The Sveconorwegian Pegmatite Province – Thousands of pegmatites without parental granite

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Abstract

The Late-Proterozoic Sveconorwegian pegmatite province in south Norway and southwest Sweden hosts seven rare element pegmatite districts with more than 5000 rare-element pegmatites. Most of these pegmatites with Niobium-Yttrium-Fluorine(NYF) signature are not related to a parental granite, but instead occur in areas of high-grade metamorphism and are the result of migmatisation and local melt collection. There are three groups of pegmatites, (i) rare-element pegmatites related to HP-HT high-grade metamorphism associated with the assembly of the Sveconorwegian orogen; (ii) rare-element pegmatites related to post-orogenic extension with LP-HT granulites; and (iii) rare-element pegmatites related to granite magmatism during post-orogenic extension.

The pegmatite formation comprises principally four periods restricted to certain tectono-metamorphic domains: (I) 1094-1060 Ma (Bamble sector), (II) 1041-1030 Ma (Idefjord terrane), (III) 992-984 Ma (Idefjord terrane, Rogaland-Hardangervidda-Telemark sector), and (IV) 922-901 Ma (Rogaland-Hardangervidda-Telemark and Bamble sectors). The observed relationships between pegmatite formation and regional high-grade metamorphism reveal that the majority of Sveconorwegian pegmatites are formed by anatexis either by crustal stacking during different stages of continental/terrane collision (HP metamorphism) (periods I to III) or by mafic magma underplating (HT metamorphism) during orogenic extension (period IV). In several provinces that have been affected both by early HP metamorphism during continental collision and by late HT metamorphism during crustal extension, there may occur several generations of pegmatites that show mineralogical and geochemical affinity even though they formed during several periods. In addition, the results imply that the majority of Sveconorwegian NYF pegmatites are not necessarily formed in an anorogenic setting in relation to A-type magmatism but in compressional or extensional orogenic settings unrelated

to pluton-scale magmatism. Thus, the genetic criteria of the pegmatite family classification (NYF versus Lithium-Cesium-Tantalum[LCT]) have to be re-evaluated.

Introduction

The close genetic relationship between regional metamorphism and formation of granitic pegmatites during the evolution of orogenic belts has been demonstrated for a number of areas worldwide. In this setting pegmatite melts are generally considered to derive from large, parental granite intrusions via fractionation, melt immiscibility and volatile enrichment (Černý 1991a, 1991b, London 2008, Černý *et al.* 2012). The widely accepted genetic relationship between granites and granitic pegmatites bases on the common observation that swarms of pegmatites occur commonly in or around granite intrusions (Černý 1991c, Černý and Ercit 2005). Some of these swarms show distinct chemical zonation suggesting a genetic association and possibly a regional tectonomagmatic event (Fig. 1). Only some chemically primitive granitic pegmatites, also known as abyssal, barren, or ceramic pegmatites, are occasionally considered to have formed directly by anatexis as a result of regional high-grade metamorphism and when no spatially related granite pluton is exposed (*e.g.*, Jahns and Burnham 1969, Simmons and Webber 2008).

The Sveconorwegian pegmatite province is part of the Sveconorwegian (Grenvillian) orogen and covers most of southern Norway and parts of southwestern Sweden including the pegmatite districts of Hardanger, Mandal, Setesdal, Bamble, Nissedal, Buskerud, and Østfold-Halland (from west to east; Müller *et al*. 2015a; for definitions of pegmatite province, districts and fields see Černý 1982) (Fig. 2). The province hosts more than 5000 pegmatite bodies and represents one of the largest pegmatite clusters in the world. The pegmatites were mined for feldspar, quartz, white mica, Sc and Be from the 1860s until today and are famous for their rare metal mineralization including REE, Be, Sc, and Ta-Nb (Brøgger 1906, Bjørlykke 1937a).

The published ages of Sveconorwegian pegmatites show a large variation from c. 900 Ma to 1090 Ma (Baadsgaard *et al.* 1984, Romer and Smeds 1996, Cosca *et al.* 1998, Scherer *et al.* 2001, Seydoux-Guillaume *et al.* 2012). Considering the size of the Sveconorwegian orogen and the number of pegmatites exposed, the data set is very limited. However, from the few data available it seems that pegmatite formation within the Sveconorwegian orogen falls into several distinct age groups of contrasting regional distribution and – to some extent – of poorly known relation to regional tectonometamorphic events (Müller *et al*. 2015b).

For the Sveconorwegian Province of SW Sweden, pegmatites that seem to show a regional pattern of mineral assemblages, geochemical signatures, and development (e.g., Brotzen 1961, Smeds 1990) were shown to be unrelated to the traditionally assumed central granite. Instead, these pegmatites seem to show a regional distribution of pegmatite ages that possibly correspond to the various tectonic units (Romer and Smeds 1996). Here, we extend this initial study to comprise areas of southern Norway, testing both (1) the link between granite and pegmatite and (2) the regional age contrasts between different pegmatite districts within the Sveconorwegian Province. More specifically the study addresses the following working hypotheses: (1) If geochemically apparently related granites and pegmatites are not coeval, it is quite possible that the traditional model of extreme fractionation and the expulsion of late-magmatic fluids from parental granite intrusions describes only one process among several that produce rare element (RE) pegmatites and that a wide range of different processes actually may result in rather similar products, i.e., highly evolved RE pegmatites. That would mean that the existing models of pegmatite formation have to be extended to include models explaining the formation of RE pegmatites by direct anatexis and the RE element enrichment in small magma volumes. (2) If pegmatites of different tectonometamorphic segments of the Sveconorwegian orogen show systematic age contrasts, do these age groups reflect the overall large-scale tectonic development of the orogen or particular tectonic situations causing local migmatisation. To address these points, we determined emplacement ages of pegmatites from different tectonometamorphic domains of the Sveconorwegian orogen, i.e., the Rogaland-Hardangervidda-Telemark sector (Tors gruve, Hidra, Mølland, Steli), Bamble sector (Flekkerøy, Tangen), and Idefjord terrane (Karlshus, Vintergruben, Grebbestad).

Regional geology

The Sveconorwegian orogeny, known as Grenville orogeny outside Scandinavia, is one of the most significant orogenic events in Earth history. It occurred between 1.2 and 0.9 Ga ago (*e.g.*, Falkum 1985, Gower et al. 1990, Bingen *et al.* 2008a, Li *et al.* 2008, Slagstad *et al.* 2017). The main orogenic belt, which extended over at least 10,000 km, is defined by zones of continent-continent collision and accretion and re-amalgamation of fragmented and attenuated crustal blocks that eventually resulted in the assembly of the Rodinia supercontinent. The Sveconorwegian orogen represents the easternmost part of this belt. It consists principally of five lithotectonic units. In this study the nomenclature of Slagstad et al. (2017) is applied to these units including, from east to west, the Eastern segment, the Idefjord terrane, the Kongsberg sector, the Bamble sector and the Rogaland-Hardangervidda-Telemark sector (Fig. 2). These units are separated by roughly N-S-trending crustal scale deformation zones of Sveconorwegian age and differ from each other in their Pre-Sveconorwegian as well as their Sveconorwegian crustal evolution, regarding both timing and style of crustal growth, deformation, metamorphism and magmatism (Fig. 3, according to Bingen *et al*. 2008a). The Sveconorwegian orogeny resulted in widespread high-grade metamorphism, partial melting and deformation of the Fennoscandian crust during several phases, i.e., the Arendal, Agder, Falkenberg, and Dalane phases (Fig. 3; Bingen *et al*. 2006, 2008a). The oldest Sveconorwegian high-grade metamorphism is recorded in the 1.14 and 1.12 Ga Arendal granulites from Bamble and the more wide-spread 1.11 to 1.08 Ga amphibolite facies event, which also affected the Idefjord terrane and Kongsberg sector. This orogenic phase is referred to as the Arendal phase (Bingen *et al*. 2008a). During the Agder phase, amphibolite to granulite-facies metamorphism occurred at 1.05 to 1.02 Ga in the Idefjord terrane and at 1.04 to 0.97 Ga in the Rogaland-Hardangervidda-Telemark sector. In the western Rogaland-Hardangervidda-Telemark sector, the Agder phase was accompanied by voluminous 1.07 to 1.02 Ga old magmatism of the Sirdal Magmatic Belt (SMB; *cf*. Slagstad *et al.* 2013, Coint *et al.* 2015). The major compressional event of the Sveconorwegian orogeny resulted at 0.98 to 0.96 Ga in high-pressure granulite and eclogite facies metamorphism in the Eastern segment. This event is referred to as the Falkenberg phase and reflects continent-continent collision. Late-Sveconorwegian extension took place between 0.97 and 0.90 Ga during the Dalane phase (Bingen *et al*. 2006). Intense late- to post-orogenic magmatism during that period was restricted to (i) the Rogaland-Hardangervidda-Telemark sector with the Rogaland Igneous Province (RIC). The RIC consists of an anorthosite-mangerite-charnockite suite, the emplacement of which was associated with HT to UHT granulite facies metamorphism (Tobi 1985, Bingen and van Breemen 1998, Möller *et al*. 2003) and the Hornblende-Biotite Granite Suite (HBG) and (ii) the Idefjord terrane with the large-scale intrusions of the Iddefjord, Bohus and Flå granites (Fig. 4) (nomenclature: the tectonometamorphic domain 'Idefjord terrane' is traditionally spelt with "d" [Åhäll and Gower 1997, Åhäll et al. 1998] whereas the 'Iddefjord granite/pluton' with "dd" [Pedersen and Maaløe 1990]).

The Sveconorwegian pegmatite province covers most of the Sveconorwegian orogen in southern Norway and parts of southwestern Sweden. The pegmatite province consists of seven pegmatite districts, namely Mandal, Setesdal, Bamble, Nissedal, Hardanger, Buskerud, and Østfold-Halland, which may cross the boundaries between different lithotectonic domains

(Figure 4). However, the individual pegmatite fields within the districts are commonly restricted to certain sectors and segments. The pegmatites are generally classified as abyssal or barren pegmatites and rare metal pegmatites with Niobium-Yttrium-Fluorine(NYF) affinity. In some areas mixed NYF-Lithium-Cesium-Tantalum(LCT) types occur, particularly in the Tørdal region (Nissedal district) (Ihlen and Müller 2009a). In some areas, the pegmatite fields are spatially related to syn- to late-orogenic granite intrusions. Traditionally, these intrusions have been supposed to be the parental granites of the neighboring pegmatite fields for example in Evje-Iveland, Froland, Østfold and Tørdal. Romer and Smeds (1996) disproved such a genetic relationship between Østfold pegmatites and the Bohus granite. Shortly thereafter Andersen (1997) showed that the Herefoss and Holtebu granites are at least 120 Ma younger than the adjacent Froland pegmatites and more recently Snook (2014) and Müller *et al.* (2015a) demonstrated that the Høvringsvatnet granite is at least 50 Ma older than the spatially related Evje-Iveland pegmatites. Although several rare metal pegmatites occur within the Bohus-Iddefjord batholith (Brøgger 1906) and in similar granites elsewhere in southern Norway, some of these pegmatites may represent rafts of older pegmatites as for instance for the Froland pegmatite field, where the Herefoss granite cuts the anatectic pegmatites of the Froland-Lillesand pegmatite fields (Müller *et al.* 2008).

Description of sampling areas and previous pegmatite dating

Hardanger (Tors gruve)

The Hardanger pegmatite district, situated at the border of the Rogaland and Hardanger counties in western Norway, comprises several clusters of predominantly abyssal muscovite pegmatites with complex zoning (Ihlen and Müller 2009b). These vein-like, steep-dipping bodies of pegmatitic granite (very coarse-grained granite with up to 1 m large porphyritic K-feldspar megacrysts) contain randomly distributed megacrystic blocky zones that occasionally have a quartz core. Besides feldspar and quartz, the blocky zones contain large crystals of muscovite (5-40 cm), biotite (0.2-2 m) and garnet (2-20 mm). Some of the blocky zones contain albite replacement zones. The bodies segregate locally into muscovite-quartz veins. The host rocks comprise tonalitic and granodioritic orthogneisses together with gneiss of volcanosedimentary origin. The sampled pegmatite Tors gruve occurs near the village Øvre Vats at the eastern margin of the Haugesund pegmatite field (Ihlen and Müller 2009b). Garnet, gahnite and uraninite are characteristic accessory minerals of the Tors gruve pegmatite. There exist no age data on the pegmatites. The columbite-(Fe) investigated in this study has the Natural History Museum of Oslo collection number 17237.

Mandal (Hidra)

The abyssal and RE pegmatites of the Mandal district are scattered along or close to the coast between Egersund in the NW and Mandal in the SE. The most significant cluster occurs on Hidra island. The pegmatite field on Hidra includes RE pegmatites that are enriched in REE. About 15 sheet-like pegmatite bodies (up to 15 m thick) are exposed in numerous feldspar mines across the island (Fig. 5). The investigated columbite-(Fe) provided by the Natural History Museum of Oslo (collection nr. 17226) originates from one of these pegmatites. These pegmatites have been of interest for mineralogical research since their discovery, as illustrated by the description of type xenotime-(Y) (Berzelius 1824). Despite detailed mineralogical work, there is little earlier work focusing on the origin and emplacement of the pegmatite melts. The pegmatites are dominated by quartz, K-feldspar, plagioclase, albite, biotite, and muscovite and show simple zoning. Graphic textures are commonly developed in the wall zone. Some pegmatites contain a massive quartz core. Common accessory minerals include monazite-(Ce), allanite group minerals, aeschynite-(Ce), xenotime-(Y), and kainosite-(Y) (e.g. Neumann 1985). The pegmatites intruded the Hidra anorthosite, which is part of the RIC. Zircon from rocks of the RIC yields U-Pb ages of 932±3 to 920±3 Ma (Schärer *et al*. 1996). More recent studies provide a U-Pb zircon age of 949±7 Ma (Andersen and Griffin 2004) and an internal mineral Sm–Nd isochron age of 968±43 Ma (Bybee et al. 2014). There is no Sveconorwegian granite, which could be considered as source of the pegmatites, exposed in the area. Uraninite from the Rymteland (Romteland according to Barth 1931) pegmatite, 35 km SE of the Hidra island and 20 km NW of Mandal, yields a concordant ^{207}Pb/^{206}Pb age of 914±6 Ma (Pasteels *et al*. 1979). This pegmatite forms an isolated body of the Mandal district within Lyngdal hornblende granite with an emplacement age of 950±5 Ma (^{207}Pb/^{206}Pb; Pasteels *et al*. 1979).

Setesdal (Mølland, Steli)

The Setesdal district extends along the Setesdal valley from Kristiansand in the south to Bygland in the north. The Evje-Iveland field with its about 400 pegmatite occurrences (Svengestøl Corneliussen *et al*. 2016) is the most significant pegmatite cluster in the area (Fig. 6). The Evje-Iveland pegmatites are RE REE and muscovite RE REE pegmatites with NYF affinity consisting of K-feldspar, plagioclase, quartz, biotite, and muscovite with minor magnetite and garnet. Common accessory minerals are beryl, allanite-(Ce), monazite-(Ce), xenotime-(Y), zircon, almandine, spessartine, gadolinite-(Y), fergusonite-(Y), rutile, ilmenite, magnetite, euxenite-(Y), aeschynite-(Ce) and –(Y), polycrase-(Y), columbite-(Fe)-columbite-(Mn)-tantalite-(Fe)-tantalite-(Mn) series, and thortveitite (Andersen 1931, Barth 1931, 1947, Bjørlykke 1934, 1937a). The pegmatites are well zoned with a granitic wall facies, a megacrystic intermediate zone, and a core zone with massive quartz and feldspar, which may form several meters large crystals. Some of the pegmatites exhibit albite replacement zones with LCT affinity that in addition to the main minerals albite and muscovite also contain topaz, columbite group minerals, fluorite, garnet, beryl, quartz, and schorl (Frigstad 1999).

The pegmatites mainly are hosted by banded amphibole gneisses (1459±8 Ma Vånne banded gneiss), gabbroic amphibolites of the Iveland-Gautestad mafic intrusion (1285±8 to 1271±12 Ma), and the Flåt-Mykleås metadiorites (1034±2 Ma; Pedersen *et al*. 2009). A gadolinite from an unspecified pegmatite from the Evje-Iveland field yields an U/Pb age of 910±14 Ma (Scherer *et al*. 2001) and a monazite-(Y) from another unspecified pegmatite gives a ^{206}Pb/^{238}U age of 906±9 Ma (Seydoux-Guillaume *et al*. 2012). The pegmatites are spatially associated with the Høvringsvatnet granite intrusion, which has been re-dated to 983±4 and 980±4 Ma (U/Pb zircon; Snook 2014) superseding older age estimates of 945±53 Ma (Pedersen 1981) and 971+63/-34 Ma (Andersen *et al*. 2002a). The investigated columbite-(Fe) and columbite-(Mn) samples have the Natural History Museum of Oslo collection numbers 17180 (Mølland) and 17198 (Steli).

