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Research paper

The Bamble Sector, South Norway: A review

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A B S T R A C T

The Proterozoic Bamble Sector, South Norway, is one of the world's classic amphibolite- to granulite-facies transition zones. It is characterized by a well-developed isograd sequence, with isolated 'granulite-facies islands' in the amphibolite-facies portion of the transition zone. The area is notable for the discovery of CO_2-dominated fluid inclusions in the granulite-facies rocks by Jacques Touret in the late 1960's, which triggered discussion of the role of carbonic fluids during granulite genesis. The aim of this review is to provide an overview of the current state of knowledge of the Bamble Sector, with an emphasis on the Arendal-Froland-Nelaug-Tvedestrand area and off shore islands (most prominantly Tromøy and Hisøy) where the transition zone is best developed. After a brief overview of the history of geological research and mining in the area, aspects of sedimentary, metamorphic and magmatic petrology of the Bamble Sector are discussed, including the role of fluids. Issues relevant to current geotectonic models for SW Scandinavia, directly related to the Bamble Sector, are discussed at the end of the review.

1. Introduction

The Bamble Sector is a classic Precambrian high-grade gneissic terrane in a 30 km wide strip along the coast of South Norway (Fig. 1), between the Permian Oslo Rift in the northeast and the city of Kristiansand in the southwest. The central part, including the Arendal region and off shore islands (notably Tromøy and Hisøy), forms a well-developed, continuous transition zone from amphibolite- to granulite-facies metamorphic grade, which has attracted both intense geological interest as well as (past) interest from mining and exploration. It was the first amphibolite- to granulite-facies transition zone in which CO_2-rich fluid inclusions were investigated and their importance in granulite genesis first recognized by Jacques Touret (1970, 1971a, 1972, 1974). CO_2-rich fluid inclusions have since been found in granulites worldwide (e.g. Touret and Huizenga, 2011, 2012; Touret and Nijland, 2012; and references therein). In the same set of studies, (Na, K)Cl brine inclusions are also reported, though the importance of (Na, K)Cl brines as 'the other' granulite-facies fluid was realized only decades later (e.g. Newton et al., 1998). Though apparently regular, the transition zone shows local variations, like 'granulite-facies islands' in the amphibolite-facies zone, which are controlled by fluid and precursor chemistry, local LILE-depletion. The transition zone developed in what was an already high-grade metamorphic terrane. The current paper provides a review of the sedimentary, magmatic and metamorphic petrology of this classic area.

2. Brief history of geological research and exploration

From the 16th century onwards, iron ore mining and smelting in the Bamble Sector became important pre-industrial activities, stimulated by the Danish crown (e.g. Kjerulf and Dahll, 1861, 1866; Vogt, 1908; Christophersen, 1974; Fløystad, 2007; Vevstad, 2008). Around 1800, the iron mines and works attracted early scientists such as the French metallurgist Gabriel Jars (1774) and the Germans Leopold von Buch (1813) and Alfred Hausmann (1812). In his

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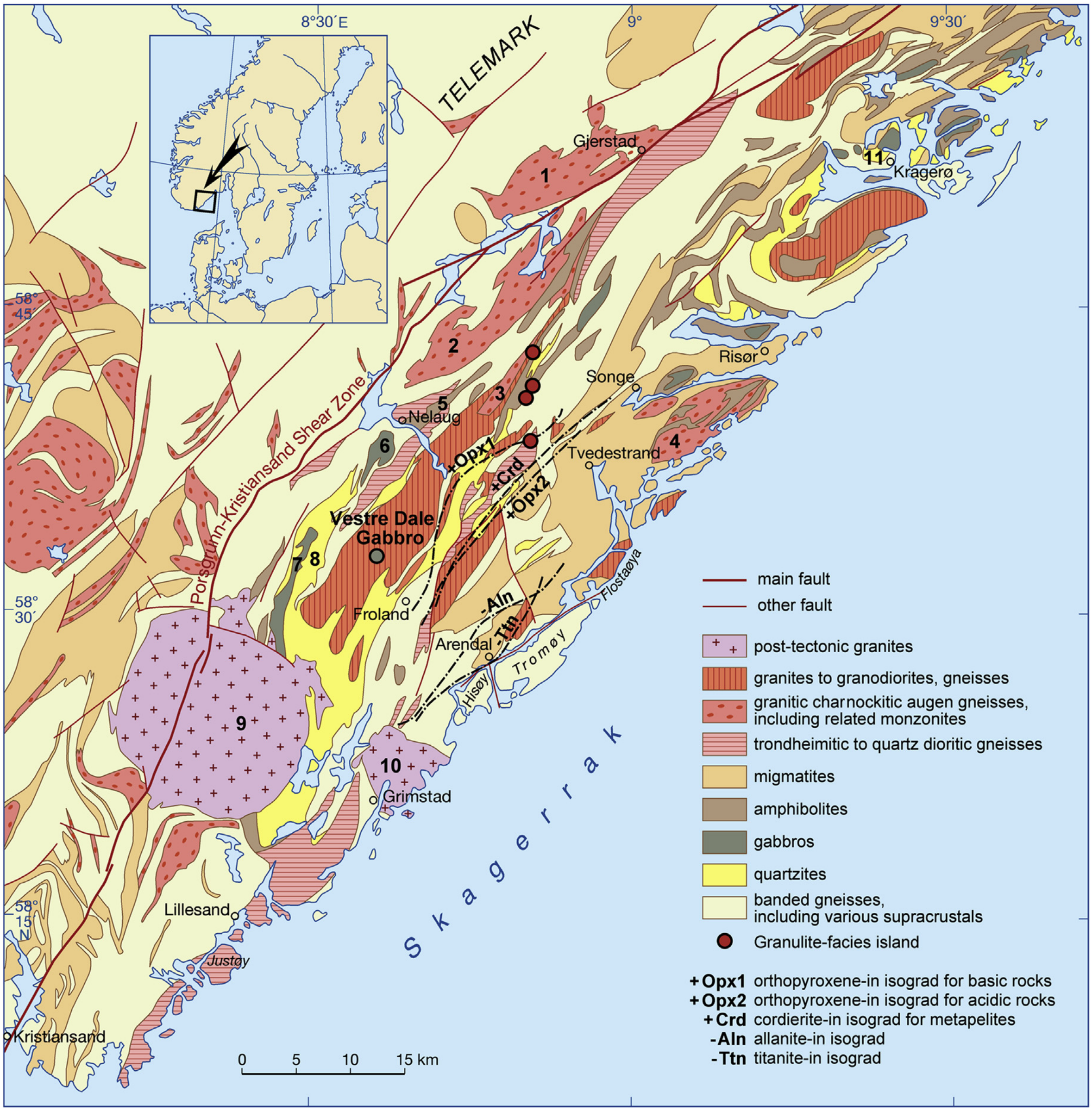

Figure 1. Geological sketch map of the central part of the Bamble Sector, South Norway, with isograds and major intrusions (Modified after Padget and Brecke, 1996; Nijland et al., 1998a). Isograds: +Opx1 – orthopyroxene-in in basic rocks, +Crd – cordierite-in, +Opx2 – orthopyroxene-in in felsic rocks, -All and -Ttn – allanite-out and titanite-out isograds (all lithologies). Lithological units: 1 – Gjerstad augen gneiss and Morkheia monzonite suite, 2 – Hovdefjell-Vegårshei augen gneiss, 3 – Ubergsmoen augen gneiss, 4 – Gjeving augen gneiss, 5 – Vimme amphibolite, 6 – Jomåsknutene gabbro, 7 – Blengsvatn gabbro, 8 – Nidelva quartzite complex, 9 – Herefoss granite, 10 – Grimstad granite, 11 – Coastal quartzite complex.

Journey through Scandinavia in the years 1806 and 1807, Hausmann (1812), remarked about the richness of the ores: '*Occurrences of small size, which would still have been very appreciated in Germany, are not mined in Norway, though these occur everywhere in the surroundings of Arendal.*' The local miners were well aware of the interest in mineral specimens: 'Not long after my arrival, and briefly after that I had told the reason for my journey, was I ran over by miners, who brought minerals from the nearby mines for sale. One would not expect such an industry in a city that far away from any mineral trade. In this extent, one does not find it in Clausthal and Freiberg' (Hausmann, 1812). Both Clausthal and Freiberg were famous German mining towns at that time. Iron mining, concentrated around Arendal and Kragerø, declined in the 2nd half of the 19th century, and was revived during both world wars in the 20th century.

