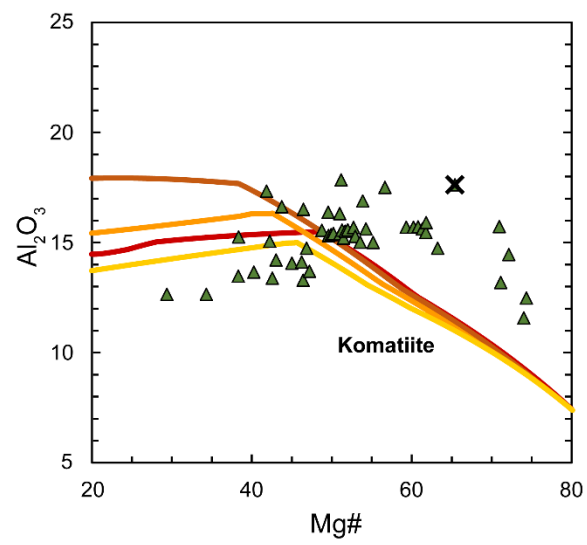
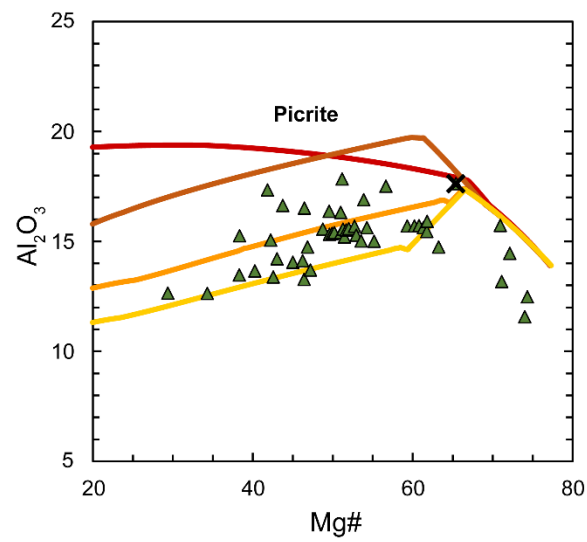






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LLD

1

3

6

10 (kbar)

▲ Bjørnesund tholeiite

✕ High-Al tholeiite

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