Bamble (Tangen, Flekkerøy)

The Bamble pegmatite district, which covers more or less the entire tectonometamorphic Bamble sector, has the highest density of pegmatite occurrences within the Sveconorwegian orogen. Main pegmatite fields are from SW to NE: Glamsland-Lillesand, Froland, Arendal, Søndeled, and Kragerø (Fig. 6). In addition, there are smaller clusters of pegmatites and isolated occurrences across the district as, for example, on Flekkerøy island at the southwestern tip of the district. According to the classification of Černý and Ercit (2005), the Bamble pegmatites comprise simple abyssal, primitive rare-element REE, and muscovite rare-element REE pegmatites with NYF affinity. A few pegmatites contain albite replacement zones and, therefore, are considered to be mixed NYF-LCT pegmatites, as for example the Tangen and Sjåen pegmatites near Kragerø. The mineralogy, mineral chemistry, structure, and genesis of the pegmatites have been extensively studied (Andersen 1926, 1931, Bjørlykke 1937a, Ihlen *et al.* 2001, 2002, Larsen *et al.* 2004, Henderson and Ihlen 2004, Müller *et al.*

2008). The pegmatites have variable contents of quartz, alkali feldspar, plagioclase, biotite, and subordinate white mica. Although accessory Y-REE-Nb-Th minerals generally are uncommon in these pegmatites, some pegmatite groups show rare mineral assemblages with monazite-(Y), xenotime-(Y), euxenite-(Y), aeschynite-(Y), fluorapatite, allanite-(Ce), schorl, thorite, and/or uraninite.

Only few pegmatites have been dated. The Gloserhei pegmatite in the Froland pegmatite field was dated at 1060+8/-6 Ma (U-Pb euxenite; Baadsgaard 1984). Cosca *et al*. (1998) published a discordant U-Pb allanite-(Ce) age (1128 Ma) for the Tvedestrand pegmatite in the Søndeled field. The same pegmatite was re-dated by Scherer *et al*. (2001) giving a 1094±11 Ma U-Pb xenotime-(Y) age. The late-Sveconorwegian Herefoss and Holtebu granites were dated at 926±8 Ma (Andersen 1997). They form a large composite intrusion with a diameter of about 15 km that separates the Glamsland-Lillesand and Froland fields.

The Tangen pegmatite belongs to the Kragerø field and lies 4 km W of the town Kragerø (Fig. 6). The zoned but irregular body is about 40 m long and up to 15 m wide and consists of quartz, oligoclase, and K-feldspar (Bjørlykke 1937b). Biotite and muscovite have not been observed. The pegmatite is characterized by several cleavelandite replacement zones that are particularly well-developed in the western part of the body. Accessory minerals include allanite-(Ce), magnetite, fluorapatite, zircon, phenakite, columbite-(Fe)-columbite-(Mn) series, schorl, and topaz. Columbite group minerals form beautiful crystals embedded in cleavelandite.

At Flekkerøy, an island 4 km south of Kristiansand, two muscovite-bearing pegmatites were exploited for K-feldspar at the turn from the 19^{th} to the 20^{th} century (Barth 1931). The investigated columbite-(Fe) originates from one of the mines, which is also rich in garnet. The pegmatites occur in amphibolite-facies amphibolites that are considered to be part of the Bamble sector The Porsgrunn-Kristiansand fault zone separating the Bamble sector from the Rogaland-Hardangervidda-Telemark sector runs to the north of Flekkerøy. The columbite-(Fe) sample investigated in this study has the Natural History Museum of Oslo collection number 17164.

Østfold-Halland (Karlshus, Vintergruben, Grebbestad)

The Østfold-Halland pegmatite district is situated in the eastern part of the Sveconorwegian orogen, crossing the Norwegian-Swedish border. The district extends more than 100 km in N-

S direction and consists of two major pegmatite fields, Rakkestad in Norway and Orust in Sweden (Fig. 7). The neighboring plutons comprise the Iddefjord and Bohus granites. Eliasson and Schöberg (1991) dated aplite-pegmatites in the Bohus granite at 919±5 Ma and 922±5 Ma ($^{206}Pb/^{238}U$ monazite-(Y) and xenotime-(Y)). Romer and Smeds (1996) published four pegmatite U-Pb ages from the southern part of the district including the Timmerhult (1038.7±3.4 Ma), Skantrop (1041.3±1.6 Ma), Högsbo (1029.7±1.4 Ma), and Skuleboda (984.3±6.4 Ma) pegmatites. The data revealed that these pegmatites are more than 50 Ma older than the granites.

The investigated pegmatites lie outside the major two pegmatite clusters at Rakkestad and Orust. The Karlshus pegmatite is hosted by the Iddefjord granite whereas the Vintergruben body occurs in amphibolitic gneisses c. 10 km NW of the Iddefjord pluton contact. Columbite-(Fe) from Grebbestad, located 50 km south of the Norwegian-Swedish border, was obtained from a small pegmatitic dyke within the Bohus granite. The studied columbite group minerals from Karlshus and Vintergruben have the Natural History Museum of Oslo collection numbers 17092 and 17103, respectively.

Results

Chemistry of columbite group minerals

The compositional variation of columbite group minerals (columbite-(Fe)-columbite-(Mn)–tantalite-(Fe)-tantalite-(Mn) solid solution series) is useful for mineralogical and genetic fingerprinting (Černý 1989, Černý and Ercit 1989, Melcher *et al*. 2008, 2015, 2016). Major and trace element contents of columbite group minerals were determined by EPMA. The analytical procedure and the concentration data are given in the supplementary material. The variation of the major elements Ta, Nb, Fe, and Mn plotted in the Ta/(Ta+Nb) vs. Mn/(Mn+Fe) diagram mainly reflects the general development of the pegmatite system with a shift to more Mn-rich and more Ta-rich minerals from the primitive sections of the pegmatite to the more evolved ones (Fig. 8; Černý 1989, Černý and Ercit 1989). Principally, the data follow two trends. Columbite-(Fe)-tantalite-(Fe) samples from Tors gruve and Karlshus roughly follow the evolution trend of "F-poor beryl type" pegmatites of Černý (1989), whereas columbite-(Fe)-columbite-(Mn) from Steli, Vintergruben, Tangen, and Mølland mark the chemical least-evolved segment of the "F-rich complex lepidolite" trend. According to Černý (1989) the "complex lepidolite" trend is typical for columbite group minerals occurring in complexly zoned, lepidolite-bearing pegmatites enriched in Li, Cs and Ta (LCT pegmatites). In general, Sveconorwegian pegmatites, however, have an overall NYF affinity with some pegmatites, including Vintergruben and Tangen, showing cleavelandite replacement zones with a LCT signature. Note, columbite group minerals from the Svecofennian NYF-type pegmatites fall in the same general fields, with the exceptions of samples from Rosendal-Skogsböle, Broddbo, and Stora Vika (Fig. 8c). The Rosendal and Skogsböle dikes have a clear LCT-type mineralogy and are hosted in gabbros that are restricted to a shear zone in the migmatite belt of southern Finland (Lindroos *et al*. 1996), the Stora Vika NYF-type dike cuts across marbles in a metasedimentary unit, and the topaz-bearing Broddbo rocks seem to be related to S-type migmatite granites.

There is a wide range of substitution and coupled substitutions possible in AB_2O_6 minerals, in particular including Y, Sc, W, Ti, Sn, and Zr at B sites, but also Ca, U, Sc, and REE at the A site (*e.g.*, Burt 1989). The substitution of these elements, although to some extent controlled by Ta/(Ta+Nb), reflects the availability of these elements for incorporation, i.e., represents a fingerprint of the source of the pegmatite melts and the conditions of melting. The contents of Sc, Ti, and Sn of Sveconorwegian and Svecofennian columbite group minerals show a positive correlation with Ta/(Ta+Nb) for Ta/(Ta+Nb) below c. 0.8 (Fig. 9). The contents of Sc, Ti, Sn, and Zr, which correlate with each other (Fig. 9), are low at low Ta/(Ta+Nb) values and increase to a maximum at intermediate Ta/(Ta+Nb) values (Fig. 9). There is a negative correlation between Sn and W. Enhanced W contents only occur at intermediate Ta/(Ta+Nb). The correlation of the contents of the various high-field strength elements indicates that substitution of one may facilitates the incorporation of other representatives of this element group. The possibility for simple or coupled substitution seems to be highest at intermediate Ta/(Ta+Nb) values. The positive correlation of Sn with Sc, Ti, and Zr and the negative correlation of Sn with W base on few Svecofennian samples. Sveconorwegian columbite group minerals have very low Sn and W contents (see also Melcher *et al*. 2016), which seems to reflect the limited availability of Sn and W rather than the restricted possibility to incorporate them. Columbite-(Fe)-columbite-(Mn) minerals from Mølland and in particular from Steli have markedly higher Sc contents than columbite group minerals from the other domains. The high Sc contents do not correlate with Ta/(Ta+Nb) (Fig. 9c). The high Sc contents reflect the availability of Sc and indicate that the incorporation of Sc is not restricted to the B site, but may also occur in the A site (*cf*. Burt, 1989).

U-Pb ages of columbite group minerals

Columbite group minerals typically have relatively high U contents that may substitute in the crystal structure for Fe and Mn or that may form micro-inclusions of uraninite or other U-rich Nb-Ta-minerals. A direct result of the high U content is that the mineral becomes increasingly metamict through time. Defects related to the decay of U and its instable daughter isotopes result in small metamict domains that initially are fully enclosed by intact columbite group minerals. With time, however, the number of the metamict domains increases and they start to overlap, forming a network of metamict zones, and eventually leading to a completely metamict mineral (*e.g.*, Romer 2003). This increasing metamictization leads to several problems relevant for dating, including: (i) loss of radiogenic Pb, (ii) addition of vagabonding Pb (of unknown isotopic composition) derived from the surrounding of the columbite group mineral or other parts of the crystal, (iii) recrystallization of metamict domains with the formation of secondary Nb-Ta-minerals (Romer *et al.* 2007) that may fractionate the U-Pb system of columbite group minerals. Romer and Wright (1992) and Romer and Smeds (1994, 1996) demonstrated that leaching (dilute HF followed by HCl and HNO_3) of the samples may result in the selective removal of the metamict domains and leave a residue that yields concordant U-Pb ages. Such columbite group minerals giving concordant age have very low contents of common Pb, as columbite group minerals have no suitable lattice sites to accommodate large Pb ions. Incomplete leaching of columbite group minerals, however, not only results in discordant data, but typically also shows high contents of common Pb. These high contents of Pb typically derive from sulfide or feldspar inclusions and from additions of external Pb of unknown composition to the metamict domains. Leached fragments of columbite group minerals show holes and fractures after dissolved micro-inclusions of uraninite and quartz-filled fractures and variably abundant elongate holes and grooves that are leached fission tracks (Romer and Smeds 1996, Romer 2003). The abundance of these tracks directly reflects the distribution of U in the crystal. Small fragments of columbite group minerals that are thoroughly leached yield concordant age data (*e.g.*, Romer and Smeds 1996, Lindroos *et al.* 1996, Baumgartner *et al*. 2006).

Sveconorwegian columbite group minerals from southern Norway are unusual, as leaching typically did not produce surfaces with metallic luster. Instead, the leached crystals have a rusty stain. A second or a third cycle of leaching only produced rare fragments with perfectly metallic surfaces. Generally, the rusty stained domains could not be removed completely. Fragments with such rusty domains do not yield concordant U-Pb ages. Instead, they yield variably normally or reversely discordant data. In some cases reverse discordance may be significant. The rusty domains reflect metamict parts of the mineral that have not been completely dissolved during attack with dilute HF and from which Pb or U was leached during HCl and HNO_3 wash. The more pervasive distribution of metamict domains in the Sveconorwegian columbite group minerals of southern Norway reflects the overall higher content of lattice-bound U in these minerals in comparison to those from the Sveconorwegian domain of southern Sweden and the Svecofennian domain of Sweden (Romer and Smeds 1994, 1996). The higher contents of lattice-bound U do not necessarily indicate higher availability of U, but may reflect the higher potential to incorporate larger amounts of U in the crystal lattice due to compositional differences (e.g., W, Sn, Ti, REE).

Recrystallization with the formation of secondary Nb-Ta minerals is observed in many columbite group mineral crystals. Such recrystallization may be related to late magmatic fluids that alter earlier formed minerals. But it also may be related to strongly metamict mineral domains. In this case, recrystallization is much younger than the mineral, as metamicization is a cumulative process that takes time. Columbite groupcrystals with perfect oscillatory zoning in BSE images, reflecting variations in Ta/Nb, have not recrystallized. In contrast, minerals whose oscillatory zoning has been partially destroyed have experienced recrystallization. In metamict domains, such post-emplacement recrystallization also results in the redistribution of U and Pb between the newly formed mineral and the rest. If the newly formed mineral is a U-hosting Nb-Ta-mineral that is not accessible for leaching, such recrystallization may generate a discordant system that remains discordant even after extensive leaching. Ionic diffusion is much faster in metamict domains than in intact crystalline material. This allows for long-lived intermediate daughters in the ^{238}U decay series (*e.g.*, ^{222}Rn, ^{226}Ra) to migrate before decaying, which eventually leads to a contrasting behavior of the ^{238}U-^{206}Pb and the ^{235}U-^{207}Pb systems (*e.g.,* Ludwig and Simmons 1991, Romer 2001). Intermediate daughter mobility, thus, may account for excess scatter in apparent ^{207}Pb/^{206}Pb ages (Romer 2003).

One or several of these open-system features may apply to the dated columbite group minerals. Contrasting removal of U and Pb during leaching results in the displacement of the data points along a line through the origin of the concordia diagram. Excess scatter about a discordia fitted to all data from one sample may be related to the formation of secondary U-bearing Nb-Ta-minerals or the uncoupling of the ^{238}U-^{206}Pb and the ^{235}U-^{207}Pb decay systems. As the unconstrained discordia lines pass within error though the origin of the diagram, disturbances related to leaching seem to dominate over other disturbances. Therefore, the most robust ages for these samples is obtained for a discordia forced through the origin of the concordia diagram. The uncoupling of the ^{238}U-^{206}Pb and the ^{235}U-^{207}Pb decay systems is mainly reflected in the excess scatter of the discordia or the clustering of the data along a short segment of the concordia.

Most samples define in the $^{206}Pb/^{204}Pb$ – $^{207}Pb/^{204}Pb$ diagram secondary lead isochrones that are within error identical with the ages obtained from the discordia intercept and that generally have a smaller age uncertainty. Because of above described possibilities of open system behavior of the U-Pb system, the slope of such lead lines in part may be affected by such disturbances, whereas the small uncertainty in age is largely due to the large range in $^{206}Pb/^{204}Pb$. We report in the following only the discordia intercept ages that have larger uncertainties and, therefore, represent more conservative age estimates.

Tors gruve. The twelve analyzed fragments define a scattered discordia that intersects at 985 ± 17 Ma and –4 ± 59 Ma (2σ; MSWD = 41). Most of the excess scatter comes from one sample with a distinctly lower $^{207}Pb/^{206}Pb$ age (Table 1). This sample also has a distinctly higher common Pb content resulting in a lower $^{206}Pb/^{204}Pb$ value (Table 1). The common Pb contents (ranging from <1 to > 1000 pg, Table 1) do not correlate with discordance or uranium content. The U contents of leached columbite group mineral samples of 70 to 160 (400) ppm does not correspond to U concentrations of the untreated crystals. As the lower intercept passes within error through the origin of the concordia diagram, the data pattern seems to reflect largely incomplete removal of metamict domains and addition of "vagabonding" Pb, whereas the U-Pb system bound to secondary minerals or the redistribution of intermediate U daughters seems to be less important. Most samples have a very low $^{232}Th/^{238}U$ ratio, which is typical for columbite group minerals (Romer and Wright 1992, Romer and Smeds 1994, 1996), in the range 0.0041 to 0.0063. The slightly higher values of 0.0097 and 0.0208 of two samples indicate that the columbite group mineral was not completely homogeneous or may have acquired vagabonding Pb with a higher $^{208}Pb/^{206}Pb$. Omitting sample Tor-4, which has a higher calculated $^{208}Pb/^{206}Pb$ than the other samples, from the calculation of the discordia yields an upper intercept at 991.6 ± 3.6 Ma and a lower intercept at –15 ± 12 Ma (2σ; MSWD = 16). We interpret this age of 991.6 ± 3.6 Ma (2σ) as the crystallization age of columbite-(Fe)-tantalite-(Fe) from Tors gruve (Fig. 10a).

Hidra. Leached columbite-(Fe) from Hidra has relatively high U contents (370 to 630 ppm) and variable, but generally high, contents of common Pb (300 to 800 pg Pb correspond to 1.0 to 3.8 ppm, Table 1). Most samples have similar Th/U ratios ($^{232}Th/^{238}U$ = 0.0040 to 0.0053). Samples with different Th/U also have slightly different Pb isotopic compositions, which most notably result in distinctly higher or lower apparent $^{207}Pb/^{206}Pb$ ages (Hid-6, Hid-

10). The discordia defined by all samples yields intercept ages at 912.9 ± 6.0 Ma and 3 ± 100 Ma (2σ; MSWD = 28). Omitting samples Hid-6 and Hid-10 reduces scatter significantly and yields intercepts at 910.7 ± 3.1 Ma and 2 ±50 (2σ; MSWD = 15). Sample Hid-6 is concordant at 905 Ma, whereas sample Hid-10 is discordant at an older age than the upper intercept of the discordia. The discordia is essentially constrained by normally and reversely constrained samples, whereas the high MSWD is largely due to the concordant and sub-concordant samples that generally have slightly older $^{207}Pb/^{206}Pb$ ages than the discordia intercept (Fig. 10b). The high "vagabonding" Pb contents have been calculated based on ^{204}Pb and assuming a typical Sveconorwegian common Pb composition. If, however, this Pb had been introduced into metamict domains of columbite-(Fe), it may have more radiogenic composition, the actual contents of "vagabonding" Pb are not only higher, but also may affect the upper intercept of the discordia. In this case, the age of the analyzed columbite-(Fe) from Hidra would be slightly older and may be in the range of 915 to 919 Ma. We prefer this slightly older age. It should be noticed that this preference does not affect any of the conclusions made in this paper.