Especially in the 19th century, nickel ore was mined from several mineralized metagabbros throughout the Bamble Sector (Vogt, 1893; A. Bugge, 1922; Jerpseth, 1979; Petersen, 1979; Boyd and Nixon, 1985; Brickwood, 1986). Base metals (Cu, Zn, Pb) were mined on a small scale and for shorter periods, the most important being the Ettedal (also called Espeland) Ag-Pb-Zn deposit (Naik, 1975; Naik et al., 1976; Tørdal, 1990; Petersen et al., 1995). Rutile was mined intermittently over the years, most notably from metasomatized gabbros (Force, 1991; Korneliussen and Furuhaug, 1993; Korneliussen, 1995). Though granulite-facies rocks in the Bamble Sector are depleted in gold (e.g. Cameron, 1989), there are several early reports of the occurrence of gold in the area (Pontoppidan, 1752; Daubrée, 1843), specifically on the island of Hisøy (Bugge, 1934; Johansen, 2007a,b). Amongst the non-metallic ores, apatite was most prominent. Around World War I, several small, short-lived apatite deposits were actively mined (C. Bugge, 1922), but the apatite ores at Ødegårdens Verk proper, operated by the Compagnie Française de Mines de Bamle and later the Norwegian Bamble A/S, formed one of the richest known apatite deposits in the early 20th century (Brøgger and Reusch, 1875; C. Bugge, 1922; Neumann et al., 1960; Bugge, 1965; Lieftink et al., 1993; Harlov et al., 2002; Engvik et al., 2009). The granite pegmatites (see below) offered many a fine mineral specimen for the natural history museums for the major capitals of 18th and 19th century Europe (e.g. Lacroix, 1889), some of them playing a role in the history of science, like an Y-bearing variety of uraninite, known as cleveite in the old literature, obtained from the Auselmyra pegmatite and sold to Mme. Curie in Paris to serve in her studies on radioactivity (Solås, 1990). Granitic pegmatites also served as a source of thorite and other Th-bearing minerals, much sought in the late 19th century, resulting in a local 'thorium boom' in the Kragerø area (Grønhaug, 2004). A more extensive overview of historic mining in the Bamble Sector may be found in Nijland and Touret (2013a,b), whereas Sandstad et al. (2012) gave a metallogenetic overview.

Significant contributions to understanding of the geology of the area in the 20th century were made by W.C. Brøgger (1906, 1934a,b), A. Bugge (1922, 1928, 1936, 1965), C. Bugge (1922), J.A.W. Bugge (1940, 1943, 1978), and T.F.W. Barth (1925, 1928, 1955, 1969). Some of the world's first radiometric age determinations were performed on the Narestø pegmatite on the island of Flosta (Holmes et al., 1955). This was soon followed by other pegmatites in the Bamble Sector (Kulp and Ecklemann, 1957; Kulp and Neumann, 1961). Already before, the uraninite variety cleveite had been used by Bakken and Gleditsch (1938) for early chemical age determinations. From the 1960's onwards, several research groups have been working intensively in the area for several decades, with detailed accounts of relationships between deformation, magmatism, and metamorphism compiled in a series of papers by Starmer (1969a,b, 1972a,b, 1976, 1977, 1978, 1985, 1987, 1990, 1991, 1993, 1996). These relationships were correlated to then current Rb-Sr and K-Ar ages. Recent U-Pb zircon, monazite, and titanite dating as well as Ar-Ar ages have since significantly changed the absolute timing of events.

3. Regional context and general outline

The Proterozoic Bamble Sector, South Norway, is part of the Southwest Scandinavian Domain, which is the latest accreted part of the Baltic Shield (Gaál and Gorbatschev, 1987; Andersen, 2005; Bingen et al., 2005, 2008a,b). Over the last decades, the regional nomenclature of different parts of the Southwest Scandinavian Domain has become a mix of sectors, segments, blocks, terranes, etc. (Fig. 2). In this review, we will use the original nomenclature of sectors and segments, purely for descriptive purposes and without any geotectonic implications, except where explicitly noted.

The Bamble Sector is a high-grade gneiss terrane, with an overall northeast-southwest trending structural style with multiple isoclinal folding (e.g. A. Bugge, 1936; J.A.W. Bugge, 1943; Starmer, 1985, 1990, 1996). It has occasionally been referred to as a mobile belt. The sector is made up of high grade, migmatized gneisses with quartzite dominated supracrustal complexes, which are prominently featured in the Froland and Kragerø areas. Several generations of gabbroic intrusions over the entire sector; and granitic-charnockitic augen gneisses along the border with the Telemark Sector. Two post-tectonic granites (Herefoss and Grimstad) have intruded the high grade terrane.

The Bamble Sector is cut off in the northeast by the Permian Oslo Rift, and otherwise separated from the Telemark Sector by the Porsgrunn-Kristiansand shear zone (Figs. 1 and 3). This mylonitic deformation zone has generally been interpreted as a terrane boundary (e.g. Starmer, 1977, 1985). It is correlated with deep, gently dipping seismic reflectors below the Bamble Sector and the Skagerrak, which cut the Moho (Fig. 3) (Lie et al., 1990, 1993; Pedersen et al., 1990; Kinck et al., 1991). The downthrow of the Bamble Sector relative to the Telemark Sector is estimated from gravimetric studies to be at least 0.5 km near the Herefoss granite (Smithson, 1963) most probably between 0.6 and 1.0 km (Starmer, 1991). More to the northeast (Nelaugvatn), gravity studies indicate downthrows of possibly over 2 km (Ramberg and Smithson, 1975). Nevertheless, the style of deformation (Falkum and Petersen, 1980; Hagelia, 1989) and distribution of Bouguer anomalies (NGU, 1971) indicate some kind of continuity between the Bamble and Telemark Sectors over the Porsgrunn-Kristiansand shear zone (Figs. 1 and 2). In addition, quartzites at Brattland, north of the Porsgrunn-Kristiansand shear zone in the Vegårshei area, show strong similarities with those of the Nidelva quartzite complex. Neodymium isotopic systematics of these quartzites supports this correlation (Andersen et al., 1995).

The continuation of the Bamble Sector below the Skagerrak is obscured by the Skagerrak graben, a continuation of the Oslo rift (Figs. 2 and 3). However, it is noteworthy that whereas the overall structural style and isograds in the Bamble Sector are concave towards the present-day coastline, a positive gravity anomaly is present below the Skagerrak with opposite (complementary?) orientation (Smithson, 1963). Aeromagnetic and gravity anomalies below the northern Skagerrak are considered to reflect a continuation of the high grade Bamble Sector (Olesen et al., 2004). Though separated by the Telemark Sector, the Bamble Sector has traditionally been correlated with the Kongsberg Sector, e.g. A. Bugge (1936), J.A.W. Bugge (1943), Starmer (1985, 1990, 1996), Bingen et al. (2005, 2008b) (Fig. 2). This correlation is disputed by Andersen (2005). The Porsgrunn-Kristiansand shear zone (Fig. 1) is intersected by a late (Permian?) brittle fault, which earlier has been referred to the Great Breccia or the Great Friction Breccia (Bugge, 1928, 1936). In order to explain the observed gravity anomalies, some authors have suggested that both the Bamble and Kongsberg Sectors may continue below the Permian Oslo rift (Fig. 2) (Afework et al., 2004; Ebbing et al., 2005). These anomalies were, however, originally interpreted as Permian cumulates below the rift (Ramberg, 1976). Assigning these anomalies to older Precambrian rocks would create a tremendous volumetric problem, because those cumulates are needed to produce the intermediate felsic magmas in the rift (Neumann, 1980), and there is no alternative location in the rift to store them.

Elaborate descriptions of the lithological relationships in the Bamble Sector have been compiled by Starmer (1985, 1990, 1996), in which the general picture was one of 1.7–1.5 Ga clastic supracrustals, being deposited on an unknown basement, metamorphosed and intruded by granitic-charnockitic and gabbroic magmas during the Gothian orogeny (1.7–1.5 Ga). These were later reworked again during the Sveconorwegian orogeny (1.25–0.9 Ga), with the intrusion of major granitic-charnockitic augen gneiss bodies at the onset of the Sveconorwegian orogeny. Geochronological studies during the last decade have, however, shown that the supracrustal suites are significantly younger whilst (last) peak metamorphism is Sveconorwegian. The oldest rocks currently recognized belong to a suite of calc-alkaline magmas, which intruded all over southern Norway during the period of 1.6–1.52 Ga (Andersen et al., 2001a, 2002a, 2004; Pedersen et al., 2009). Most sedimentary suites postdating this event, coincided in time with the ill defined and controversial Gothian orogeny (1.75–1.55 Ga; Gaál and Gorbatschev, 1987). In the Proterozoic, the Bamble Sector was intruded by several pulses of basic and felsic magmas ending with the intrusion of the post-tectonic Herefoss and Grimstad granites (Fig. 1), which marked the end of the Sveconorwegian

Figure 2. Descriptive division of the Southwest Scandinavian Domain (Berthelsen, 1980; Gaál and Gorbatschev, 1987). The division does not imply any genetic connotations, as discussed in Section 7.

orogeny. In the central part of the Bamble Sector, a well-developed transition zone from amphibolite- to granulite-facies grade occurs in both the supracrustals and in the intruding basic and felsic magmatic rocks (Fig. 1) (Touret, 1971b; Nijland and Maijer, 1993). This transition zone is related to the Sveconorwegian orogeny (Kullerud and Machado, 1991; Kullerud and Dahlgren, 1993; Knudsen et al., 1997; Cosca et al., 1998), though field relations demonstrate an older, pre-Sveconorwegian high-grade migmatitic event (Starmer, 1985, 1991, 1996; Nijland and Senior, 1991).

Geological maps of the area have been published by Touret (1968), Starmer (1987), and, most recently, on a 1:250,000 scale by Padget and Brekke (1996), based on underlying 1:50,000 scale

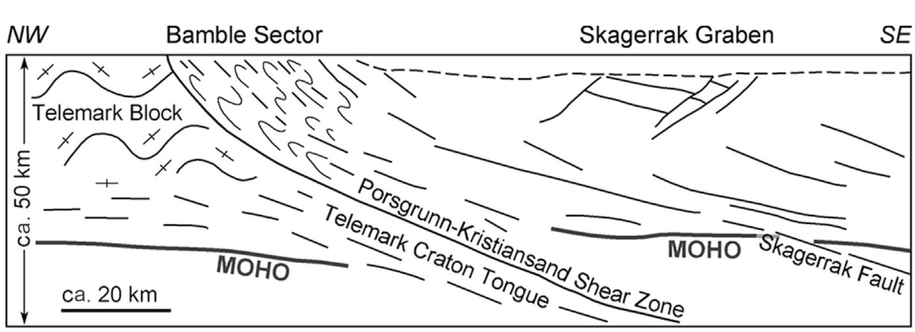

Figure 3. Deep structure of the Bamble Sector and its relationship to the Telemark block and Skagerrak graben (Modified after Lie et al., 1993).

maps (Padget, 1993a,b,c, 1997; 1999). A full bibliography of the geology of the Bamble Sector is given in the Electronic supplement to this paper.

4. Sedimentary petrology

4.1. Hisøy-Merdøy supracrustal suite

The granulite-facies Hisøy-Merdøy supracrustal suite occurs on the islands of Hisøy, Merdøy, Torungen, and the western tip of Tromøy, and several smaller islands (Fig. 1). It is characterized by relatively thinly banded quartzitic gneisses with intercalations of amphibolite (Nijland, 1993; Andersen et al., 1995). Within these decimetre to metre scale alterations of quartzitic rocks, millimetre to centimetre thick sillimanite-garnet-biotite seams are frequent. Such alterations have been interpreted as metamorphosed soil horizons (e.g. Fujimori and Fyfe, 1984). Cordierite-orthamphibole rocks occur as small lenses within the sequence.

Neodymium isotopic studies (Andersen et al., 1995) and SIMS studies of detrital zircons (Knudsen et al., 1997) have demonstrated the presence of Svecofennian and Archaean components in the provenance area of the clastic metasediments. T_{DM} Nd ages typically range from 1.79 to 1.93 Ga (excluding two odd much older ages) for the quartzitic rocks, and from 1.38 to 1.71 Ga (excluding one odd much older age) for the amphibolites (Andersen et al., 1995). A $^{207}Pb/^{206}Pb$ SIMS age on the youngest detrital zircon encountered in Hisøy-Merdøy supracrustal suite rocks, 1367 $\pm$ 50 Ma, provides a weak maximum age limit of sedimentation estimate for these supracrustals (Knudsen et al., 1997).

4.2. Nidelva quartzite complex

The Nidelva quartzite complex is exposed between the post-tectonic Herefoss granite and the Nidelva river (Fig. 1), possibly continuing on the eastern shores of the Nidelva (Starmer, 1985; Nijland et al., 1993a). The Nidelva quartzite complex can possibly be correlated with the Coastal quartzite complex in the Kragerø area (Starmer, 1985; Padget, 1990, 2004; however, see Section 4.4). The main constituents of the Nidelva quartzite complex are massive, relatively pure quartzites with minor intercalations of metapelites (including sillimanitic nodular gneisses), calcsilicate rocks, marbles, and amphibolites. In addition, the Nidelva quartzite complex contains many small intercalated bodies of several peculiar rock types, viz. cordierite-orthoamphibole rocks; alternating preiswerkite-tourmaline-biotite-marialitic-scapolite and pargasitite rocks (Visser et al., 1998); garnet-cummingtonite rocks; tourmaliniferous quartzites and conglomerates; and tourmalinites. These generally occur as small lenses, but tourmalinifeours quartzites and tourmalinites may stretch over considerable distances. Fine grained, very K-feldspar-rich rocks, with up to 80 vol.% microcline and lesser amounts of quartz, plagioclase, mica, and opaques have been encountered at one level within the Nidelva quartzite complex, and grade laterally into feldspar-bearing quartzites (Kloprogge, 1987; Van Linschoten, 1988). Local sulphidic horizons have been mined for Cu in the past (e.g. Robyn et al., 1985; Nijland and Touret, 2013b). The pure quartzites locally preserve sedimentary structures, including desiccation cracks (Fig. 4), large, metre scale cross bedding, as well as small, decimetre scale through cross bedding (Nijland et al., 1993a). At least two different intraformational conglomerates occur within the Nidelva quartzite complex. Both are monomict, but one, the Reddal conglomerate, is relatively unflattened, and occupies a considerable inferred area (Padget and Breivik, 1991). The other, the Neset conglomerate, has been intensively flattened (Nijland et al., 1993a). Another difference is the presence of abundant tourmaline in the matrix of the Neset conglomerate, which gives the matrix a bluish black appearance. The combination of sedimentary structures, lithologies, and '*chemical fossils*', i.e. rock types interpreted as meta-evaporites, have led Nijland et al. (1993a) to propose a continental depositional environment, although a near-shore one could not be excluded. Padget (2010) proposed a shelf system in an open seaway as the depositional environment, suggesting that the Miocene Utsira formation in the North Sea could be a modern analogue. The well-known corundum-bearing gneisses, occurring north of Froland (Oftedahl, 1963; Nijland et al., 1993b), have been interpreted as metamorphosed kaolinite-bauxite weathering crusts (cf. Serdyuchenko, 1968).

Figure 4. Fossil dessication cracks in the Nidelva Quartzite Complex at Tellaugstjern (Froland area).

In case of the Nidelva quartzite complex, the minimum age of deposition is constrained by the Sm-Nd whole rock age of the intruding basic dykes at 1472 $\pm$ 69 Ma (Nijland et al., 2000). Whereas a limit for the maximum age of sedimentation is given by a $^{207}Pb/^{206}Pb$ SIMS age on the youngest detrital zircon encountered, viz. 1450 $\pm$ 40 Ma (de Haas et al., 1999). T_{DM} Nd ages for the quartzites range from 1.69 to 1.93 Ga (Andersen et al., 1995). A limit to the maximum age of deposition of the Coastal quartzite complex in the Kragerø area is given by a $^{207}Pb/^{206}Pb$ SIMS zircon age of 1484 $\pm$ 15 Ma (Åhäll et al., 1998). Given that the number of zircon grains analyzed in both studies is less than one would currently think to be necessary, both age limits are considered to be weak. Like the Nidelva quartzite complex, the Coastal quartzite complex is dominated by quartzites with occasional well-preserved sedimentary structures (Morton, 1971).

4.3. Selås banded gneisses

The Selås banded gneisses were first denominated as such by Touret (1966, 1968, 1969). They comprise a series of well banded, quartzofeldspathic gneisses alternating with amphibolites that occur in the area between Selås and Ubergsmoen (Fig. 1). They stretch down to the southwest, along Stemtjern, towards Flaten, near the Nidelva River. In general, individual bands in the quartzofeldspathic gneisses do not exceed a few cm in thickness. Banding may partly reflect primary compositional layering, but is definitively enhanced by migmatization, i.e. the gneisses show well developed stromatitic leuco-, meso-, and melanosomes. Mineralogically, the main constituents are quartz, K-feldspar, plagioclase, biotite, and opaque phases. Accessories are apatite, tourmaline, and zircon. The quartz-rich feldspathic gneisses alternate with more pure quartzitic bands. The gneisses contain frequent sulphidic and graphitic intervals. Sulphidic intervals commonly contain pyrite and chalcopyrite, but locally, layer-bound sulphidic mineralizations may have developed, including the Ettedal mine mentioned above. At Ettedal, the mineralization is accompanied by tourmalinites and associated with amphibolites. Locally, small lenses of marble, calcsilicate rocks, and metapelite occur within the Selås banded gneisses.

The Selås banded gneisses have been interpreted as metamorphosed turbidites (Touret, 1966). Starmer (1985) considered the gneisses to represent deep-water sediments with metavolcanic intercalations. Gammon (1966) suggested that sulphidic horizons (the so-called *fahlbands*) in comparable gneisses in the Kongsberg Sector were derived from sapropelic muds. Other authors (e.g. Pedersen, 1984) have suggested exhalative origins. A minimum age of deposition for the Selås banded gneisses is indicated by the 1460 ± 21 Ma (U-Pb zircon) age of the Vimme amphibolite intruding the gneisses (De Haas et al., 2002a).