Flekkerøy. Nine columbite-(Fe) fragments from Flekkerøy define a discordia with intercepts at 915.4 ± 1.6 Ma and 9 ± 15 Ma (2σ; MSWD = 8; Fig. 10c). Most of the samples plot reversely discordant. Although the samples have contrasting contributions of common Pb, the samples have similar Th/U ratios ($^{232}Th/^{238}U$ = 0.0045 to 0.0073) and apparent $^{207}Pb/^{206}Pb$ ages (912 to 918 Ma). Thus, the discordance is interpreted to reflect incomplete removal of metamict domains and the discordia intercept at 915.4 ± 1.6 Ma (2σ) is our best age estimate.

Mølland. The analyzed samples of leached columbite-(Mn) from Mølland are particular in their high U content (700 to 1300 ppm) and rather homogeneous $^{232}Th/^{238}U$ ratios (0.0110 to 0.0126; except for sample Møl-9 with 0.129). Apparent $^{207}Pb/^{206}Pb$ ages, which range from 897 to 905 Ma and account for the excess scatter of the discordia, show no systematic relation with normal and reverse discordance and may be caused by mobility of intermediate U-daughters in metamict domains. The 10-point discordia intersects the concordia at 900.7 ± 1.8 Ma (2σ; MSWD = 10.8) and –1 ± 28 Ma (Fig. 10d). We interpret the upper intercept of 900.7 ± 1.8 Ma (2σ) as emplacement age of the pegmatite.

Steli. The analyzed sample from Steli shows a broad range of normal and reverse discordance with a general tendency of smaller samples to the less discordant, which may indicate that metamict domains in the sample interior are more efficiently removed from smaller fragments. Most of the excess scatter is due to one sample with a distinctly higher apparent $^{207}Pb/^{206}Pb$ age (Tve-1, Table 1). This sample also has a distinctly higher $^{232}Th/^{238}U$ ratio (0.0614) than the other samples (0.0047 to 0.0091). Omitting this sample from the discordia significantly reduces the scatter (4 ± 59 and 913 ± 13 Ma 2σ, MSWD = 57), but does not affect the intercept ages significantly (–1 ± 32 and 910.2 ± 7.1 Ma 2σ, MSWD = 27). Similar to the samples from Hidra, the concordant and sub-concordant samples from Steli tend to fall in a cluster with a relatively broad range of apparent $^{207}Pb/^{206}Pb$ ages (897 to 927 Ma). Most of these concordant samples have slightly older ages than the intercept age of the discordia, indicating that a slightly older age in the range of 913 to 919 possibly is a better age estimate than the intercept age.

Tangen. Columbite-(Fe)-columbite-(Mn) from Tangen differs from other Sveconorwegian columbite group minerals by its markedly older age (1082.3 ± 4.5 Ma 2σ, MSWD = 28) and its unusually high Th contents in the leached samples (14 to 90 ppm Th, based on measured U contents and $^{232}Th/^{238}U$ of 0.040 to 0.129; Table 1). Although the discordia defined by the analyzed 11 samples shows significant excess scatter, there is no obvious outlier and the lower intercept passes within error through the origin of the diagram. The intercept age of 1082.3 ± 4.5 Ma (2σ) represents the best estimate for the emplacement age of the Tangen pegmatite.

Karlshus. Leached columbite-(Fe)-tantalite-(Fe) fragments from Karlhus yield normally discordant and concordant data. The ten samples define a highly scattered discordia that intercepts at 904 ± 11 Ma and 109 ± 58 Ma (2σ, MSWD = 122). The non-zero lower intercept and the large scatter are due to three samples that have markedly younger apparent $^{207}Pb/^{206}Pb$ ages and are characterized by higher $^{232}Th/^{238}U$ values (0.0085 to 0.0436) than the other samples (0.0050 to 0.0057). Omission of these samples yields an upper intercept age of 906.3 ± 5.9 Ma (2σ, MSWD = 41). Note, the five concordant samples do not overlap, but form a cluster along the concordia that indicates that there may have been some intermediate daughter mobility and that the discordia intercept may be slightly too young. The Karlhus pegmatite possibly may be as old as 915-917 Ma.

Vintergruben. Columbite-(Fe) from the Vintergruben pegmatite is rather homogeneous with narrow ranges in U contents, Th/U ratios, and apparent $^{207}Pb/^{206}Pb$ ages. The discordia intercepts at 908.9 ± 1.4 and -13 ± 12 Ma (2σ, MSWD = 5.6). Concordant samples scatter along the concordia at a slightly older apparent $^{207}Pb/^{206}Pb$ age (910.3 ± 0.9 Ma, 2σ) than the intercept age (Fig. 10h), whereas the variably discordant samples have slightly younger apparent $^{207}Pb/^{206}Pb$ age (906.4 ± 0.6 Ma, 2σ). This apparent contrast in apparent $^{207}Pb/^{206}Pb$

ages indicates that there had been some mobility of intermediate daughter isotopes of the ^{235}U and ^{238}U decay series,

Grebbestad. Only a very tiny columbite-(Fe) crystal was available for dating and after leaching only sufficient material for one single fraction was left. This sample yields a concordant point with a $^{206}Pb/^{238}U$ age of 921.8 ± 3.4 Ma (2σ). This sample has a relatively high measured $^{206}Pb/^{204}Pb$ value, a low common Pb content, and a low $^{232}Th/^{238}U$ ratio (0.0056). As the latter two suggest that there was no addition of vagabonding Pb, we interpret this age of 921.8 ± 3.4 Ma (2σ) to represent the age of the pegmatite. This age is identical with the $^{206}Pb/^{238}U$ ages of 922 ± 5 and 919 ± 5 Ma U of monazite-(Y) from an aplite-pegmatite within the Bohus granite (Eliasson and Schöberg 1991), some 30 km to the south of the Grebbestad location. Eliasson and Schöberg (1991) interpreted this age to date the crystallization of the Bohus granite.

Discussion

Sveconorwegian pegmatites in relation to magmatic events

Table 2 summarizes published and new age data of Sveconorwegian pegmatites. Pegmatite formation falls principally into four periods:

(I) 1094-1060 Ma (3 pegmatites; Bamble sector)

(II) 1041-1030 Ma (3 pegmatites, Idefjord terrane)

(III) 992-984 Ma (2 pegmatites, Idefjord terrane and Rogaland-Hardangervidda-Telemark sector)

(IV) 922-901 Ma (9 pegmatites, Rogaland-Hardangervidda-Telemark and Bamble sectors, Idefjord terrane)

Pegmatites are generally very rare in the Eastern segment and the Riddabo pegmatite is the only one of them that has been dated so far. With an age of 942 Ma, this pegmatite possibly represents a temporally and regionally isolated event at the NE edge of the orogen (Fig. 11).

The traditional model for RE pegmatite genesis involving a parental granite with a zoned pegmatite field with increasingly more evolved pegmatites at larger distance from the granite (*e.g.*, Černý 1991a, 1991b, London 2008, Černý *et al*. 2012) directly implies that the granite and the pegmatites should have essentially the same age. Examples for such pegmatite fields include the Archean Yellowknife pegmatite field, Northwest Territories, Canada (Černý

1991c), the Archean Rush Lake pegmatite group of the Cat Lake–Winnipeg River pegmatite district, Manitoba, Canada (Goad and Černý 1981), the Variscan Fregeneda-Almendra pegmatite field, Spain (Roda-Robles 1999) and the the Albera pegmatite field, Pyrenees, France (Malló *et al*. 1995). In the Sveconorwegian orogeny, only few pegmatites of the Østfold-Halland district show such an age relation (Table 2). In contrast, rare-element pegmatites that do not show a close temporal and chronological relation to a parental granite, most likely did not form as evolved late-stage melts, but may represent highly enriched minimum melts in migmatite belts. Examples are the pegmatite province of Borborema, Brazil (*e.g.,* Beurlen *et al.* 2014), Maine, USA (*e.g.,* Simmons *et al*. 1996, 2013) and Alto Ligonha, Mozambique (*e.g.,* Cronwright 2014).

Most rare-element pegmatites of the Sveconorwegian orogenic belt are spatially not related to granites. Actually, granites that are emplaced within the same tectonic segment as the pegmatite field typically are younger (Idefjord, Bamble) or older (Rogaland-Hardangervidda-Telemark) than the pegmatites and do not show a close spatial relation to the pegmatites with the exception of the Evje-Iveland, Froland and Tørdal fields. Pegmatites that formed during the periods I, II and III are not related to granitic plutonism, whereas period IV pegmatites overlap and partially post-date the wide-spread HBG magmatism in the Rogaland-Hardangervidda-Telemark sector and Idefjord terrane (Fig. 3). Pegmatites of period IV, however, seem to be restricted to the SW Rogaland-Hardangervidda-Telemark sector (Hidra, Evje-Iveland, and Farsund pegmatites) and the Iddefjord and Bohus HBG granites of the Eastern segment, with the exception of the Flekkerøy pegmatite (4 km S of Kristiansand) that seems to be hosted by amphibolites of the Bamble sector. The position of the Flekkerøy pegmatite, however, is unclear as it is located a few hundred meters south of the Porsgrunn-Kristiansand fault zone, which is separating the Bamble sector and the Rogaland-Hardangervidda-Telemark sector (Starmer 1991). The rocks on both sides of the shear zone are similar in this area and resemble rocks of the Rogaland-Hardangervidda-Telemark sector.

The pegmatites from Hidra, Evje-Iveland, Farsund, and Flekkerøy occur E to SE of RIC, with the Hidra field being situated within the RIC (Fig. 11). The RIC emplaced between 1011 and 917 Ma (Schärer *et al.* 1996, Andersen and Griffin 2004, Bybee *et al.* 2014), prior to or almost simultaneously with the pegmatite emplacement. The emplacement of the RIC falls together with regional low-pressure high-temperature granulite facies metamhorphism (“M2”, Bingen *et al.* 2008a) dated at 927±7 Ma (Möller *et al.* 2003). Whether the RIC caused the metamorphism (the metamorphic high-grade isogrades [osumilite and pigeonite] are more or less parallel to the RIC contact) or the RIC intruded the already ductile reacting

(metamorphosed) area is still a matter of discussion (*e.g.*, Bingen *et al.* 2008b). Whatever the heat source of the area was, the formation of the pegmatite melt is related to the M2 event. Because there is no indication of HBG granites in the area, which could act as source of the pegmatites, it is likely that the pegmatite melts formed by low-degree partial melting of amphibolitic rocks as suggested by Müller *et al.* (2015a) for the Evje-Iveland pegmatites.
-IV pegmatites in the Idefjord terrane. Vintergruben, Karlshus, and Grebbestad (Østfold-Halland district) are located within or close to the HBG granites of Iddefjord and Bohus. In these cases the pegmatite are spatially and temporally related to the HBG granites. Pegmatites of the Orust-Trollhättan area (period II) north of Gothenburg (Timmerhult, Skantrop, Skuleboda), however, are 51 to 113 Ma older than the neighboring Bohus granite (Table 2). Thus, there are two pegmatite generations in the Østfold-Halland district: an older generation (period II) formed by anatexis and a younger, pluton-related generation (period IV).

Sveconorwegian pegmatites in relation to metamorphic events

The Grenville orogen, of which the Sveconorwegian orogen is the easternmost part, is generally interpreted as a result of the collision of Laurentia and Amazonia at c. 1.1 Ga. In the Grenville Province, Canada, two major orogenic events are distinguished: (1) the collision-stage of the Ottawan phase (1090 –1020 Ma) including orogen collapse at ca. 1020 Ma and (2) the Rigolet phase (1010–980 Ma), which involved renewed contraction and further collapse (Rivers 2008). During the Ottawan phase most allochthonous medium-pressure segments formed at 1090–1050 Ma, whereas the allochthonous low-pressure segments were formed at from 1050 to 1020 Ma. Based on only a very few age data the formation of the Grenvillian pegmatites seems to be limited to two periods: from 1060 to 1050 Ma (Bussy *et al.* 1995, Ketchum *et al*. 1998, Lentz and Creaser 2005, Easton and Kam 2008) and from 1000 to 940 Ma (Černý 1990, Corfu and Easton 2001). Both periods represent the transitional orogenic stage from thrusting and migmatization to orogenic extensional collapse and delamination. The Grenvillian pegmatites display commonly NYF signature, with particular abundance of U (Černý 1991c). Černý (1991c) concluded that the pegmatites might have anatectic origin because potential igneous parents of several pegmatite fields, such as the Bancroft-Renfrew field, were not identified in the field or geochemically..

For comparison, in the Sveconorwegian Province the oldest high-grade metamorphism (Arendal phase) occurred locally at 1140 to 1120 Ma and more widespread at 1110 to 1080 Ma in the Bamble sector, which also affected the Idefjord terrane and Kongsberg sector

(Figure 3; Bingen *et al.* 2008a). Amphibolite to granulite-facies metamorphism (Agder phase) is recorded from Idefjord terrane at 1050 to 1020 Ma and from Rogaland-Hardangervidda-Telemark sector at 1040 to 970 Ma. The major compressional event of the Sveconorwegian orogeny resulted at 980 to 960 Ma in high-pressure granulite and eclogite facies metamorphism in the Eastern segment (Falkenberg phase). Late-Sveconorwegian extension took place between 970 and 910 Ma during the Dalane phase (Bingen *et al.* 2006). The intense late- to post-orogenic anorthosite and HBG magmatism during that period was restricted to the Rogaland-Hardangervidda-Telemark sector, which coincidences with high- to ultrahigh-temperature granulite facies metamorphism (Tobi *et al.* 1985, Bingen and van Breemen 1998, Möller *et al*. 2003). Large HBG granite intrusions occur also in the Idefjord terrane (Fig. 4).

The range of absolute ages for metamorphism and orogenic relaxation of the Grenville Province is remarkably similar to the Sveconorwegian domains (*e.g.*, Cosca et al. 1991, Mezger *et al*. 1992, 1993, Tuccillo *et al*. 1992, McLelland *et al.* 2010). The Ottawan phase coincides with the Arendal and Agder phase developed in the Idefjord terrane and Kongsberg and Bamble sectors (Fig. 3). The formation of the Ottawanian (Grenvillian) pegmatites (1060 to 1050 Ma) resembles the period I (1094-1060 Ma) of the Sveconorwegian pegmatite formation. The Rigolet phase overlaps with the amphibolite- to granulite-facies metamorphism (M1) of the Telemark Domain. Grenvillian pegmatites emplaced during the late stage of the Rigolet phase (1000-940 Ma) correspond temporally to that of period III (992-984 Ma) of Sveconorwegian pegmatites. Pegmatites resembling the Sveconorwegian periods II and IV have been not recorded so far from the Grenville Province, and the young HT-LP granulite-facies (M2) metamorphism and the HBG and RIC magmatic events have no temporally equivalents in Canada. These observations provide compelling evidence that Baltic and Laurentia experienced a similar or perhaps the same middle Proterozoic orogenic evolution and, thus pegmatite-forming events before their eventual breakup.

In the following the relationship between pegmatite formation events (periods I-IV) and regional metamorphism in the Sveconorwegian part of the Grenville orogen is discussed more in detail.

Period I (1094-1060 Ma) of pegmatite formation is related the early Sveconorwegian amphibolite-facies metamorphism between 1140 and 1080 Ma in the Bamble and Kongsberg sectors (Arendal phase; Cosca *et al.* 1998, Bingen *et al.* 2008b). The event is interpreted to be a result of crustal thickening (thrusting) due to collision of the Sveconorwegian terranes onto the Baltic shield. Heating of the thickened crust eventually resulted in melting of lower sections of the thickened crust. However, there is no significant plutonism recorded for this period except the wide-spread pegmatite formation in the Bamble and Kongsberg sectors. In fact, period I is a period of plutonic quiescence at the scale of the orogen (Fig. 3; Bingen *et al.* 2008a). The slight delay of pegmatite melt formation in relation to the peak metamorphism (1110-1090 Ma) suggests that the melts collected during the initial stage of tectonic unroofing. In the case of the Froland field the anatexis was related to progressive, subhorizontal compressional deformation along the Porsgrunn-Kristiansand Fault Zone causing thrusting-enhanced crustal melting (Henderson and Ihlen 2004, Müller *et al.* 2015a). The clustering of other contemporary pegmatites in Bamble and Kongsberg sectors (Fig. 6) imply a similar structure-controlled formation of pegmatite melts.

Period II (1041-1030 Ma) comprises only pegmatites of the Halland field in the Idefjord terrane North of Gothenburg, Sweden (Romer and Smeds 1996; Fig. 11). The pegmatite formation coincides with the high-pressure amphibolite- to granulite-facies metamorphism between 1050 and 1025 Ma (Agder phase; Bingen *et al*. 2008b) and is unrelated to the neighboring Bohus granite due to the age difference of more than 100 Ma (Table 2). Pegmatite formation, which is interpreted as the result of lower-crust anatexis, is slightly younger than peak metamorphism (~1050 Ma). The N-S to NW-SE alignment of the Østfold pegmatites parallel to major, orogeny-parallel shear zones (Fig. 7) suggests a tectonic control of the melt formation and assembly.

During period III (984-992 Ma) the Rogaland-Hardangervidda-Telemark sector of was affected by intermediate-pressure regional amphibolite metamorphism between 1035 and 970 Ma (M1 event, Agder phase; Bingen *et al*. 2008b). SIMS monazite dates at 1032 ±5 and 990 ±8 Ma in a granulite, situated in the central-western Rogaland-Hardangervidda-Telemark sector, north of the area affected by the M2 metamorphism, demonstrate granulite-facies conditions in some areas during M1 metamorphism (Bingen *et al*. 2008b). The recorded granulite-facies conditions are relatively close to the Tors Gruve suggesting anatectic origin of the pegmatite. However, neither a regional metamorphic event nor a major plutonic event is recorded in the Idefjord terrane where the Skuleboda pegmatite emplaced at 983 Ma. Romer and Smeds (1996) concluded that the formation of the Skuleboda pegmatite is related to the post-kinematic consolidation of the Sveconorwegian Province. It implies that the pegmatite provides a minimum age for the last major thrusting in the compressional phase of the Sveconorwegian orogeny.