4.4. General sedimentary picture

Starmer (1985, 1990, 1996) interpreted the Nidelva and Coastal quartzite complexes and Selås banded gneisses as overlying sedimentary formations. The former represent shallow water sediments (however, see Section 4.2 above) and the latter, overlying the quartzite complexes, represent deep water sediments with intercalated volcanics. Padget (2010) also divided the metasediments in the Bamble Sector into a lower and an upper series. He considered the Selås banded gneisses (grouped together with similar gneisses by Padget (2010) as the Sundebru gneisses) and the Nidelva quartzite complex as lateral equivalents in the lower series. Both are overlain by the Stavseng and Rore-Eikeland metapelites with intercalated marls. According to the interpretation of Padget (2010), the upper series are again made up by quartzites. The Selås banded (Sundebru) gneisses are overlain by quartzites from several local depositional systems in the Kragerø area (including Arøy and associated islands; Morton et al., 1970; Morton, 1971). All together they have been previously referred to as the Coastal quartzite complex. This was correlated with the Nidelva quartzite complex (see above). The Messel and Øynesvatn quartzites of Padget (2010) are then deposited on top of the Nidelva quartzite complex. Sedimentary rocks on Merdøy are considered to be equivalent to metapelites in the upper part of the lower series and the sediments from the upper series.

Crucial to the interpretation of the depositional setting of the different sedimentary series and complexes is the combination of relict sedimentary structures and lithological characteristics such as bulk chemistry. Cordierite-orthoamphibole rocks occur within all three series, viz. the Nidelva quartzite complex, the Selås banded gneisses, and the Hisøy-Merdøy supracrustal suite. In the Bamble Sector, these have been interpreted as metamorphosed evaporites (Touret, 1979; Beeson, 1988; Nijland et al., 1993a); metamorphosed low temperature altered mafic volcanics (Visser, 1995); or synmetamorphic metasomatic rocks (Engvik et al., 2011), whereas in other terranes several other origins have been proposed (see references in Touret and Nijland, 2012). Definitive elucidation of their origin(s) would provide a crucial argument in the debate on the origin of the Bamble metasediments. The high B content in the cordierite-orthoamphibole rocks, several quartzites, and the matrix of conglomerates from the Nidelva quartzite complex in Padget's (2010) lower series, and in cross-bedded quartzites from Arøy (J. Kihle pers. com., 1990) in the upper series, should also be taken into account. Another characteristic lithology is the nodular gneisses, i.e. metapelites with (variably flattened) sillimanite-quartz nodules (e.g. Brøgger, 1934b; Elliot and Morton, 1965; Nijland et al., 1993a; Fig. 5). Their occurrence is not restricted to one sedimentary series (for whichever interpretation above) and their origin is also crucial but open. A tectonic origin (Macaudière and Touret, 1969), due to dealkalinization as proposed elsewhere (Losert, 1968; Eugster, 1970), as well as a sedimentary origin as clay balls, comparable to those occurring in the German Buntsandstein (Nijland et al., 1993a), have been suggested.

In addition to the sedimentary series described above, Padget (2010) suggested that conglomerates occurring at Krokelia and Stemvatn represent a late episode of erosion, postdating peak metamorphism but predating intrusion of the Herefoss and Grimstad granites. Given the cooling and uplift path of the Bamble Sector (see Section 6.4 below), sedimentary deposition in this period seems to be rather unlikely.

5. Magmatism

5.1. Regional calcalkaline gneisses and Tromøy gneiss complex

Except for the supracrustals described in Section 4, a considerable part of the geological mass in the Bamble Sector is made up by calcalkaline granodioritic to tonalitic orthogneisses (Fig. 1). On the mainland, these intruded at 1.52–1.60 Ga (Table 1). These calcalkaline gneisses have major and trace element characteristics corresponding to those of moderately evolved modern continental arc settings and comparable to contemporaneous calcalkaline gneisses in other terranes from the Southwest Scandinavian Domain, except those of the Kongsberg Sector and the Stora-Le Marstrand belt in SW Sweden (Andersen et al., 2004). Combined with other data, it appears that these calcalkaline magmas belong to a phase of continuous felsic arc magmatism along the margin of the Baltic Shield from at least 1.66–1.50 Ga (Åhäll et al., 2000; Andersen et al., 2002a, 2004).

The bulk of the charno-enderbitic gneisses on the island of Tromøy are part of the meta-igneous Tromøy gneiss complex, dated

Figure 5. Sillimanite nodular gneiss (Oksevatn).

Table 1
Age constraints on magmatic activity in the Bamble Sector (Rb-Sr and K-Ar ages excluded).

Age (Ma)	Intrusion	Method	Reference
1601 ± 11	Gjerstadvatn tonalite	U-Pb zircon (concordant)	Andersen et al., 2004
1592 ± 13	Justøy tonalite (Hornborgsund)	U-Pb zircon (concordant)	Andersen et al., 2004
1591 ± 14	Justøy tonalite (Justøya)	U-Pb zircon (concordant)	Andersen et al., 2004
1584 + 17/-14	Arendal charnockitic gneiss	U-Pb zircon	A. Råheim, unpubl. data
1542 ± 8	Flosta gneiss	U-Pb zircon	Kullerud and Machado, 1991
1524 ± 11	Jomås granodiorite	U-Pb zircon (concordant)	Andersen et al., 2004
1479 ± 22	Nelaug gneiss	U-Pb zircon	De Haas et al., 2002a
1472 ± 69	Blengsvatn basic dykes	Sm-Nd whole rock	Nijland et al., 2000
1420 ± 18	Flosta charnockitig gneiss	U-Pb zircon (concordant)	Andersen et al., 2004
1235 ± 13	Jomåsknutene gabbro	U-Pb zircon	Graham et al., 2005
1207 ± 14	Vestre Dale gabbro	Sm-Nd WR + Pl + Opx	De Haas et al., 2002b
1205 ± 9	Drivheia gneiss	U-Pb zircon	Heaman and Smalley, 1994
1198 ± 8	Tromøy mafic gneiss	U-Pb zircon (concordant)	Knudsen and Andersen, 1999
1187 ± 2	Gjerstad augen gneiss	U-Pb zircon	Heaman and Smalley, 1994
1183 ± 8	Hisøy tonalite	U-Pb zircon (concordant)	Andersen et al., 2004
1175 ± 37	Kragerø hydrothermal dolomite	Sm-Nd whole rock	Dahlgren et al., 1993
1168 ± 2	Hovdefjell-Vegårshei augen gneiss	U-Pb zircon	A. Råheim and T.E. Krogh unpubl. data in Field et al., 1985
1152 ± 2	Gjeving augen gneiss	U-Pb zircon	Kullerud and Machado, 1991
1134 + 7/-2	Morkheia monzonite	U-Pb zircon	Heaman and Smalley, 1994
1094 ± 11	Tvedestrand pegmatite	U-Pb xenotime	Scherer et al., 2001
1060 + 8/-6	Gloserheia pegmatite	U-Pb euxenite	Baadsgaard et al., 1984
989 ± 8	Grimstad granite	U-Pb zircon	Kullerud and Machado, 1991
926 ± 8	Herefoss granite	Pb-Pb minerals	Andersen, 1997

at 1198 ± 13 Ma with a metamorphic overprint at 1125 ± 23 Ma (U-Pb SIMS zircon; Knudsen and Andersen, 1999). Rocks belonging to this phase of igneous activity also occur on the neighbouring island of Hisøy (dated at 1178 ± 9 Ma, U-Pb zircon) and possibly elsewhere in the area (Andersen et al., 2004). The Tromøy gneiss complex is made up of metaluminous, low-K mafic gneisses and tonalites with trace element signatures resembling those of evolved magmas in modern oceanic island arcs. These gneisses are subsequently intruded by trondhjemitic dykes originating from anatectic melting of leucogabbroic or dioritic members of the complex at about 1100 Ma (Knudsen and Andersen, 1999).

5.2. *Basic magmatism*

Gabbroic magmas intruded the Bamble Sector during two periods. The intrusion of cross cutting basic dykes constrains an older generation of gabbros, including the Blengsvatn gabbro, to a younger age limit of 1.47 Ga (Sm-Nd whole rock; Nijland et al., 2000). Several other gabbros intruded the Bamble Sector around 1.2 Ga. These include the Jomåsknutene gabbro, previously assigned a much older Sm-Nd whole rock age (de Haas et al., 1993a), but dated by U-Pb zircon at 1235 ± 13 Ma (Graham et al., 2005), and the small Vestre Dale gabbro, dated at 1207 ± 14 Ma by a Sm-Nd whole rock + plagioclase + orthopyroxene isochron (de Haas et al., 2002b). A remarkable feature is the relatively small scale and abundance of the gabbroic intrusions. Some are only tens of metres in diameter at outcrop level. Nevertheless, they can show distinct chemical zonations from troctolitic to olivine to ferrogabbro like the Vestre Dale gabbro (de Haas et al., 1992), or from orthopyroxenite to orthopyroxene troctolite to troctolite in the Messel gabbro (Brickwood, 1986). They can also show metamorphosed but otherwise well preserved igneous modally graded layering (Fig. 6) and magmatic sedimentary features (e.g. de Haas et al., 1993b). Associated with the gabbros are nickel sulphide mineralizations, which have been actively mined (Boyd and Nixon, 1985; Brickwood, 1986).

All gabbros have tholeiitic signatures. However, within the group of ca. 1.2 Ga gabbros (i.e. those actually dated and those from field relationships deduced to belong to the same period of basic magmatism), two distinct geochemical populations are present. These include those enriched in LREE and LILE such as the Vestre Dale gabbro, Flosta gabbro, and a part of the Jomåsknutene gabbro, and those depleted in LREE and LILE, such as the Arendal gabbro, Tromøy gabbro, and the remaining part of the Jomåsknutene gabbro (de Haas, 1992; de Haas et al., 1993a). The Vestre Dale gabbro exhibits high whole rock Ni and MgO contents, with low initial $^{87}Sr/^{86}Sr$ ratios, indicating a basaltic parental liquid. However, forsterite contents in the olivine are too low to have been in equilibrium with primary, mantle-derived melts; the gabbros crystallized from magmas that had already fractioned olivine (de Haas, 1992; de Haas et al., 1992). Gabbros from both populations have clear negative Nb anomalies (Atkin and Brewer, 1990; de Haas et al., 1993a). LREE, LILE, Sr and Nd isotope characteristics have been interpreted to reflect derivation from a single, variably metasomatized mantle source that came into existence during the early Mesoproterozoic events (de Haas et al., 1993a, 2000).

In both sets of gabbros, coronitic microstructures between olivine and plagioclase and between ilmenite and plagioclase are found. Their occurrence (Sjögren, 1883) was noted only a few years after their first description in Sweden by Törnebohm (1877).

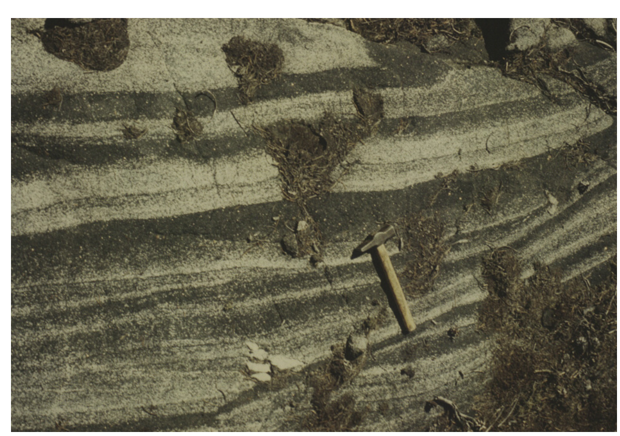

Figure 6. Metamorphosed but otherwise well preserved modally graded layering in the small Kverve gabbro (Froland area).

The origin of these microstructures has been debated since, both in terms of metamorphic (e.g. Törnebohm, 1877; Lacroix, 1889; Ashworth, 1986) and late magmatic subsolidus reactions (e.g. Adams, 1893; Joesten, 1986a,b). Detailed SEM, REE, and Sm-Nd mineral isotope data on olivine-plagioclase coronas from the 1.21 Ga Vestre Dale gabbro show that the coronas formed as a result of multistage, late magmatic processes, with initial formation of orthopyroxene by partial dissolution of olivine as an inner shell, subsequent formation of orthopyroxene + spinel symplectites as an outer shell, and final replacement of this precursory outer shell by calcic amphibole, with local availability of fractionated magma as the limiting factor (de Haas et al., 2002b; Fig. 7).

Besides the gabbroic intrusions, several small, isolated ultrabasic bodies occur in the Bamble Sector that are not associated with the metagabbros. These include (spinel) lherzolite bodies at Solemsvatn, Gullknap, and Østebø; dunite at Frivoll and Nelaugtjern; orthopyroxene-clinopyroxene hornblendite at Åsvann; and corundum-actinolite rocks at Bjormyr. The Solemsvatn spinel lherzolite and the Nelaugtjern dunite are among the most primitive basic rocks encountered in the Bamble Sector and Telemark Sector, with minor LREE enrichment and slight HREE depletion for the Solemsvatn lherzolite and significant HREE depletion, Eu anomalies, and Mg-rich olivine (Fo_{88}) for the dunite. Neodymium-depleted mantle model ages of 1.63–1.78 Ga and 1.44–1.77 Ga for the Solemsvatn lherzolite and Nelaugtjern dunite, respectively, provide minimum estimates for the timing of lithosphere formation and enrichment (de Haas et al., 2000).

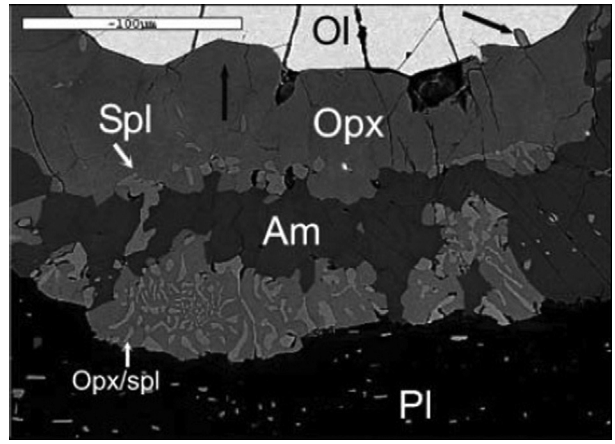

Figure 7. SEM microphotograph of subsolidus coronitic microstructure in the Vestre Dale gabbro with an inner shell of columnar orthopyroxene, and an original outer shell of orthopyroxene + spinel symplectite, partially replaced by amphibole (After de Haas et al., 2002b).

5.3. Granitic-charnockitic augen gneisses

A suite of granitic to charnockitic magmas, now augen gneisses, were intruded in the Bamble Sector along and across the boundary with the Telemark Sector as well as in the central part of the sector between 1.12 and 1.19 Ga (Fig. 1). These comprise, in part, the augen gneisses from Hovdefjell-Vegårshei (1168 ± 2 Ma, U-Pb zircon; A. Råheim and T.E. Krogh unpubl. data in Field et al., 1985); Ubergsmoen (ca. 1.12 Ga, Pb-Pb; Andersen et al., 1994); Gjeving (1152 ± 2 Ma, U-Pb zircon; Kullerud and Machado, 1991); and Gjerstad (1187 ± 2 Ma, U-Pb zircon; Heaman and Smalley, 1994). They also include the younger Morkheia monzonite suite associated with the Gjerstad augen gneiss (1134 + 7/−2 Ma, U-Pb zircon; Heaman and Smalley, 1994), as well as the undated Laget body. The Pb isotope systematics of the Ubergsmoen augen gneiss indicates that magmas were extracted from the mantle to form a crustal precursor at 1.9–1.6 Ga, i.e. prior to or during the Gothian orogeny. This was followed by anatexis, igneous differentiation, and synmetamorphic emplacement at ca. 1.12 Ga (Andersen et al., 1994).

These magmas intrude an already high-grade gneiss complex, dated at ca. 1.6 Ga; Andersen et al., 2004), in which the main gneissosity and stromatitic migmatization were isoclinally folded with development of new axial planar leucosomes. Both phases of deformation and migmatization are cut by augen gneisses (D1–D3 of Starmer (1985); D1/MIG1–D2/MIG2 of Nijland and Senior (1991); Fig. 8). The augen gneisses represent excellent time markers for the separation of Sveconorwegian and earlier metamorphic events. Around some of the intrusions, contact metamorphic aureoles developed (Hagelia, 1989; Nijland and Senior, 1991; see Section 6.3). The augen gneisses themselves have widely been considered as synkinematic intrusions, with the magmatic pyroxene assemblage being almost completely metamorphically recrystallized (Touret, 1967a, 1968; Hagelia, 1989; Nijland and Senior, 1991; Andersen et al., 1994).