Period-IV pegmatites (901-922 Ma) formed at the end of a period of voluminous late orogenic HBG magmatism peaking at ca. 930 Ma (*e.g.*, Vander Auwera *et al*. 2011) and, thus, it is the only pegmatite-forming period of the Sveconorwegian orogenesis which temporally coincidences to (late-)orogenic magmatism. The magmatism is related to late Sveconorwegian orogenic extension (Dalane phase). The magmatism was accompanied by a low-pressure, high- to ultrahigh temperature metamorphic event at c. 930 to 920 Ma. The large-scale heat source for this metamorphism and extensive magmatism, which is unique to the Rogaland-Hardangervidda-Telemark sector (Bingen *et al.* 2008b), was large-scale and long-lasting mafic underplating according to Hansen *et al.* (1996), Andersen *et al.* (2007b) and Vander Auwera *et al.* (2011). The underplating is evident, apart from the formation of the RIC, for example, from the juvenile nature of the 918-Ma-old Tørdal granite and the presence of distinct, mantle-derived components in the other HBG granites (Andersen *et al.* 2002a, b, 2007a, b). Underplating caused partial melting in the lower to middle crust which can be observed today, for example, at the so-called Iveland wall exposed in the center of the Iveland village (Fig. 12). The wall display partial melting of Iveland-Gautestad amphibolites and banded gneisses and the related formation of zoned pegmatites. The exposure is in the center of the Evje-Iveland pegmatite field and representative for the host rock assemblage and relationship in the area. Geochemical modeling indicates that the Evje-Iveland pegmatite melts formed by 15 to 30% partial melting of the amphibolites (Snook 2014). The underplating was partly contemporaneous with, but essentially followed by, crustal extension. The strongly increased basal heat flow into the crust by magmatic underplating triggered the delamination of the mantle lithosphere. However, it is very difficult to infer the tectonometamorphic history of the entire crust from the study of exposed crystalline complexes, which usually show only distinct crustal and metamorphic levels. In the Rogaland-Hardangervidda-Telemark sector, the anatectic low- to mid-crustal sheets are exposed only in certain areas, such as the Evje-Iveland field. As discussed above the period-IV pegmatites in the Idefjord terrane, Karlshus, Vintergruben and Grebbestad, are related to the HGB granites of Bohus and Iddefjord.

The observed relation between pegmatite formation and major high-grade metamorphic events may reflect two processes: (i) crustal stacking during different stages of continental/terrane collision (HP metamorphism) (periods I to III) and (ii) emplacement of mantle-derived melts into the lower or middle crust with large-scale LP- to MP-HT thermal overprint (period IV) during orogenic extension. In several provinces that have been affected both by early HP metamorphism during continental collision and by late LP or MP metamorphism during late- to post-orogenic crustal extension, there may occur several generations of rare-element pegmatites that are widely separated in time (Idefjord terrane, Bamble sector; Fig. 3).

We could show that most of the Sveconorwegian pegmatites having commonly a NYF signature formed by anatexis in an orogenic setting. The setting contradicts the general opinion that NYF pegmatites are affiliated with anorogenic suites that formed in an extensional setting involving A-type magmas containing crust and mantle components (Černý 1991a, Martin and De Vito 2005, London 2008, Černý *et al*. 2012). LCT pegmatites are generally considered to be members of orogenic (calc-alkaline) S-type suites that formed in an orogenic subduction setting. Thus, the genetic characteristics of the family classification (NYF versus LCT) are not applicable in the case of the Sveconorwegian pegmatites because the composition of the pegmatite melt depends entirely on the type of melted source rock (mostly amphibolites) and not on differentiation via pluton-sized intrusions of melt-characterizing S- or A-type signature. Scenarios of pluton-unrelated, orogenic formation of RE pegmatites of are illustrated in Fig. 13. In contrast to "classical" pluton-related LCT and NYF pegmatites, pluton-unrelated RE pegmatites may be lacking Li (therefore "CT" instead of "LCT") or F (therefore "NY" instead of "NYF") depending on the Li and F abundance in the molten source rock.

Chemical variability of columbite group minerals and its petrogenetic implication

Variation of major element composition of columbite group minerals is largely controlled by fractionation, i.e., a general increase of Mn/(Mn+Fe) and Ta/(Ta+Nb) with pegmatite evolution, and by pegmatite type, which is largely defined by mineral assemblage (*cf.* Černý 1989). Thus, compositional differences with pegmatite type also may reflect that other minerals, such as tapiolite, ixiolite, or wodgingite, compete for the same elements as columbite group minerals.

The trace element signature of columbite group minerals seems to be controlled by two factors; i.e., (i) source compositions, which control the availability and the partitioning of particular trace elements during partial melting and (ii) fractionation of the pegmatite melt, which has two aspects (a) the presence of minerals that strongly sequester particular trace elements and, thus, reduce their availability for incorporation in columbite group minerals and (b) the composition of columbite group minerals, i.e., Ta/(Ta+Nb), as compositions far from end-member compositions seem to have a higher potential to incorporate available trace elements than the end-members.

Anatectic melting is controlled by the availability of water and, thus, by the stability of hydrous phases such as muscovite, biotite, and amphibole. The stability of these phases determines the pressure and temperature conditions of melting and their amount determines the volume of melt that may be generated (*e.g.,* Clemens and Vielzeuf 1987, Vielzeuf and Schmidt 2001). The chemical composition of the protoliths has a two-fold control on the composition of migmatitic melts. First, the major element composition controls which mineral phases are stable and, thus, influences the conditions of incipient melting and the maximum amount of melt that may be generated by the complete consumption of the hydrous phases. The protolith composition determines the mineral assemblage at melting conditions. Thereby, the protolith composition determines, second, not only which trace elements are available for redistribution between melt and restite, but also determines the distribution of these trace elements among the rock forming minerals. In particular for trace elements that do not form minerals of their own, the substitution into major phases may strongly influence whether the element is available for partitioning into a melt or not. For instance, in a rock that contains muscovite and biotite, incipient melting will be driven by the decomposition of muscovite (*e.g.,* Clemens and Vielzeuf 1987) and elements that tend to have higher contents in muscovite than in biotite (*e.g.*, Bea et al. 1994, Yang and Rivers 2000) will be available for redistribution, whereas elements that tend to concentrate in biotite rather than in muscovite (*e.g.*, Sn and W) initially will not be available for redistribution. Whether trace elements that become available for redistribution into the melt when their host breaks down also partition into the melt also depends on the partition behavior of the remaining phases. For instance, the breakdown of muscovite will release Li, Cs, B, and Ta that will partition between the melt and residual muscovite. If these elements partition preferentially into the melt, the initial melt with retain these elements and Li, Cs, B, and Ta even may partition from stable muscovite into the melt. Thus, the initial melt will be strongly enriched in these elements. Continued melting may result in a dilution of the contents of these elements in the melt. In contrast, if the elements Li, Cs, B, and Ta partition into residual muscovite rather than into the melt, early melts may not be particularly enriched in these elements. A higher degree of melting will slowly increase the content of these elements, whereas repeated extraction of melts may result in higher Li, Cs, B, and Ta contents in late melt batches. The above example illustrates the controlling nature of the restite mineral assemblage on the melt composition. Thus, apart from availability the restite mineral assemblage plays a critical role on the trace element inventory of migmatitic melts. For elements that preferentially fractionate into the melt, early small-volume melts may be particularly enriched, and continued melting may mainly result in their dilution in the melt. In contrast, for elements that rather partition into the restite material, only the extraction of early melts may result in particular enrichment of these elements in late melts. Thus, whether a migmatitic melt becomes enriched in particular trace elements also may be related to the amount of melting and the history of melt extraction.

The role of protolith and restite possibly is best illustrated by the distribution of Sn, W, and Sc. All Sveconowegian pegmatites have very low contents of Sn and W, even though some of the pegmatites occur in areas with HT metamorphism. Only two Svecofennian pegmatites have high contents of Sn or W, Broddbo and Stora Vika. These two pegmatites are spatially related to high-grade metamorphic and migmatitic metasedimentary rocks. Thus, the enhanced Sn or W contents of these rocks likely reflect the role of HT metasedimentary rocks versus HT meta-igneous rocks as a source for the pegmatite melts. In contrast, Sc contents are high in columbite group minerals from the Sveconorwegian orogeny and low in columbite group minerals from Scecofennian pegmatites – independent whether they occur in LT or HT metamorphic and migmatitic areas. Thus, the high Sc contents of columbite group minerals from Sveconorgegian pegmatites, which in some pegmatites also are related with the occurrence of other Sc minerals (*e.g.,* thortveitite [Schetelig 1911] and bazzite [Neumann 1961, Bergstøl and Juve 1988]), seem to reflect the protoliths. Actually, it is noteworthy that particularly high Sc contents occur in columbite group minerals from Steli, Vintergruben, Karlshus, and Flekkerøy (Fig. 9).

Conclusion

Available age data for pegmatites and spatially related granite intrusions and regional metamorphic phases of the Sveconorwegian orogen demonstrate:

(1) The comparison of the four periods of pegmatite formation with the regional metamorphic events reveals that (1) the events are regionally limited to one or two tectonometamorphic domains and (2) the four periods fall within or shortly after high-grade metamorphic events related to orogenic stacking or extension. These relationships suggest that the majority of Sveconorwegian pegmatites formed by anatexis. The spatial coincidence and chemical similarities of pegmatite swarms and neighboring granite intrusions does not imply necessarily a genetic relationship. Instead, there may be a large age gap between pegmatite and granite emplacement. Thus, large swarms of rare metal pegmatites with NYF affinity do not necessarily need a parental granite, but may form directly via anatexis as shown for the

pegmatite fields of Hidra, Evje-Iveland, Froland, Haugesund and Halland in the Sveconorwegian Province.

(2) Mineralogical similarities of neighboring pegmatite fields does not imply similar magmatic or metamorphic melt-forming events, but rather reflects the repeated prevalence of comparable pressure and temperature conditions and source rocks favorable for the formation of rare-metal pegmatites.

(3) The regional chemical zoning of the pegmatite fields in the Sveconorwegian orogen is influenced by large scale tectonic structures rather than by granite intrusions. The formation of pegmatite and granite melts in the same area but at different stages of the orogenic development indicates that pressure, temperature, and protolith composition possibly are not the sole factors controlling whether pegmatites or granites form, but that the extent of melting and the mode of melt extraction also may be important.

(4) NYF pegmatites are not necessarily formed in an extensional anorogenic setting in relation to A-type magmatism as generally suggested. The Sveconorwegian NYF and mixed NYF-LCT pegmatites are commonly formed by anatexis in compressional or extensional orogenic settings. Thus, the genetic characteristics of the family classification (NYF versus LCT) has to be re-evaluated.

(5) The range of absolute ages for metamorphism and orogenic relaxation of the Grenville Province is remarkable similar to the Sveconorwegian Province. The Grenvillian Ottawan phase coincidences with the Sveconorwegian Arendal and Agder phase developed in the Idefjord terrane and Kongsberg and Bamble sectors, and the Grenvillian Rigolet phase overlaps with the Agder phase of the Rogaland-Hardangervidda-Telemark sector. Pegmatite formation events in both provinces show also temporary relationships suggesting that the Grenvillian pegmatites are predominantly formed by anatexis similar to the pegmatites of the Sveconorwegian Province. These correlations are evident for similar or perhaps the same middle Proterozoic orogenic evolution and pegmatite-forming events in the Baltic and Laurentian Shields before their eventual breakup as suggested already by Romer (1996).

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Appendix 1

Methods

Electron probe microanalysis. Columbite group mineral compositions were determined in 2001 and 2002 at GFZ German Research Centre for Geosciences, Potsdam, Germany, using a Cameca SX 50 microprobe equipped with four wavelength-dispersive spectrometers. The microprobe was operated at 20 kV acceleration voltage and a beam current of 40 nA. Concentrations were determined using metal and oxide standards for calibration. Mineral fragments were mounted together in composite polished sections. The analytical results are shown in the Supplementary Material.

TIMS U-Pb dating. The distribution of U in columbite group minerals may be very heterogeneous, which with time results in domains that are strongly damaged by α-recoil, eventually leading to local metamictization of the mineral. The superposition of many damage zones of α-recoil eventually results in an interconnected networt of metamict zones with local sections that are only little damaged as they contain smaller contents of U (Romer et al. 2007). The metamict domains may experience significant redistribution of U and Pb, leading to overall loss or gain of U and Pb. To avoid problems related with such open system behavior of the U-Pb system of columbite group minerals, all fragments have been leached in 20% HF, followed by 6N HCl and 7N HNO_3. This leaching in different acids typically removes fracture fills of quartz, sulfides, and metamict domains. Usually, it results in higher $^{206}Pb/^{204}Pb$ values (Romer and Wright 1992) and yields concordant data (Romer and Smeds 1996; Lindroos et al. 1996). The leached grains had a metallic luster and showed variable intensity of pitting of the surface (Romer 2003). Most Sveconorwegian columbite group minerals showed anomalous leaching behavior as they showed only small sections with metallic luster and typically developed a brown stain. Repetition of the complete leaching procedure improved the situation, although the stained domains could not always be removed completely. Fragments without brown stain only were obtained for very small fragments of columbite group minerals. Only the fragments without brown stain gave concordant or subconcordant data, whereas the other fragments gave variably discordant data (Table 1).

Columbite group minerals were dated at University of Bergen, Norway, in 1996 using a mixed ^{208}Pb-^{235}U tracer and at GFZ German Research Centre for Geosciences, Potsdam, Germany, in 1997 using a mixed ^{205}Pb-^{235}U tracer. Sample leaching and separation of Pb and U followed the procedures described in Romer and Smeds (1996) and Baumgartner et al.

(2006). Isotope ratios were determined on a Finnigan MAT262 multi-collector mass spectrometer using Faraday collectors and ion-counting using static multi-collection. The higher common Pb contents in some samples largely reflect the larger size of the used fragments of the columbite group minerals and essentially reflect the less efficient removal of damaged sections in larger fragments.

Supplementary material

Table SM1. Chemical composition of columbite group minerals from the Sveonorwegian and the Svecofennian domains of Norway and Sweden.

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Figures

Figure 1. Schematic diagram for an idealized pegmatite field illustrating the spatial distribution of different pegmatite types to a parental pluton (redrawn from Černý, 1991). Different colors highlight the mineralogical-chemical zonation across the pegmatite field from barren pegmatites within or close to the parental pluton to pegmatites enriched in Li, Cs, Be, Ta and Nb with increasing distance from the parental granite. Note, this diagram implies that zoned pegmatite fields are derived from a granite intrusion and the pegmatites should have essentially the same age as their parental intrusion.

Figure 2. A – Simplified map of southern Norway and southwestern Sweden showing the domains and segments of the Sveconorwegian orogen (colored areas), major faults and thrust zones and orogenic magmatism. Modified from Bingen et al. (2008a). Shear and thrust zones: EZ – Elverum shear zone, KTBZ – Kongsberg-Telemark Boundary Zone, MUL – Mandal-Ustaoset shear zone, MZ – Mylonite zone, PKFZ – Porsgrunn-Kristiansand Fault Zone, SFDZ – Sveconorwegian Frontal Deformation Zone, VF – Vardefjell shear zone. Metamorphic grades of the Sveconorwegian orogeny as given in the explanation: amph – amphibolite facies, ecl – eclogite facies, granul – granulite facies. B – Inset showing the location of map A at the southern tip of Scandinavia.

Figure 3. Synopsis of high-grade metamorphic events and ages for magmatic events – shown as probability curves (black) for the five lithotectonic sectors of the Sveconorwegian orogen. Pegmatite ages are shown as red (this study) and blue (literature data) lines, respectively. Modified from Bingen et al. (2008a) with complementary data from Slagstad et al. (2013) and Coint et al. (2015). For locations of hornblende-biotite granites (HBG), Rogaland Igneous Complex (RIC) and Sirdal Magmatic Belt (SMB) see Figure 2. HP – high-pressure, MP – medium-pressure, LP – low-pressure.

Figure 4. The Sveconorwegian Pegmatite Province extending over southern Norway and southwestern Sweden showing the extent of individual pegmatite districts (areas enclosed by solid blue lines): 1 – Mandal, 2 – Setesdal, 3 – Bamble, 4 – Nissedal, 5 – Hardanger, 6 – Buskerud, 7 – Østfold-Halland. Igneous rocks: Bl – Blomskog granite, Bo – Bohus granite, Flå – Flå granite, H – Herefoss granite, Id – Iddefjord granite, T – Tørdal granite. Modified from Ihlen and Müller (2009a).

Figure 5. Geological map of Hidra Island with pegmatite locations. The granitic pegmatites are hosted by anorthosite and leuconorite of the Rogaland Igneous Complex (RIC).

Figure 6. Simplified map showing the distribution of pegmatites and pegmatite fields in the Bamble sector and Rogaland-Hardangervidda-Telemark sector. G – Grimstad granite, H – Herefoss granite, Ho – Holtebu granite, Hø – Høvringsvatnet granite. Modified from Müller *et al*. (2015a).

Figure 7. Simplified geological map showing the distribution of pegmatites in the northern part of the Østfold-Halland pegmatite district within the Idefjord terrane.

Figure 8. Quadrilateral classification diagram of columbite group minerals according to Černý (1989) showing the variation in Mn-Fe and Ta-Nb of columbite group minerals from Sveconorwegian pegmatites. (a) General fractionation trends for columbite group minerals in various pegmatite types. Composition seems to evolve to higher Ta/(Ta+Nb) and/or Mn/(Mn+Fe) with increasing fractionation and seems to be related to the fluorine activity of the system and the nature of Li-bearing minerals (in particular spodumene, pollucite, and 'lepidolite'; numbered arrows, Černý, 1989). Note that the entire compositional space may be encompassed by a single pegmatite system (broad white and grey arrows; Černý, 1989). Pegmatite types: (1) F-poor beryl, (2) F-poor complex spodumene, (3) F-rich complex spodumene, (4) F-rich complex 'lepidolite', (5) F-rich complex petalite-spodumene with 'lepidolite' or pollucite. (b) Compositional variation of Sveconorwegian columbite group minerals from NYF-type pegmatites of southern Norway and southwestern Sweden (grey fields base on Svecofennian columbite group minerals shown in frame c; BDD = Broddbo; STV = Stora Vika). (c) Compositional variation of Svecofennian columbite group minerals from NYF-type pegmatites of Sweden and southern Finland (for sample description see Romer & Smeds 1994, 1997, Lindroos *et al.* 1996, Romer 1997). Concentrations were determined with EPMA. The full data set is presented in the Supplementary Material Table SM1.

Figure 9. Compositional variation of Sveconorwegian columbite group minerals. (a) Deviation from the diagonal line in the Nb vs. Ta/(Ta+Nb) diagram reflects the extent of substitution of Nb and Ta by other highly charged ions. (b) Deviation from the diagonal line

in the Fe vs. Mn/(Mn+Fe) diagram reflects the extent of substitution of Fe and Mn by little charged ions. Note, if the A and B sites of AB_2O_6 minerals like columbite group minerals were occupied only by Ta,Nb and Mn,Fe, respectively, the data in (a) and (b) would fall on the diagonal of the diagram. (c) There is a general increase of Sc with Ta/(Ta+Nb), except for columbite-(Fe) from Steli that shows high Sc at low Ta/(Ta+Nb). (d) There is no systematic relation between Sc and Mn/(Mn+Fe). (e) All Sveconorwegian columbite group minerals have very low Sn contents (typically at or below detection limit). A few Svecofennian columbite group minerals have higher contents of Sn. The high-Sn samples come from pegmatites hosted by or associated high high-temperature S-type migmatite rocks and metasedimentary rocks. (f) For samples with significant contents of Sc, there is a positive, but regionally different correlation between Ti and Sc. Grey fields for Svecofennian columbite group minerals are shown for orientation (dark grey: STV = Stora Vika; light grey: all other pegmatites; BDD = Broddbo). Concentrations were determined with EPMA. The full data set is presented in Supplementary Material Table SM1.

Figure 10. U-Pb data of leached columbite group minerals from southern Norway. Analytical data are shown at 2σ uncertainties, except for Tors gruve and Tangen data that are shown as squares for better visibility. Note the excess scatter of subconcordant Tveit, Karlshus, and Vintergruben samples (insets). Data from Table 1, for discussion see text.

Figure 11. Map of the Sveconorwegian orogen showing the regional distribution of pegmatite ages.

Figure 12. A - Road cut in Iveland called “Iveland wall” (Evje-Iveland pegmatite field) representing a snapshot of anatectic melting of amphibolites (Iveland-Gautestad amphibolites) and the formation of leucocratic pegmatite melt (neosome). B – Detail of the road cut exposing the relationship between restite and expelled leucogratic pegmatite melt. C – Detail of the road cut showing a zoned pegmatite with graphic wall zone, coarse-grained intermediate zone, and quartz core.

Figure 13. Schematic crustal profile illustrating the contrasting controls on the formation of pegmatites in a pluton-related and in a pluton-unrelated scenario. Rare metal pegmatites formed in a pluton-unrelated setting maybe lacking Li (therefore “CT” instead of “LCT”) or F (therefore “NY” instead of “NYF”).

Table 1. U-Pb analytical results for columbite group minerals from pegmatites of the Sveconorwegian domain of southern Norway and Sweden.

Sample [a]	Weight (mg)	Concentrations (ppm)		$^{206}Pb/^{204}Pb$	Common lead (pg)	Radiogenic Pb (at%) [c]			Th/U [d]	Atomic ratios[c]			Apparent ages (Ma) [e]		
		U	Pb	Measured ratios [b]		^{206}Pb	^{207}Pb	^{208}Pb		$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
Tors gruve, Øvre Vats, Rogaland															
Tor-1	1.030	153	31.1	3737	504	92.82	6.72	0.46	0.0055	.21595	2.1567	.07243	1261	1167	998
Tor-2	1.151	155	20.9	15110	51	92.86	6.73	0.41	0.0049	.14550	1.4533	.07244	876	911	998
Tor-3	1.147	324	39.0	3839	694	91.66	6.62	1.72	0.0208	.12634	1.2573	.07218	767	827	991
Tor-4	0.399	89.2	18.3	275	1450	92.75	6.44	0.81	0.0097	.17733	1.6977	.06944	1052	1008	912
Tor-5	0.280	140	20.4	2543	98	92.85	6.70	0.45	0.0054	.15510	1.5424	.07212	930	948	989
Tor-6	0.294	160	23.3	2734	115	92.85	6.71	0.44	0.0053	.15442	1.5379	.07228	926	946	992
Tor-7	0.091	158	24.7	6530	8	92.90	6.71	0.39	0.0047	.16801	1.6722	.07219	1001	998	991
Tor-8	0.091	71.0	26.7	11400	2	92.97	6.69	0.34	0.0041	.40605	4.0256	.07190	2197	1639	983
Tor-9	0.081	113	25.0	13000	<1	92.92	6.70	0.38	0.0045	.23947	2.3797	.07207	1384	1237	988
Tor-10	0.068	239	26.0	8240	2	92.90	6.71	0.39	0.0047	.11711	1.1663	.07223	714	785	992
Tor-11	0.050	402	25.8	11200	<1	92.92	6.71	0.37	0.0044	.06936	0.6907	.07223	432	533	993
Tor-12	0.153	166	26.4	2260	102	92.77	6.71	0.53	0.0063	.16741	1.6692	.07232	998	997	995
Hidra, Vest-Agder															
Hid-1	0.679	633	74.6	3494	894	93.11	6.45	0.44	0.0052	.12539	1.1978	.06928	762	800	907
Hid-2	0.591	384	60.6	3386	645	93.17	6.46	0.37	0.0044	.16812	1.6071	.06933	1002	973	909
Hid-3	0.507	312	50.6	3212	474	93.18	6.46	0.36	0.0043	.17248	1.6489	.06934	1026	989	909
Hid-4	0.351	374	50.7	2853	358	93.16	6.46	0.38	0.0045	.14396	1.3771	.06938	867	879	910
Hid-5	0.206	547	74.8	2414	368	93.08	6.46	0.45	0.0053	.14470	1.3855	.06945	871	883	912
Hid-6	0.121	354	50.0	3160	112	93.54	6.46	0.00	0.0000	.15077	1.4396	.06925	905	905	906
Hid-7	0.092	477	67.9	7310	42	93.18	6.47	0.35	0.0041	.15352	1.4703	.06946	920	918	913
Hid-8	0.071	458	66.5	2150	129	93.15	6.49	0.36	0.0043	.15307	1.4702	.06966	918	918	918
Hid-9	0.049	472	66.7	10950	6	93.19	6.47	0.34	0.0040	.15297	1.4648	.06945	918	916	912
Hid-10	0.082	552	81.4	1345	306	92.96	6.52	0.52	0.0062	.15225	1.4723	.07013	914	919	932
Flekkerøy, Kristiansand, Vest-Agder															
Fle-1	0.640	273	38.1	9524	119	93.12	6.47	0.41	0.0048	.15045	1.4421	.06952	904	907	914
Fle-2	0.193	372	67.1	4115	157	92.93	6.45	0.62	0.0073	.19261	1.8445	.06945	1136	1062	912
Fle-3	0.389	196	39.5	4815	161	93.05	6.47	0.48	0.0057	.21614	2.0722	.06954	1261	1140	915
Fle-4	0.530	315	42.8	3135	425	93.01	6.47	0.52	0.0062	.14411	1.3829	.06960	868	882	916
Fle-5	0.104	418	60.1	14550	13	93.13	6.49	0.38	0.0045	.15557	1.4937	.06963	932	928	918
Fle-6	0.067	822	117	20500	10	93.11	6.48	0.41	0.0048	.15357	1.4731	.06957	921	919	916
Fle-7	0.091	798	111	37600	4	93.13	6.48	0.39	0.0046	.15070	1.4453	.06956	905	905	915
Fle-8	0.059	563	80.2	24500	2	93.09	6.48	0.43	0.0051	.15399	1.4781	.06962	923	921	917
Fle-9	0.083	711	99.9	25200	56	92.98	6.46	0.56	0.0066	.15177	1.4541	.06949	911	912	913
Mølland, Iveland, Aust-Agder															
Møl-1	0.234	743	114	4028	335	92.62	6.93	0.99	0.0118	.16275	1.5488	.06902	972	950	899
Møl-2	0.552	889	104	10760	262	92.61	6.39	1.00	0.0119	.12579	1.1965	.06899	764	799	898
Møl-3	0.396	697	92.9	4583	393	92.63	6.40	0.97	0.0115	.14176	1.3511	.06913	855	868	903
Møl-4	0.351	910	108	6622	276	92.61	6.39	1.00	0.0119	.12657	1.2039	.06898	768	802	898
Møl-5	0.672	670	103	15000	233	92.63	6.39	0.98	0.0116	.16578	1.5761	.06895	989	961	897
Møl-6	0.062	1280	181	12800	43	92.55	6.39	1.06	0.0126	.15186	1.4467	.06909	911	909	901
Møl-7	0.057	1060	149	26550	7	92.64	6.40	0.96	0.0114	.15195	1.4483	.06913	912	909	903
Møl-8	0.067	1200	169	22660	18	92.60	6.40	1.00	0.0119	.15163	1.4442	.06908	910	908	901
Møl-9	0.048	1170	182	18650	13	84.31	5.82	9.87	0.1288	.15294	1.4566	.06908	917	913	901
Møl-10	0.028	1000	134	6730	22	92.66	6.41	0.93	0.0110	.14316	1.3658	.06920	862	874	905
Tveit, Iveland, Aust-Agder															
Tve-1	1.238	98.4	18.7	4783	261	92.11	6.52	1.37	0.0164	.20164	1.9679	.07079	1184	1105	951
Tve-2	1.770	162	15.7	14700	72	92.88	6.46	0.66	0.0078	.10438	1.0008	.06954	640	704	915
Tve-3	1.207	128	14.4	9627	62	92.85	6.43	0.72	0.0085	.12103	1.1559	.06927	737	780	907
Tve-4	0.385	59.1	15.6	318.4	1040	92.85	6.41	0.74	0.0088	.23537	2.2415	.06907	1363	1194	901
Tve-5	0.303	48.4	10.5	727.1	227	92.85	6.43	0.73	0.0087	.21790	2.0791	.06920	1271	1142	905
Tve-6	0.496	67.6	17.3	261.6	2270	92.61	6.44	0.95	0.0113	.27510	2.6369	.06952	1567	1311	914
Tve-7	0.220	53.1	13.2	705.6	207	92.76	6.45	0.80	0.0095	.24924	2.3897	.06954	1435	1240	915
Tve-8	0.093	110	15.67	3580	20	92.94	6.45	0.61	0.0072	.15313	1.4649	.06938	919	916	910
Tve-9	0.156	31.0	4.70	747	47	92.74	6.49	0.77	0.0091	.15314	1.4769	.06995	919	921	927
Tve-10	0.062	107	15.1	7480	<1	92.97	6.42	0.61	0.0072	.15212	1.4493	.06910	913	910	902
Tve-11	0.070	104	14.6	4930	2	93.11	6.42	0.47	0.0056	.15170	1.4423	.06895	911	907	897
Tve-12	0.116	90.4	13.1	1910	30	92.87	6.46	0.67	0.0079	.15231	1.4596	.06950	914	914	914
Tve-13	0.1230	87.0	12.6	1850	40	92.95	6.47	0.58	0.0069	.15239	1.4632	.06964	914	915	918
Tangen, Kragerø, Telemark															
Tan-1	1.232	228	75.6	9314	558	86.81	6.53	6.66	0.0860	.33903	3.5163	.07522	1882	1531	1074
Tan-2	1.346	260	43.0	6303	506	86.21	6.49	7.30	0.0949	.16469	1.7087	.07525	983	1012	1075
Tan-3	1.826	179	63.0	7090	943	87.18	6.54	6.29	0.0809	.35444	3.6650	.07499	1956	1564	1068
Tan-4	0.243	357	74.4	3927	240	89.99	6.79	3.22	0.0401	.21490	2.2363	.07547	1255	1193	1081

Tan-5	0.296	246	76.7	2446	506	85.75	6.47	7.78	0.1017	.30336	3.1538	.07540	1708	1446	1079
Tan-6	0.219	354	89.2	3778	267	86.66	6.51	6.83	0.0883	.25012	2.5923	.07517	1439	1299	1073
Tan-7	0.051	709	135	25700	3	83.97	6.35	9.68	0.1292	.18522	1.9312	.07562	1095	1092	1085
Tan-8	0.066	423	75.0	14400	7	89.62	6.77	3.61	0.0451	.18450	1.9202	.07549	1092	1088	1081
Tan-9	0.068	344	62.1	10000	12	88.42	6.68	4.90	0.0621	.18513	1.9296	.07560	1095	1091	1084
Tab-10	0.059	530	99.2	4540	64	85.69	6.48	7.83	0.1024	.18420	1.9206	.07562	1090	1088	1085
Tan-11	0.088	460	84.1	13920	18	86.63	6.54	6.83	0.0884	.18370	1.9130	.07553	1087	1086	1083
Karlshus, Råde, Østfold															
Råd-1	1.545	672	87.5	6010	1410	92.71	6.32	0.97	0.0115	.13900	1.3068	.06819	839	849	874
Råd-2	1.518	657	66.8	11120	540	93.01	6.41	0.58	0.0069	.10965	1.0413	.06887	671	725	895
Råd-3	1.863	568	53.5	1233	4890	90.37	6.05	3.58	0.0436	.09413	0.8688	.06694	580	635	836
Råd-4	0.356	387	32.5	2262	285	93.00	6.28	0.72	0.0085	.08865	0.8255	.06753	548	611	854
Råd-5	0.538	906	117	18025	182	93.05	6.44	0.51	0.0060	.13914	1.3272	.06918	840	858	904
Råd-6	0.101	626	87.8	11600	36	93.05	6.43	0.52	0.0062	.15118	1.4414	.06915	908	906	903
Råd-7	0.082	666	95.9	2260	213	92.98	6.45	0.57	0.0067	.15150	1.4497	.06940	909	910	911
Råd-8	0.082	829	117	22000	14	93.04	6.45	0.51	0.0060	.15293	1.4615	.06931	917	915	908
Råd-9	0.120	622	88.1	9560	59	93.00	6.44	0.56	0.0066	.15241	1.4553	.06925	915	912	906
Råd-10	0.100	650	90.2	16100	22	93.08	6.42	0.50	0.0059	.14988	1.4262	.06902	900	900	900
Vintergruben, Ånnerød, Våler, Østfold															
Vin-1	0.884	304	51.2	13550	146	92.99	6.44	0.57	0.0067	.18155	1.7333	.06924	1075	1021	906
Vin-2	0.632	332	49.4	16010	73	92.94	6.43	0.63	0.0075	.16081	1.5352	.06924	961	945	906
Vin-3	0.596	337	52.8	12260	116	92.98	6.44	0.58	0.0069	.16866	1.6106	.06926	1005	974	906
Vin-4	0.572	294	57.8	4195	378	92.99	6.44	0.57	0.0067	.20985	2.0045	.06928	1228	1117	907
Vin-5	0.111	373	53.1	15200	11	92.96	6.45	0.59	0.0070	.15351	1.4686	.06939	921	918	910
Vin-6	0.127	412	58.7	15800	16	92.97	6.45	0.58	0.0069	.15380	1.4715	.06939	922	919	910
Vin-7	0.114	356	50.4	12700	15	93.10	6.46	0.44	0.0052	.15316	1.4655	.06940	919	916	911
Vin-8	0.075	457	65.2	10100	17	92.96	6.45	0.59	0.0070	.15378	1.4714	.06940	922	919	911
Vin-9	0.097	451	63.8	20000	6	92.99	6.44	0.57	0.0067	.15273	1.4584	.06926	916	913	906
Grebbestad, Bohus län															
Gre-1	0.014	795	115	2690	23	93.06	6.47	0.47	0.0056	.15370	1.4724	.06948	922	919	913

a Small fragments from single columbite group mineral grains. Fragments were selected to show only fresh fracture surfaces. All samples were leached with 20% HF before sample dissolution. Most grains developed rusty stains during the HCl and HNO_3 washing stages, indicating that metamict domains were not completely removed. Therefore, the leaching procedure was repeated until the remaining grains had surfaces with metallic surfaces. Apparently, most Sveconorwegian columbite group minerals had distinctly higher pre-leaching U contents than Svecofennian crystals used in earlier studies (*e.g.,* Romer & Smeds 1994, 1996). Although the analyzed fragments eventually had perfect surfaces, it is unclear whether the metamict domains had been removed completely also from interior part accessible to leaching. The high discordance of some samples indicates that this apparently was not always possible.

b Lead isotope ratios corrected for fractionation, blank and isotopic tracer. Samples were analyzed in 1995 and 1996 at Department of Earth Science, University of Bergen, Norway, using a ^{208}Pb-^{235}U mixed isotopic tracer and in 1999 at GFZ German Research Centre for Geosciences, Potsdam, Germany, using a ^{205}Pb-^{235}U mixed isotopic tracer. Apart from the larger sample size used for those samples that had to be split for isotope dilution, the data from both laboratories closely correspond and show the effects of the same secondary processes affecting the metamict domains. Analytical details are given in Romer & Smeds (1996). During the measurement period total blanks were less than 15 pg and 10 pg, resepctively, for lead and less than 1 pg for uranium.

c Lead corrected for fractionation, blank, isotopic tracer, and initial lead with the composition according to Stacey & Kramers (1975).

d ^{232}Th/^{238}U calculated from radiogenic ^{208}Pb/^{206}Pb and the age of the sample.

e Apparent ages were calculated using the constants of Jaffey *et al.* (1971) recommended by IUGS. λ_{238} = 1.55125 E-10 y^{-1}, λ_{235} = 9.848 E-10 y^{-1}.