Of these intrusions, the Morkheia monzonite suite displays all the features of an anorthosite-monzonite-charnockite suite, except for the presence of major cumulate anorthosites (Milne and Starmer, 1982). However, at least one large anorthosite xenolith occurs at Morkheia Summit. The Morkheia monzonite suite is composed of (meta) gabbros and diorites, together with granodioritic (augen) gneisses, i.e., if one assumes that the Gjerstad Augen Gneiss is a member of the complex. Various primary magmatic structures are present in the least deformed area of the diorite. The gabbros range from olivine ferrogabbro to ferrogabbro. The diorites range from ferrosyenodiorite via mangerite to monzonite. The rocks have high to extremely high Fe/Mg ratios; are depleted in Mg, V, Ni, and Cr; and are enriched in Mn, K, Na, Ti, Zr, Ba, P, and La (Milne and Starmer, 1982). The anorthosite xenolith has a primary assemblage of plagioclase + olivine + spinel + orthopyroxene + late biotite. Coronas of colourless clinoamphibole have developed around olivine, whereas spinel is often rimmed by talc. Metamorphic orthopyroxene developed at the expense of magmatic biotite, likely a contact metamorphic effect due to the surrounding intrusion. The Morkheia monzonite suite itself consists of a virtually undeformed core and mylonitized marginal zones, amongst them the so-called *inverse augen gneisses* of Touret (1968), with mafic augen in a leucocratic matrix. The marginal zones contain augen of clinopyroxene, sometimes replaced by hornblende, and perthititc porphyroclasts. The clinopyroxene often has extremely long tails of fine-grained hornblende + biotite ± orthopyroxene. After the mylonitic deformation, assumed to be identical to the D3 shear deformation in the Ubergsmoen augen gneiss (cf. Nijland and Senior, 1991), large poikiloblastic orthopyroxene developed at the expense of biotite and hornblende. Although the core is macroscopically undeformed and the coronas seem to be unstrained, microstructures in olivine present in the fayalite mangerite of Touret (1967b) indicate severe deformation.

Both the Ubergsmoen and Hovdefjell-Vegårshei augen gneiss are elongated, somehat assymetric bodies and have been mapped as zoned intrusions with charnockitic cores surrounded by granitic rims (Touret, 1968; Hagelia, 1989). In the case of the Hovdefjell-Vegårshei augen gneiss, this includes the charnockitic parts in the southwest and the granitic parts in the northeastern part of the intrusion. The Ubergsmoen augen gneiss shows charnockitic domains throughout the entire intrusion, though less along the margins. The intrusion contains both mafic (gabbro, amphibolite) xenoliths as well as fine grained gneiss xenoliths, occasionally with a stable orthopyroxene + scapolite + plagioclase assemblages. The augen in the Ubergsmoen augen gneiss are made up of coarse grained K-feldspar, often partially or completely recrystallized to

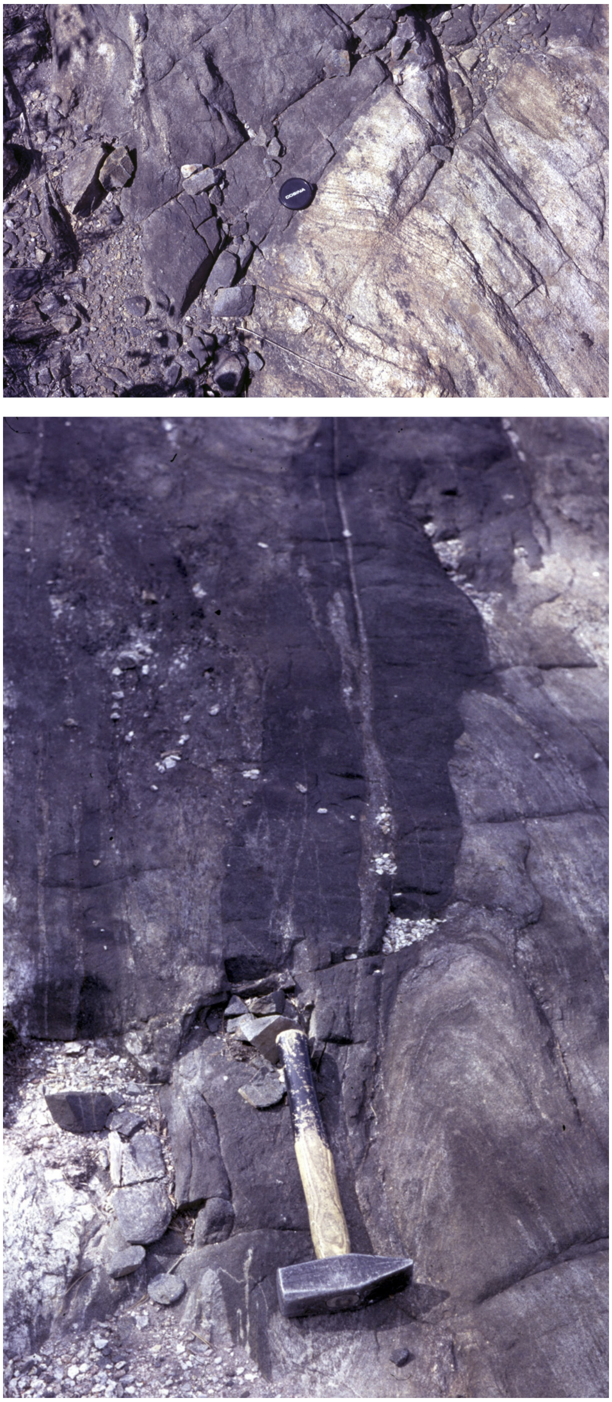

Figure 8. Well developed, folded leucosomes in granodioritic to tonalitic gneiss truncated by metamorphosed basic dykes. As the dykes themselves have a contact metamorphic granulite-facies imprint by the early Sveconorwegian Ubergsmoen augen gneiss, the truncated leucosomes provide evidence for older, pre-Sveconorwegian high-grade metamorphism (Nijland and Senior, 1991).

equigranular, perthitic microcline, in a matrix of medium grained, polygonal plagioclase + quartz. Accessory zircon, apatite, and allanite are common. Ilmenite and rare pyrrhotite, chalcopyrite, and pyrite are present in the mafic domains. Mafic minerals in the Ubergsmoen augen gneiss document four successive metamorphic stages. These include recrystallized ortho- and clinopyroxene + plagioclase, which are succeeded by hornblende (hastingite) + quartz ± biotite, and later overprinted locally by garnet ± clinopyroxene. Orthopyroxene may be extremely Fe-rich, with ferrosilite contents of up to 91%, but show a considerable range in composition ($En_{6-25}Fs_{68-91}Wo_{0-3}$) (Vogels, 1991; Lieftink, 1992). Later retrogression resulted in the replacement of orthopyroxene by grunerite + magnetite ± quartz and the formation of grunerite between orthopyroxene and hornblende. With an X_{Mg} of 0.20 (Verheul, 1992), the experimental data by Fonarev and Korolkov (1980) constrain the formation of grunerite at ca. 730–740 °C and 500 MPa.

In case of the Hovdefjell-Vegårshei augen gneiss, fluid inclusion data indicate an early H_2O-poor, CO_2-N_2-rich fluid for the charnockitic stage (Ploegsma, 1990). CO_2-rich fluid inclusions have also been encountered in the Ubergsmoen augen gneiss, but the N_2-component is absent here (J.L.R. Touret, pers. com., 1992). In part of the Ubergsmoen augen gneiss, (Na,K)Cl brines occur as fluid inclusions, associated with the late formation of garnet. Accompanying plagioclase is often scapolitized. This close spatial relationship between (Na,K)Cl brine inclusions and a late anhydrous assemblage indicates that infiltration by low H_2O activity (Na,K)Cl brines resulted in progressive dehydration during retrograde cooling and uplift, giving rise to apparently high grade mineral assemblages (Nijland and Touret, 2000).

5.4. Granitic pegmatites

Parts of the fame of the Bamble Sector are the many fine mineral specimens found in the granite pegmatites (Nijland et al., 1998b). Well known among the granitic pegmatites are those of Gloserheia (Bjørlykke and Sverdrup, 1962; Åmli, 1975, 1977; Baadsgaard et al., 1984; Harlov, 2012a), Narestø (Forbes and Dahll, 1855; Andersen, 1931; Eakin, 1989), Lauvrak (Ihlen et al., 2001), and Auselmyra (Bakken and Gleditsch, 1938) in the Froland area, and Lindvikskollen, Kalstad, and Tangen pegmatites in the Kragerø area (Brøgger, 1906; Andersen, 1931; Green, 1956; Larsen, 2008). These granitic pegmatites are very coarse-grained with feldspar and biotite crystals up to metres in length. The pegmatites from the Froland area show the typical zoned structure of complex pegmatites, with an occasional border zone, a wall zone, and one or more intermediate zones surrounding a core (Bjørlykke, 1937; Åmli, 1977; Larsen, 2002). The pegmatites consist of (macroperthitic) K-feldspar, plagioclase, and quartz, with accessory biotite, muscovite, apatite, and tourmaline. The occurrence of so-called *solstein*, i.e. oligoclase with interspersed hematite flakes, is an attractive feature of several pegmatites in the area (e.g. Weibye, 1847; Divljan, 1960; Copley and Gay, 1978, 1979). The pegmatites are enriched in REE, Nb, and Ta (Larsen, 2002). Common accessory minerals include xenotime, monazite, allanite-(Ce), gadolinite, columbite, euxenite-(Y), fergusonite, samarskite, uraninite, and thorite. More rarely, aeschinite-Y, yttrotantalite-Y, fourmanierite, uranophane, kasolite, hellandite, and phenakite occur (Brøgger, 1906; Brøgger et al., 1922; Bjørlykke, 1939; Nijland et al., 1998b and references therein). The granitic pegmatites of the Froland area, like those from the Evje-Iveland district, were derived from parental magmas with low Sr. The Froland pegmatites had a relatively HREE-rich, LREE-poor source (Larsen, 2002). They belong to the mixed type, i.e. intermediate between the Li-Cs-Ta and Nb-Y-F families of pegmatites (Černý, 1991). While the chemistry of feldspars and biotite reflects changes in melt composition, the quartz trace element chemistry is, however, remarkably similar for all pegmatites in the Froland area (Müller et al., 2008).