Table 2. Age compilation for Sveconorwegian pegmatites and spatially related granite intrusions.

Pegmatite field	**Pegmatite age (Ma)**	**Ages of neighboring granite (Ma)**	**Minimum age difference (Ma)**
Eastern Segment			
Riddabo	941.6 ± 1.4[8] Riddabo	No granite exposed	-
Idefjord Segment			
Østfold	*906.3±5.9[1] Karlshus*	918±7[3] (Iddefjord)	ages overlap
	908.9±1.4[1] Vintergruben	918±7[3] (Iddefjord)	ages overlap
Halland	*921.8±3.4[1] Grebbestad*	922±5[2] (Bohus)	ages overlap
	984.3±6.4[8] Skuleboda	922±5[2] (Bohus)	51
	1038.7±3.4[8] Timmerhult	922±5[2] (Bohus)	108
	1041.3±1.6[8] Skantrop	922±5[2] (Bohus)	113
Gothenburg	1029.7 ± 1.4[8] Högsbo	No granite exposed	-
Bamble Domain			
Froland	1060+8/-6[9] Gloserhei	926±8[10] (Holtebu, Herefoss)	122
Arendal	1094±11[6] Tvedestrand	No granite exposed	-
Kragerø	*1082.3±4.5[1] Tangen*	No granite exposed	-
Flekkerøy	*915.4±1.6[1] Flekkerøy*	No granite exposed	-
Telemark Domain			
Evje-Iveland	*900.7±1.8[1] Mølland*	981±6[7] (Høvringsvatnet)	63
	910.2±7.1[1] Steli	981±6[7] (Høvringsvatnet)	64
	910±14[6] Frikstad	981±6[7] (Høvringsvatnet)	52
	906±9[5] Mølland	981±6[7] (Høvringsvatnet)	61
Hidra	*911±3[1] Hidra*	No granite exposed	-
Farsund	914±6[3] Rymteland	930±28[11] (Lyngdal)	ages overlap
Haugesund	*991.6±3.6[1] Tors gruve*	No granite exposed	-

Italics: U-Pb columbite ages determined in this study.
Data sources: 1 – this study, 2 - Eliasson and Schöberg (1991), 3 - Pedersen and Maaløe (1990), 4 - Pasteels et al. (1979), 5 - Seydoux-Guillaume et al. (2012), 6 - Scherer et al. (2001), 7 – Snook (2014), 8 – Romer and Smeds (1996), 9 – Baadsgaard et al. (1984), 10 - Andersen (1997), 11 – Pedersen and Falkum (1975).

Figure 1

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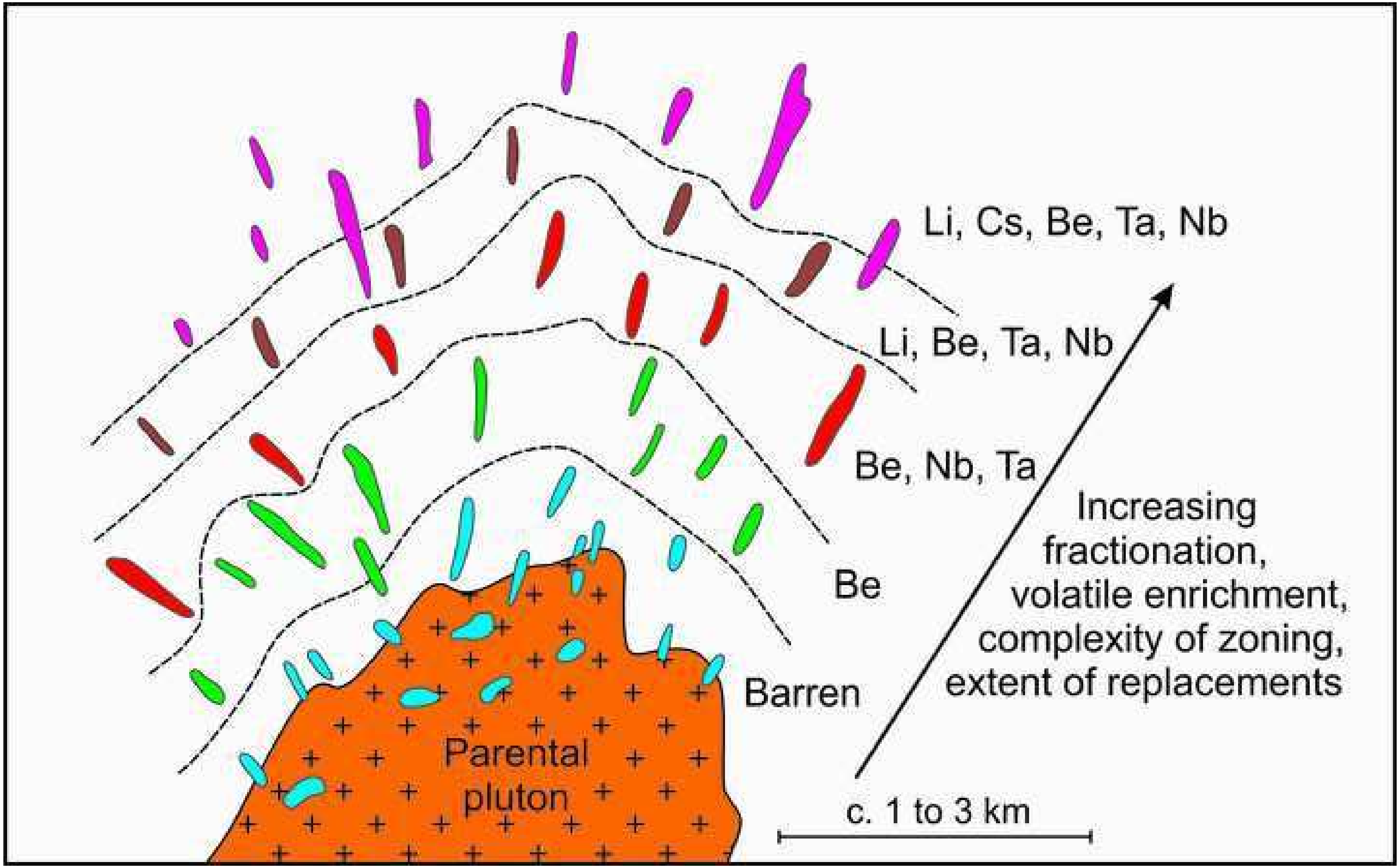

Figure 2

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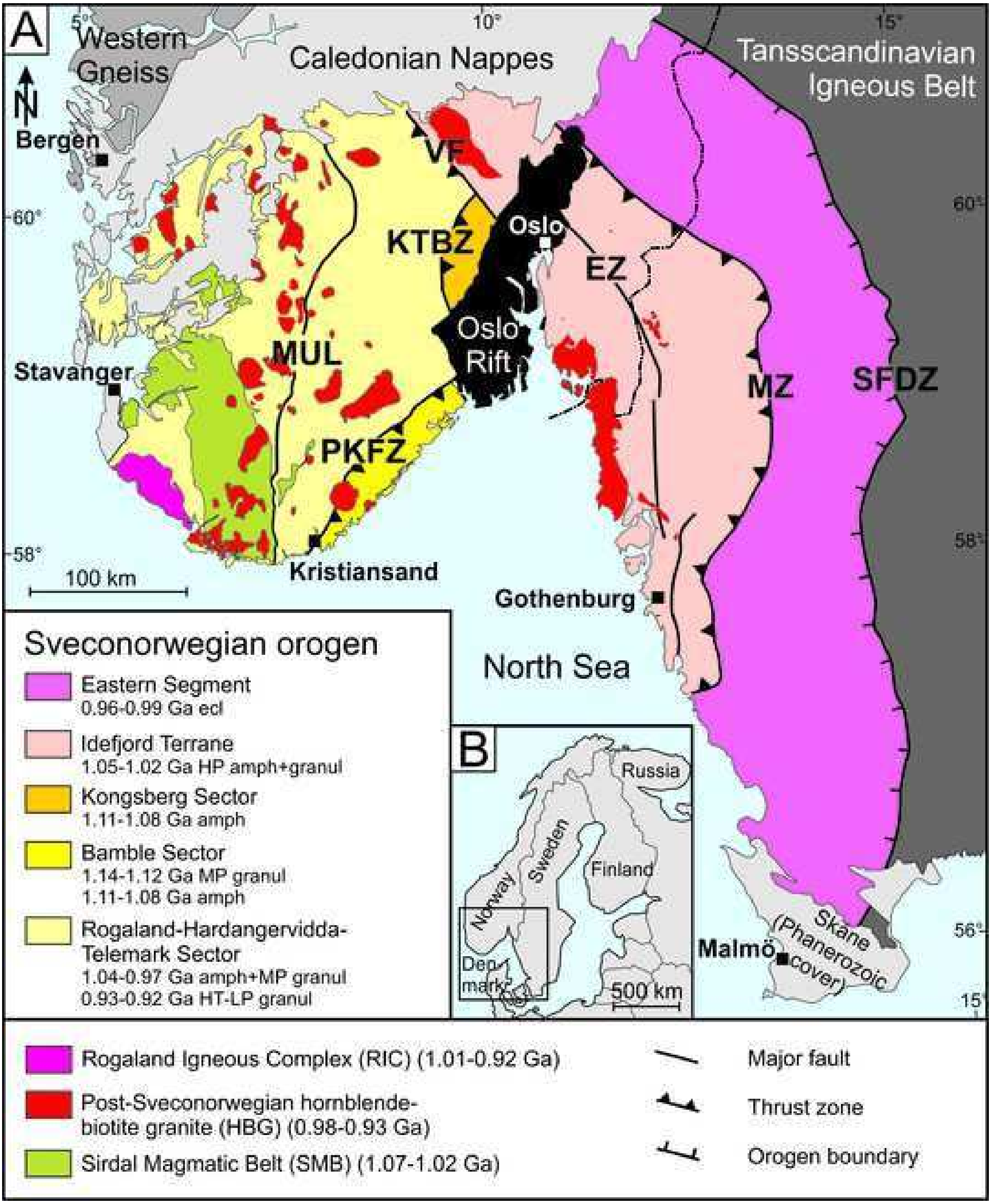

Figure 3

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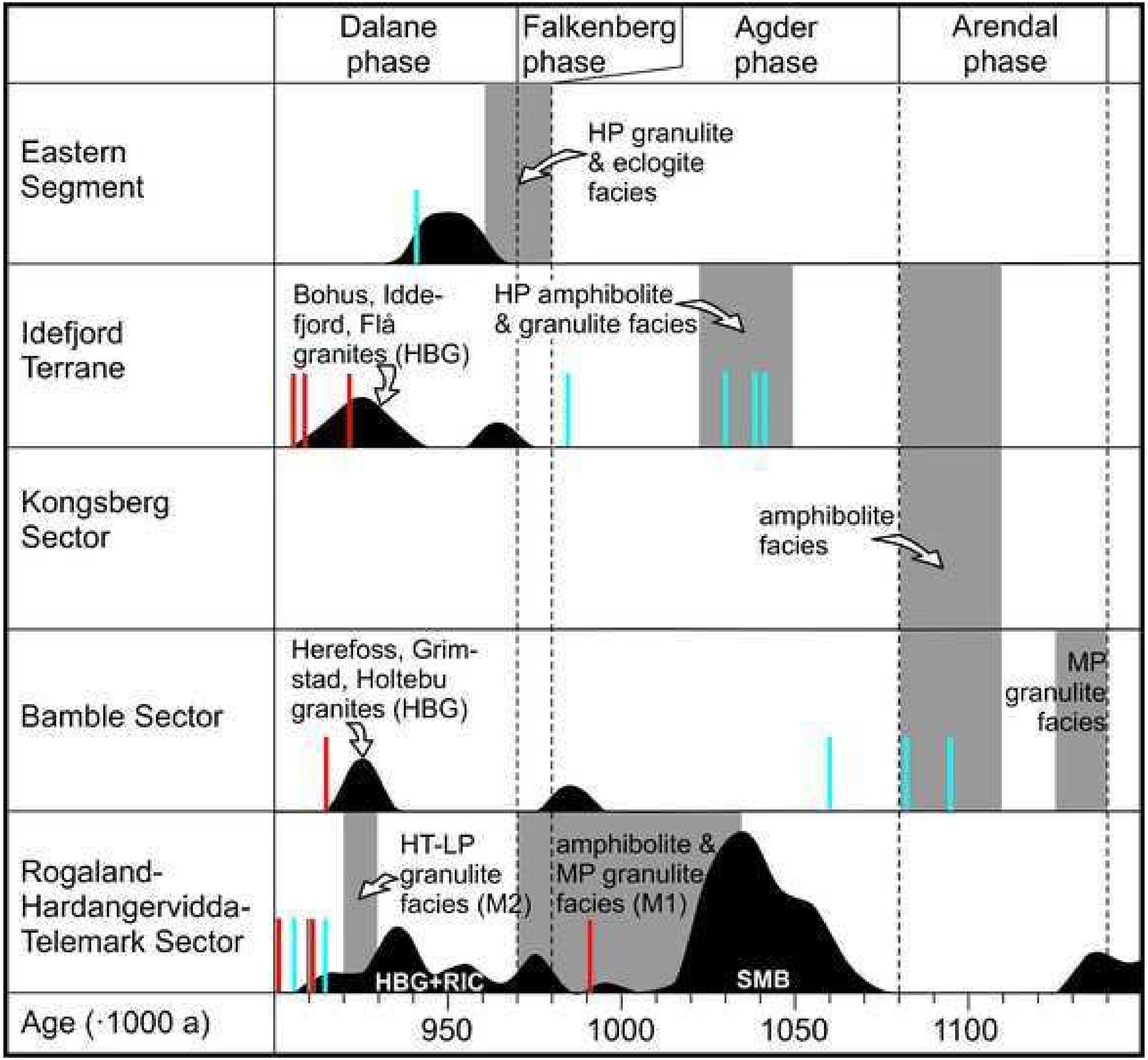

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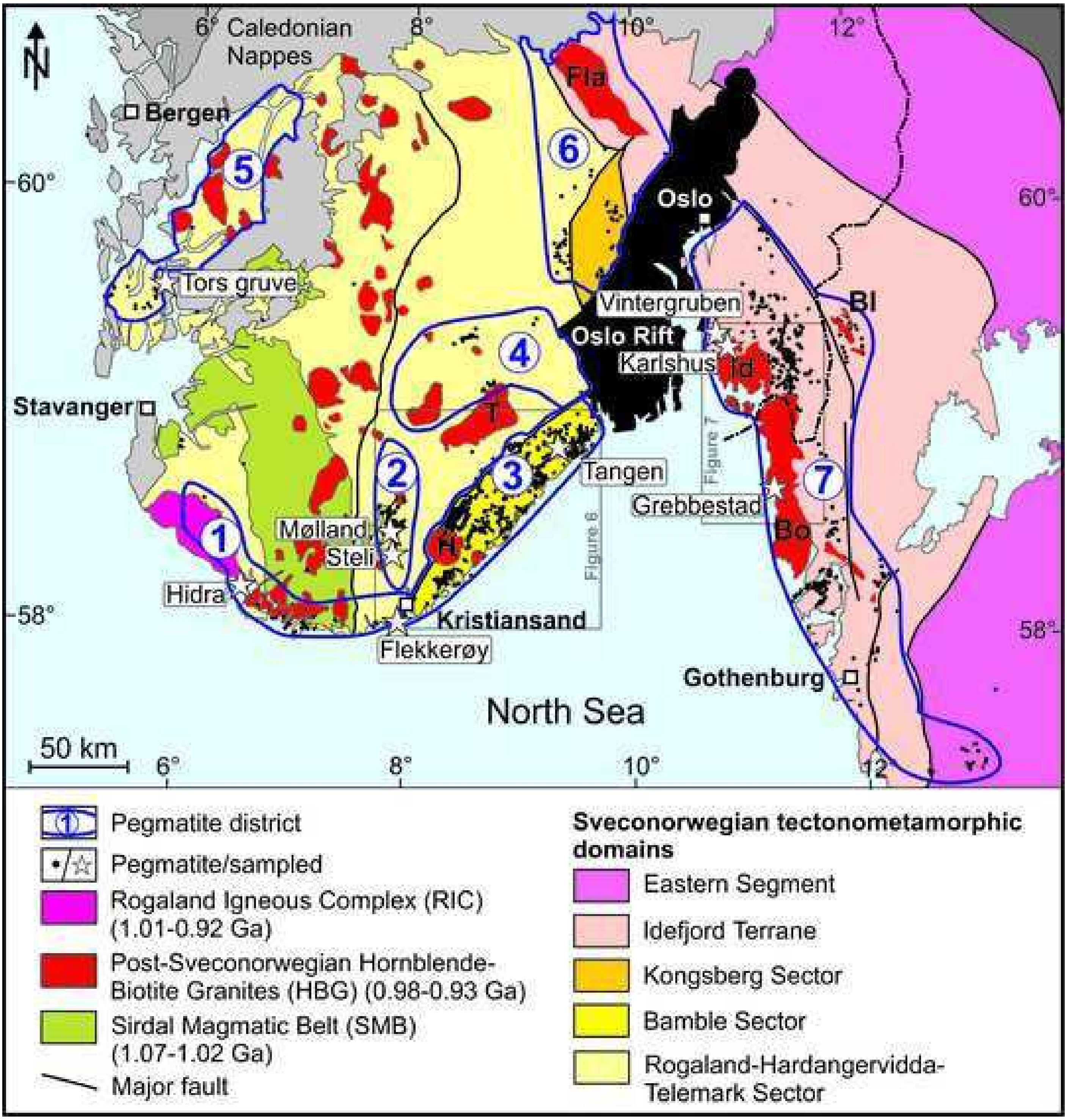

Figure 5

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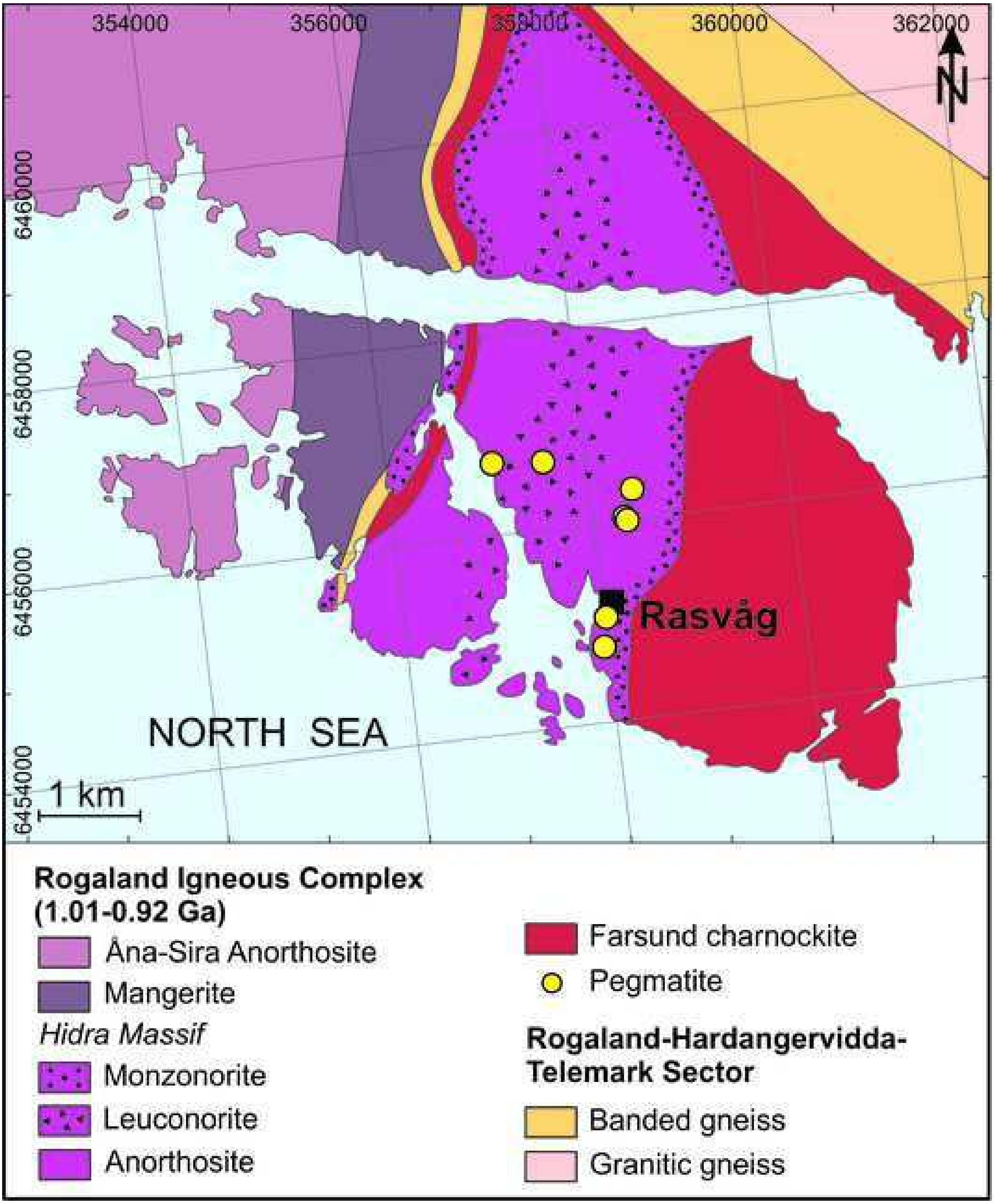

Figure 6

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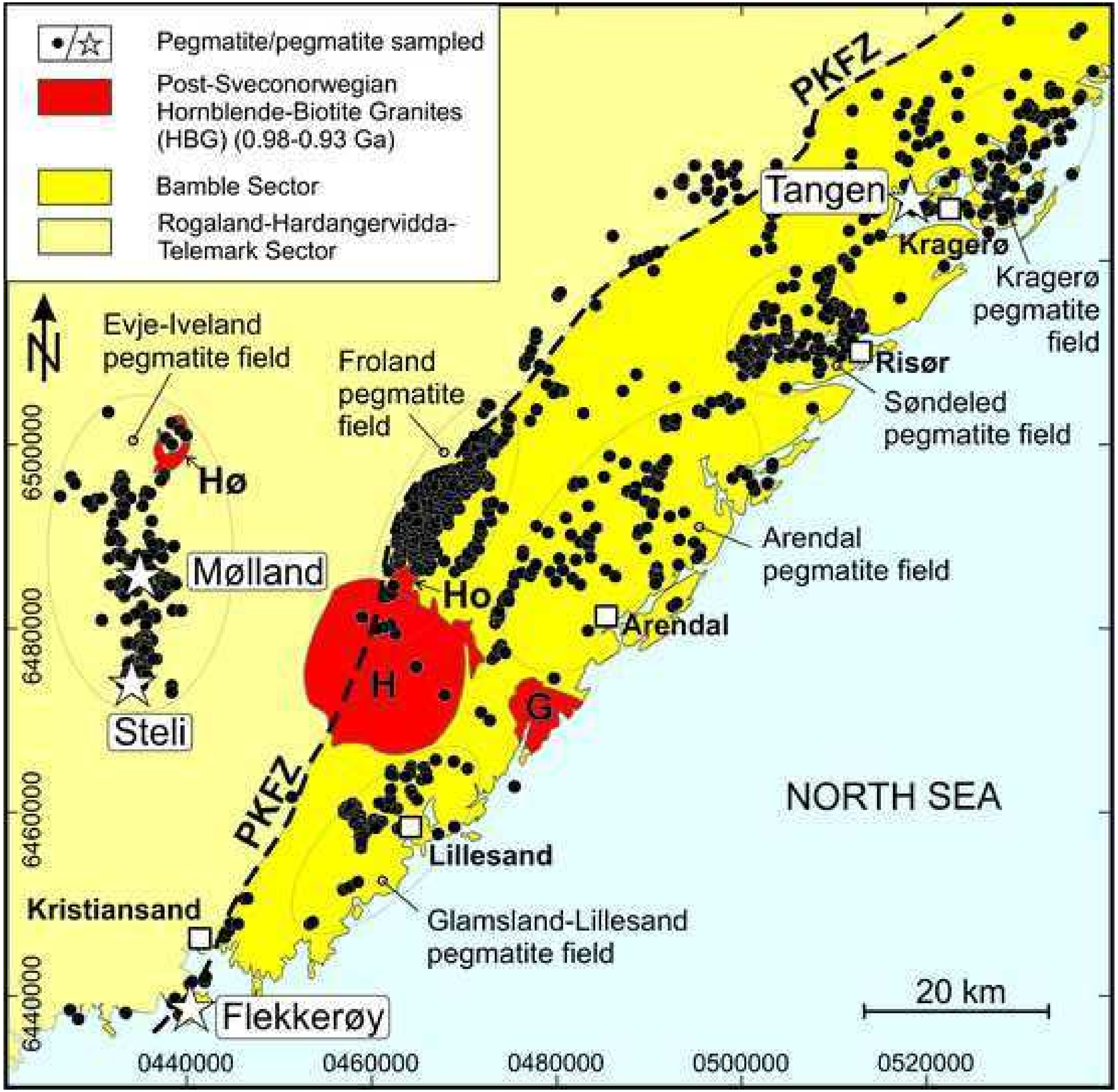

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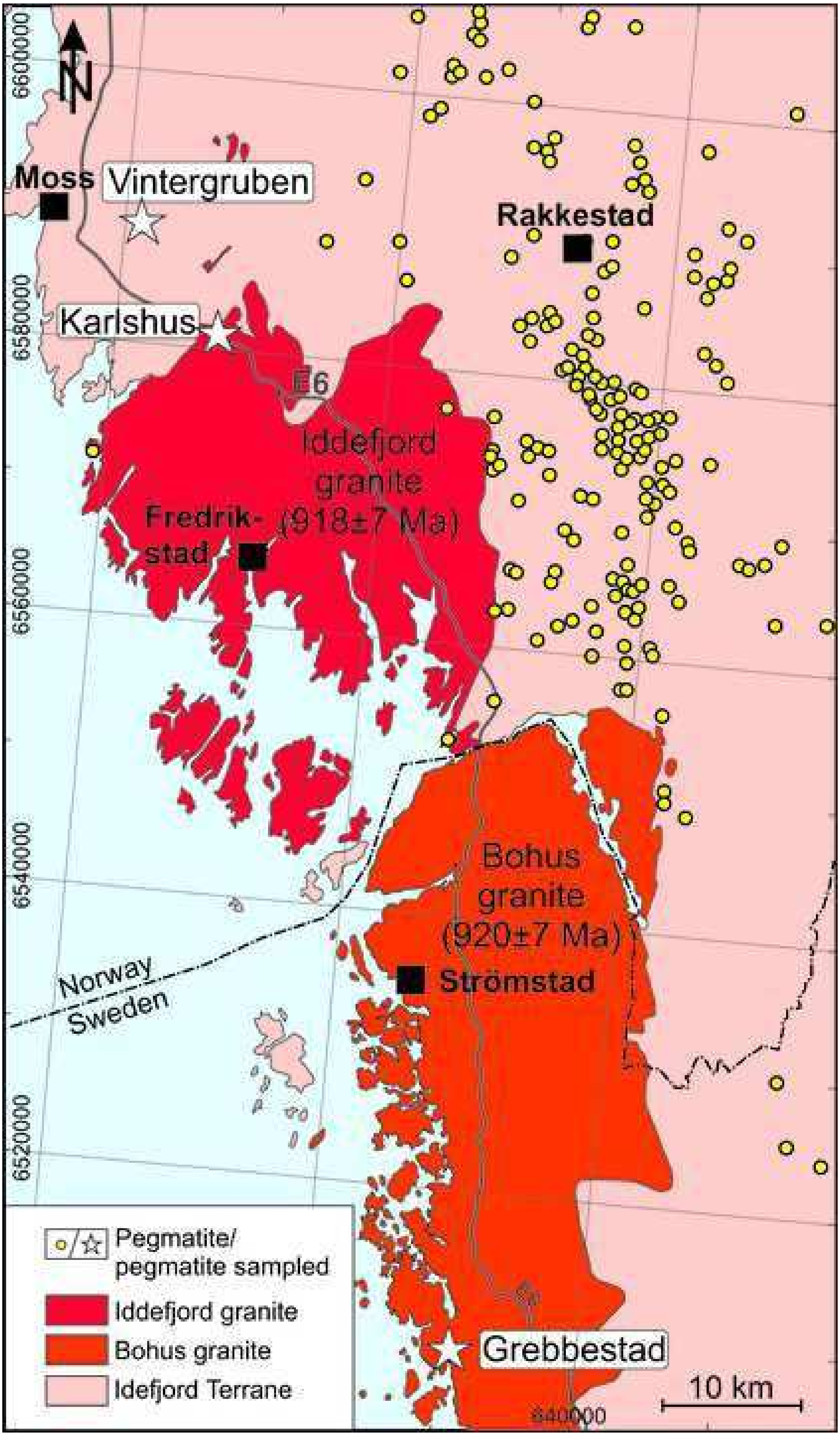

Figure 8

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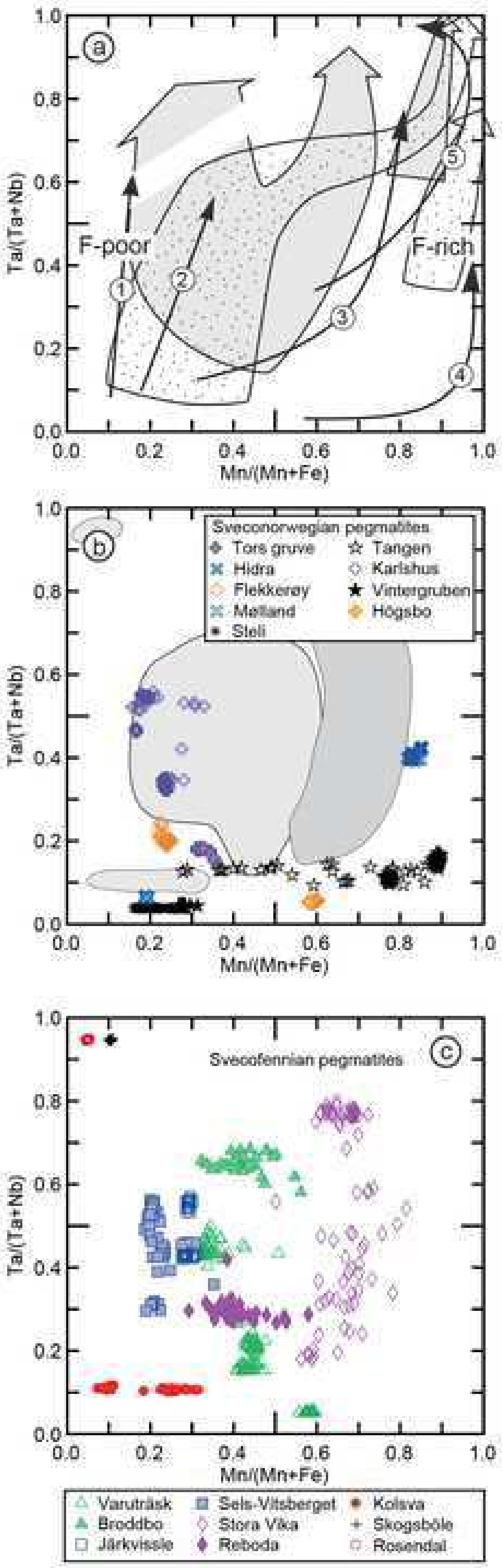

Figure 9

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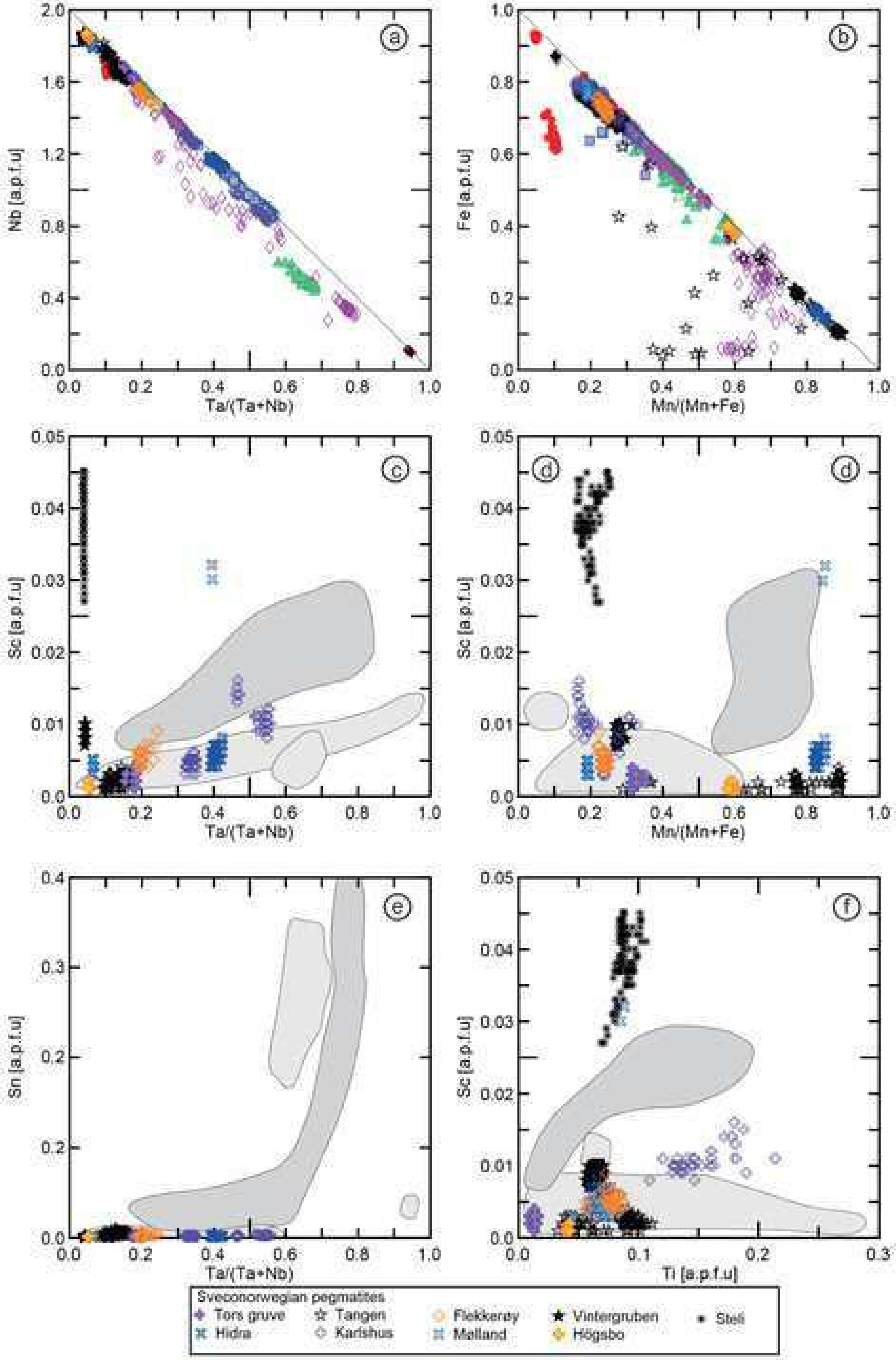