Most of the age determinations for the pegmatites reflect closure ages. The only well-dated pegmatites are those at Gloserheia at 1060 + 8/−6 Ma (U-Pb euxenite; Baadsgaard et al., 1984) and one near Tvedestrand at 1094 ± 11 Ma (U-Pb xenotime; Scherer et al., 2001). The implication of this age is that REE-enriched granitic pegmatites are considerably older than the post-tectonic Herefoss and Grimstad granites (see Section 5.5 below) and are synorogenic (cf. Müller et al., 2008). Indeed the pegmatites underwent deformation kinematically related to west-verging thrust and fold tectonics along the Porsgrunn-Kristiansand shear zone roughly around 1.1 Ga (Henderson and Ihlen, 2004). A second group of pegmatites are the so-called low-angle pegmatites. These are thin (<2 m thick), barren, granitic pegmatite sheets, which generally intrude their country rocks at a low angle with respect to the horizontal (Nijland, 1993). They cut across and hence postdate the 1.06 Ga granitic sheets on Tromøy (Rb-Sr whole rock, Field and Råheim, 1979).

5.5. Post-tectonic granites

Two post-tectonic granites feature prominently on a geological map of the Bamble Sector, viz. the Grimstad and Herefoss granites (Fig. 1). The Herefoss granite is a nearly circular granitic body emplaced over the margin of the Bamble and the Telemark Sectors. Gravity data indicate a funnel-shaped body (Smithson, 1963). The pluton is made up of two medium- to coarse-grained bodies, with a smaller, fine grained and more differentiated granite (individually called the Holtebu granite) extending north from the main body (Elders, 1963; Annis, 1974). Whole rock analysis by Elders (1963) shows 64–75 wt.% silica and minor amounts of normative wollastonite or corundum. Sr-Nd isotope relationships show derivation from two sources, viz. a crustal source residing in a moderately LILE-enriched 1.6–1.9 Ga crustal reservoir and a mantle component younger than 1.5 Ga. Intrusion of the Herefoss granite is constrained by a Pb-Pb mineral isochron of 926 ± 8 Ma (Andersen, 1997) and U-Pb zircon upper intercept age of 920 + 16/−27 Ma (Andersen et al., 2002b).

The Grimstad granite is a roughly egg-shaped pluton cut off by the present day coastline. Gravity data indicate a cylindrical-shaped body (Smithson, 1963). The pluton is made up of medium grained granite with small, fine-grained granite and dykes as well as monzonitic enclaves in the main body. Aplitic dykes cut across both the granite and monzonitic enclaves. Part of the granite is porphyritic, with mantled plagioclase and K-feldspar (Christie et al., 1970). The pluton shows a chemical zonation, with total Fe and CaO increasing and K_2O decreasing towards the core (Christie et al., 1970). The granite has been dated by the U-Pb zircon method at 989 ± 8 Ma (Kullerud and Machado, 1991). Both the Herefoss and Grimstad granite belong to a suite of post-tectonic granitic intrusions in south Norway, whose intrusion is thought to have been related to the collapse of the Sveconorwegian orogen (Eliasson, 1992; Andersen et al., 2002b), though some granites (including Grimstad) are relatively old.

5.6. Phanerozoic magmatism

Phanerozoic magmatism in the Bamble Sector is mainly manifested by the intrusion of late basic to ultrabasic dykes (dolerites, lamprophyres, and rhombporphyry dykes). Most of these dykes are related to Permian Oslo Rift magmatism (Carstens, 1959; Sundvoll and Larsen, 1993), whereas some intruded during the Tertiary (Storetvedt, 1968). Some of these dykes are possible pre-Permian, with one yielding a Sm-Nd whole rock age of 354 ± 71 Ma (Moree et al., 1996). Some contain vacuoles with hydrocarbons (Dons, 1975).

6. Metamorphism

6.1. Pre-Sveconorwegian high-grade metamorphism

Isotopic age determinations over the last two decades demonstrate a Sveconorwegian age for granulite-facies metamorphism in the Bamble Sector (see below). Isotopic mineral age determinations, as such, are generally not considered to reflect Gothian (or other Pre-Sveconorwegian) high-grade metamorphism anymore. However, field relationships unequivocally demonstrate the presence of Pre-Sveconorwegian, presumably Gothian, high-grade metamorphism in the form of widespread migmatization, which regionally reached upper amphibolite-facies (Starmer, 1969a,b, 1972a,b, 1985, 1990, 1993; Nijland and Senior, 1991). These well developed stromatitic migmatites (Gupta and Johannes, 1982) were already deformed prior to the intrusion of Early Sveconorwegian intrusions such as the granitic-charnockitic Ubergsmoen augen gneiss (Fig. 8).

6.2. Sveconorwegian high-grade metamorphism

The central part of the Bamble Sector, i.e. in the region around Arendal and including the islands of Tromøy, Hisøy, and associated smaller islands, shows a well developed amphibolite- to granulite-facies transition zone, with granulite-facies rocks occurring on Tromøy, Hisøy and other islands along the coast and up to several kilometres inland (Fig. 1). The remainder of the Bamble Sector generally consists of upper amphibolite-facies rocks with some exceptions (see below). Starting inland in the amphibolite-facies zone and moving towards the coast, the transition to granulite-facies is characterized by an isograd sequence consisting of muscovite-out in quartzitic rocks, cordierite-in in metapelitic rocks, orthopyroxene-in in metabasic rocks, and orthopyroxene-in in granitoid gneisses, which nearly coincide with allanite-out and titanite-out in the gneisses, metapelites, and amphibolites (Touret, 1971b; Nijland and Maijer, 1993; Fig. 1). In the highest-grade portion of the granulite-facies zone (centred on the Arendal area, Tromøy, and Hisøy), orthopyroxene is particularly abundant in the tonalitic (enderbitic) leucosomes (Fig. 9). Granulite-facies dehydration bands formed at the contact between amphibolites and tonalitic gneisses (Fig. 10). In the granulite-facies metabasites and tonalites, ubiquitous K-feldspar micro-veins occur (Harlov et al., 1998; Fig. 11), similar to those documented in several other tonalitic granulite-facies terranes (e.g. Coolen, 1980; Hansen et al., 1984; Harlov and Förster, 2002; Hansen and Harlov, 2007; see also discussion in; Touret and Nijland, 2012). The isograds are accompanied by the increasing recrystallization of sillimanite from a fibrolitic habit to a euhedral prismatic habit. In addition, isopleths for Ti in hornblende and biotite in basic rocks increase with increasing metamorphic grade from amphibolite-facies to granulite-facies. Calculated $Fe^{2+}/(Fe^{3+} + Fe^{2+})$ ratios of both biotite and hornblende also vary with metamorphic grade (Nijland, 1993).

Like most terranes, the prograde P-T path is only recorded by specific rock types of suitable bulk chemistry (Fig. 12). Visser and Senior (1990) deduced the P-T path of Na-Mg-rich cordierite-orthoamphibole rocks from the Froland area in the amphibolite-facies part of the transition zone. Their P-T path is essentially clockwise. The oldest assemblage present in these rocks (M1) is made up by andalusite + gedrite + tourmaline. M2 involves replacement of andalusite by kyanite, formation of staurolite, and strong Na-Al-Mg zoning in orthoamphibole, reflecting an increase in metamorphic conditions from 500 to 650 °C and 400 to 800 MPa. Peak metamorphism is documented in two stages, M3a and M3b. M3a (600–700 °C, 600–700 MPa) involved the formation of cordierite ± corundum at the expense of kyanite, staurolite, and orthoamphibole, and the formation of cordierite rims between orthoamphibole + corundum. It also involved the formation of Fe-Al-rich kornerupine as coronas between biotite and various oxide phases (Zn-rich spinel, ilmenite, rutile, corundum). P-T conditions for the latter coronas are estimated at 630–720 °C, 600–800 MPa (Visser, 1995), in general agreement with M3a. M3b reflects a static

Figure 9. Orthopyroxene-bearing leucosomes in mafic gneiss at Hove on the island of Tromøy.