Figure 10

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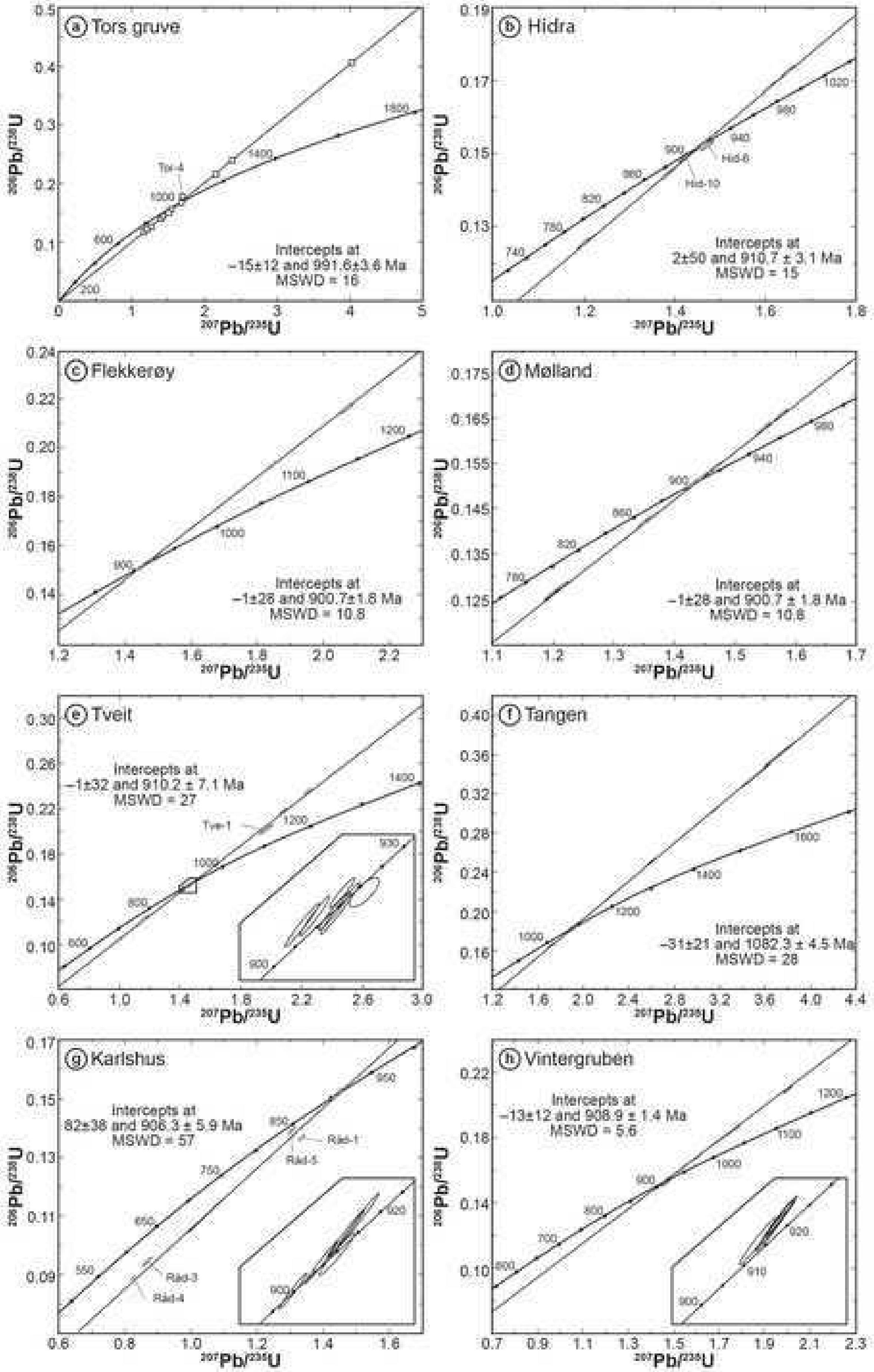

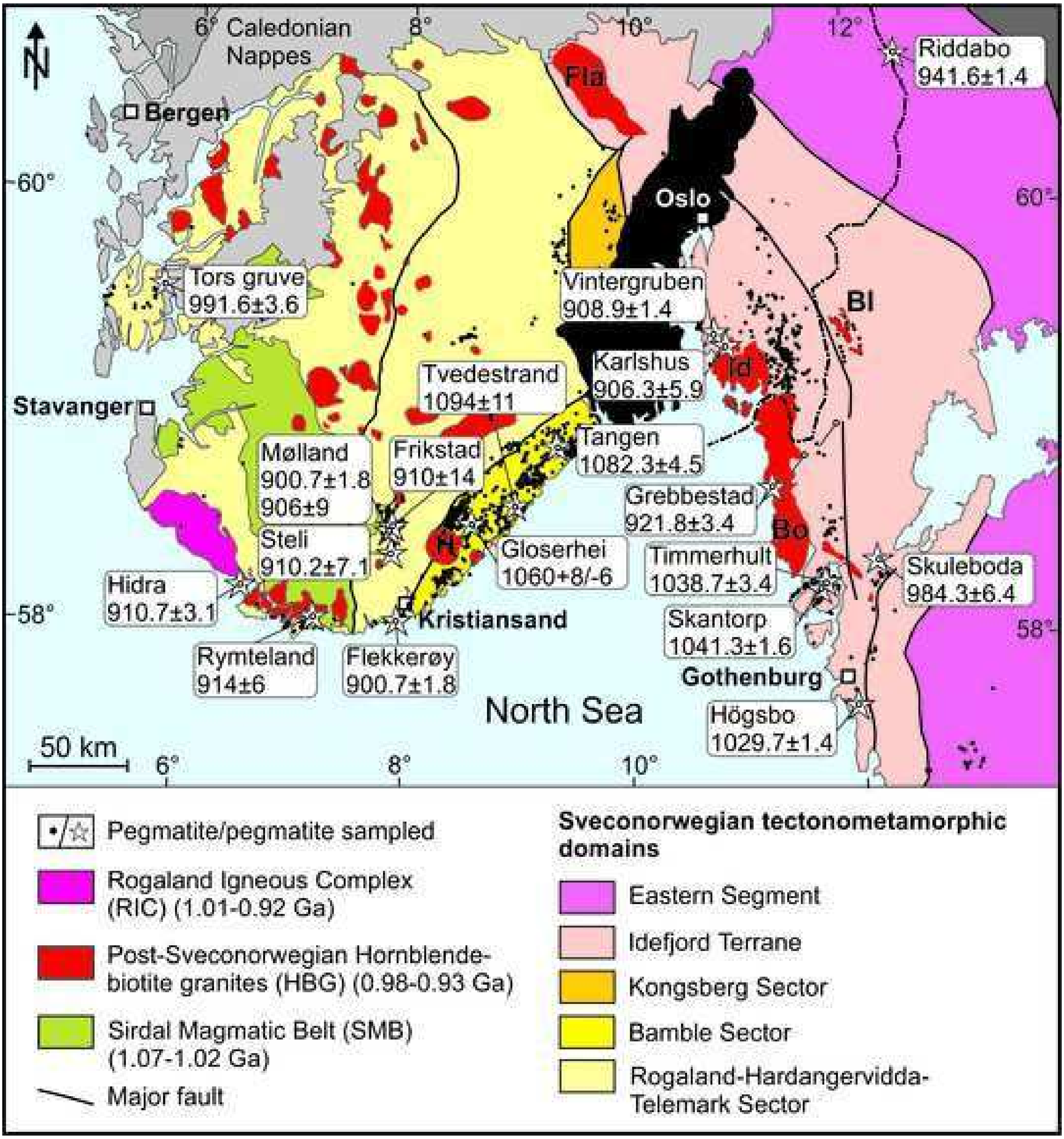

Caledonian Nappes
Bergen
Stavanger
Oslo
Kristiansand
Gothenburg
North Sea
Flå
Bl
Id
Bo
H
Riddabo 941.6±1.4
Tors gruve 991.6±3.6
Vintergruben 908.9±1.4
Karlshus 906.3±5.9
Tvedestrand 1094±11
Tangen 1082.3±4.5
Mølland 900.7±1.8 906±9
Frikstad 910±14
Grebbestad 921.8±3.4
Steli 910.2±7.1
Gloserhei 1060+8/-6
Timmerhult 1038.7±3.4
Skuleboda 984.3±6.4
Hidra 910.7±3.1
Skantorp 1041.3±1.6
Rymteland 914±6
Flekkerøy 900.7±1.8
Högsbo 1029.7±1.4
50 km
6°
8°
10°
12°
60°
58°
Pegmatite/pegmatite sampled
Rogaland Igneous Complex (RIC) (1.01-0.92 Ga)
Post-Sveconorwegian Hornblende-biotite granites (HBG) (0.98-0.93 Ga)
Sirdal Magmatic Belt (SMB) (1.07-1.02 Ga)
Major fault
Sveconorwegian tectonometamorphic domains
Eastern Segment
Idefjord Terrane
Kongsberg Sector
Bamble Sector
Rogaland-Hardangervidda-Telemark Sector

Figure 12

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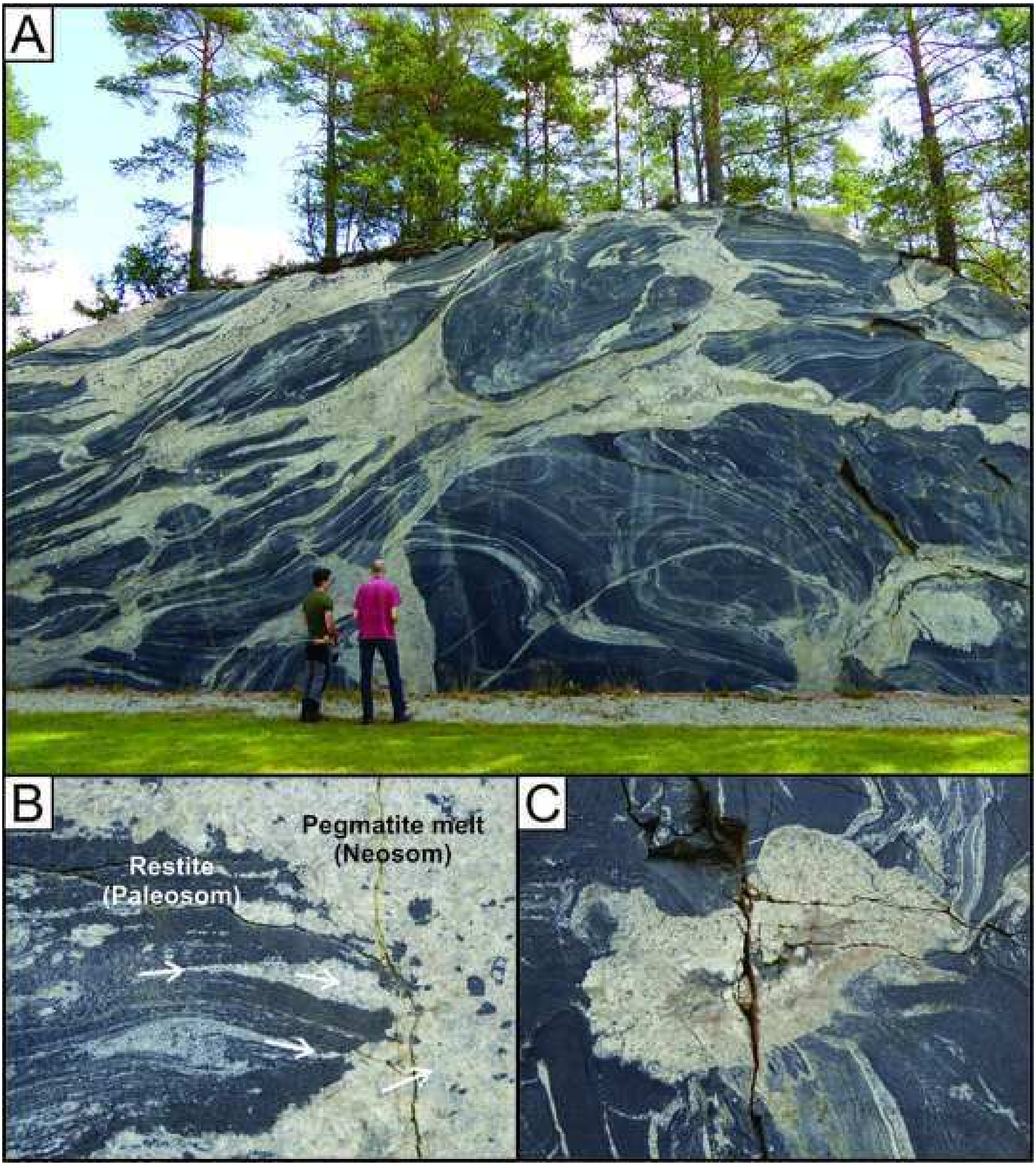

Figure 13

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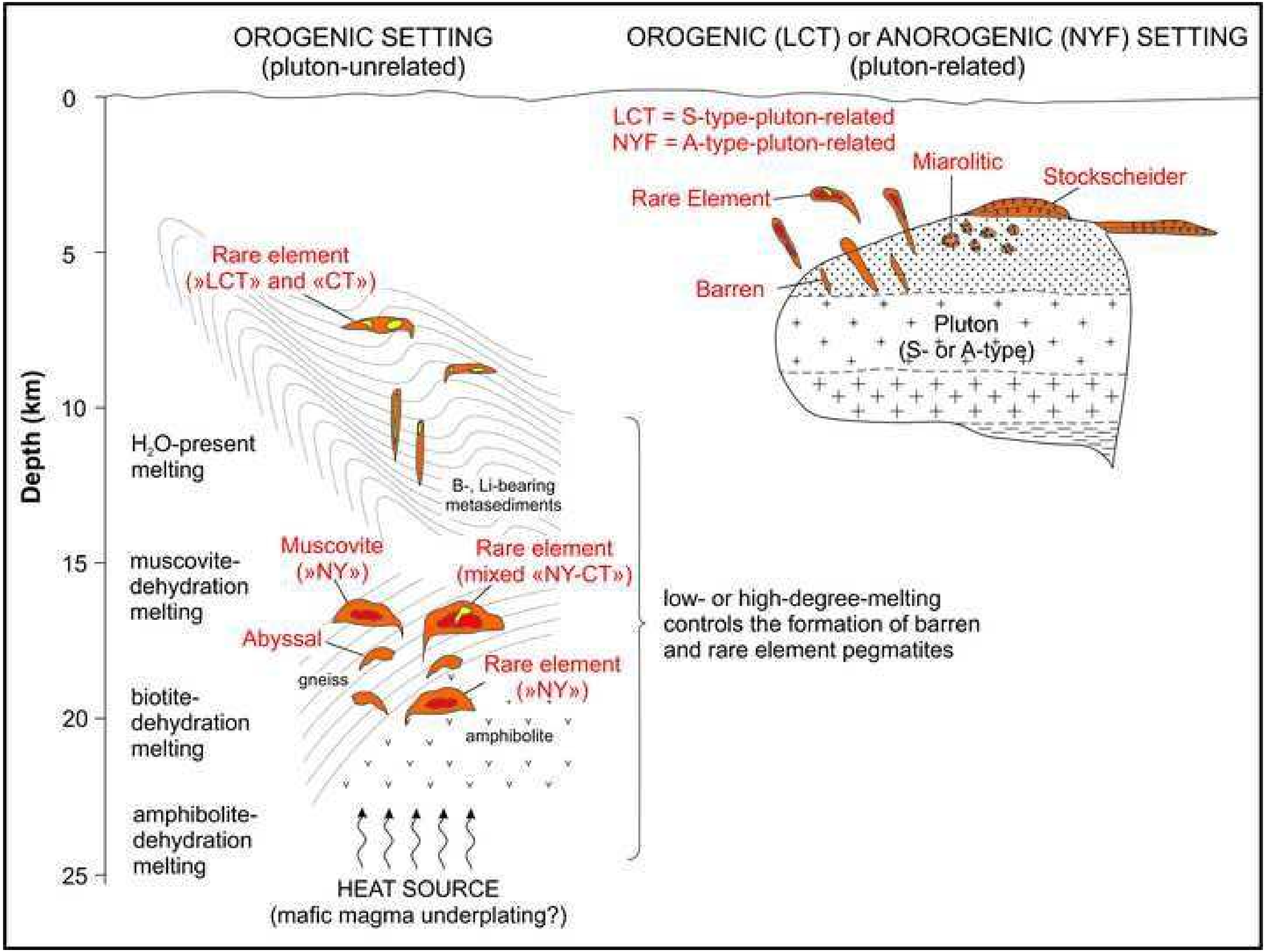

Supplementary Material

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