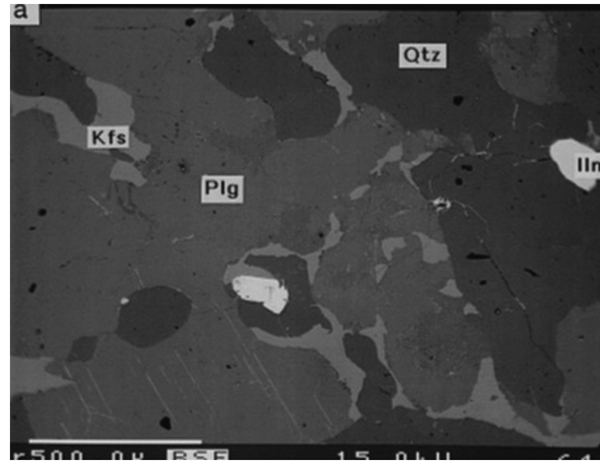

Figure 11. BSE image of K-feldspar microveins at the contact between plagioclase and quartz (Harlov et al., 1998).

metamorphic climax involving the development of garnet at 740 ± 60 °C, 700 MPa. Retrograde metamorphism in these rocks involved formation of talc + kyanite + quartz (M4a, 350–600 °C, 600–700 MPa) and chlorite + kyanite + andalusite + quartz (M4b, 420–530 °C, 300–400 MPa). Granulite-facies metapelites on the islands of Hisøy and Torungen record a three stage metamorphic evolution (Knudsen, 1996). Assemblages enclosed in garnet, viz. staurolite + chlorite + albite, staurolite + hercynite + ilmenite, cordierite + sillimanite, and hercynite + biotite ± sillimanite, define a prograde M1 at 360 ± 50 MPa with maximum temperatures of 750–850 °C. They are thought to be related to the thermal effects from basic magmatism prior to peak metamorphism. The latter, M2, is characterized by quartz + plagioclase + K-feldspar + garnet + biotite ± sillimanite with P-T conditions of 790–884 °C, 590–910 MPa. Retrograde M3 amphibolite-facies assemblages in the metapelites indicate temperatures of 516–581 °C at 170–560 MPa. If these stages reflect a continuous P-T path, this path is counter-clockwise, in contrast to that of Visser and Senior (1990). This may be explained either by a different evolution of the coastal zone with respect to the mainland, or, alternatively, that the oldest phase of metamorphism does not belong to the same event. The latest, high temperature phase of regional metamorphism has, over the last decade, been shown to be Sveconorwegian. An overview of relevant mineral ages is given in Table 2.

Figure 10. Dehydration band between amphibolite and tonalitic gneiss, Tromøy.

Hornblende-plagioclase thermometry and garnet-hornblende-plagioclase-quartz barometry indicate P-T conditions of ca. 750 °C and 710 MPa for the amphibolite-facies rocks (Nijland and Maijer, 1993). P-T estimation utilizing garnet-orthopyroxene, orthopyroxene-clinopyroxene, hornblende-plagioclase and titanomagnetite-ilmenite thermometry and garnet-orthopyroxene-plagioclase-quartz and garnet-plagioclase-aluminosilicate-quartz barometry indicate temperatures and pressures of ca. 795–830 °C and 700–740 MPa for the granulite-facies rocks (Harlov, 1992, 2000a,b; Nijland and Maijer, 1993; Knudsen, 1996). Kihle et al. (2010) obtained considerably higher temperature and pressure estimates of 930 °C and 1000 MPa for a quartz + corundum-bearing sapphirine + garnet boudin on the island of Hisøy. They attributed lower P-T estimates to be '*due to extensive overprinting by fluid-present conditions*', though the lower P-T estimates mentioned above involve low α_{H_2O}, orthopyroxene-bearing assemblages.

The upper amphibolite-facies area is dotted with several 'granulite-facies islands' north of the orthopyroxene-in isograds (Fig. 1). These occur as two different types. Type 1 consists of Mg-rich coriderite-orthoampibolite rocks, which show peak metamorphic orthopyroxene and/or kornerupine-bearing assemblages (Visser and Senior, 1990; Visser, 1993, 1995). In type 2, the local action of (Na,K)Cl brines resulted in the formation of typical granulite-facies assemblages in metapelites. These included the breakdown of biotite + quartz to orthopyroxene + K-feldspar and sapphirine + albite ± spinel assemblages at Hauglandsvatn (Nijland et al., 1998a; Fig. 13) and the formation of sapphirine + corundum in metagabbro at Ødegården (Engvik and Austrheim, 2010).

After the peak of Sveconorwegian metamorphism, the coastal zone and the adjacent part of the amphibolite-facies area underwent isobaric cooling (Visser and Senior, 1990; Nijland et al., 1993b). An exception to this is the Nelaug area, directly adjacent to the Porsgrunn-Kristiansand shear zone, where a P-T increase seems to have followed initial cooling (Nijland, 1993).

6.2.1. Fluid composition

The granulite-facies rocks are characterized by the occurrence of high-density CO_2 fluid inclusions in orthopyroxene-bearing tonalitic gneisses (Touret, 1970, 1971a,c, 1985). Gaseous CO_2 ± N_2

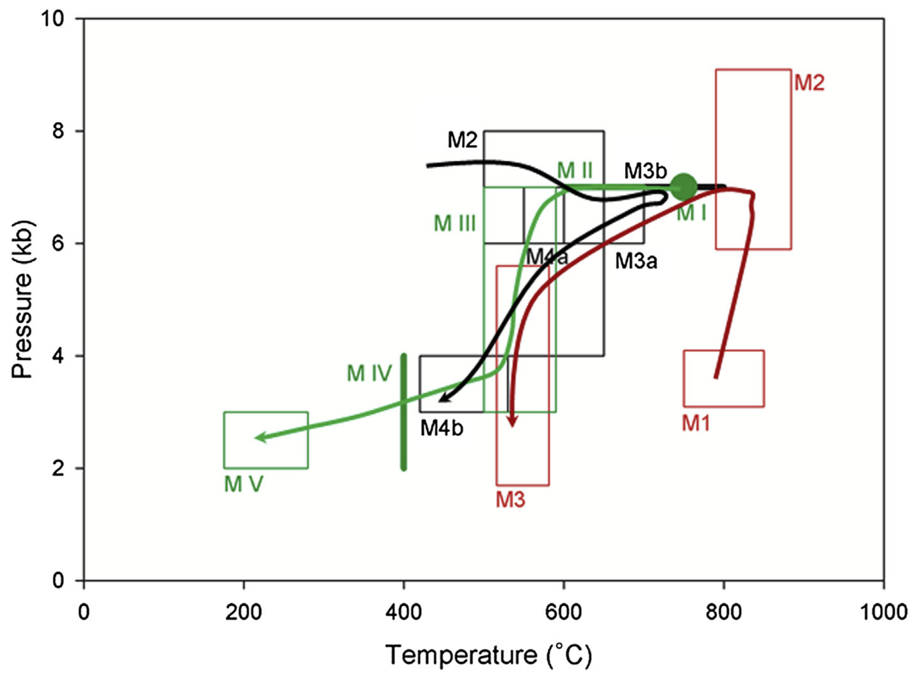

Figure 12. Summary of prograde and retrograde P-T paths for the central part of the Bamble area. In black, the P-T path as recorded by cordierite-orthoamphibole rocks in the amphibolite facies Froland area (Visser and Senior, 1990); in red, the P-T path as recorded by metapelites in the granulite facies Hisøy-Torungen area (Knudsen, 1996); in green, the cooling and uplift path deduced from the Froland corundum-bearing rocks (Nijland et al., 1993b). Note that modelling by Sørensen (2007) shifts temperatures of the latter by about hundred degrees lower.

inclusions show a wide range of homogenization temperatures between −27 and 31 °C, corresponding to densities of 1.06 and 0.47 g/cm^3 (Touret, 1985; Van den Kerkhof et al., 1994). A genetic relationship between the occurrence of CO_2-rich fluids and the development of anhydrous granulite-facies assemblages was suggested and has been debated since, especially the source and mode of transfer of these carbonic fluids into the lower continental crust. Carbon isotopes indicate a juvenile signature for the CO_2 (Hoefs and Touret, 1975; Van den Kerkhof et al., 1994). In addition, orthopyroxene-bearing dehydration rims contain magmatic CO_2 (Knudsen and Lidwin, 1996). In contrast to the fluid inclusions, with increasing metamorphic grade IR spectroscopic data indicate that the cordierite channels show a decrease in CO_2, type-II H_2O, Na, and possibly Li, whereas X_{H_2O} and type-I H_2O-contents are variable (Visser et al., 1994).

Other indicators of fluid activity, in both the amphibolite and granulite-facies rocks, include the carbon and oxygen isotope systematics of graphite and carbonate in metasedimentary rocks (Broekmans et al., 1994), and the halogen chemistry of apatite and hydrous silicates (Nijland et al., 1993c). These demonstrate that here fluid equilibria were local and not affected by pervasive streaming of CO_2; rather, isotope equilibria reflect premetamorphic trends (Broekmans et al., 1994). The occurrence of CO_2 fluid inclusions is complemented by the occurrence of (Na,K)Cl brines, in particular in metasedimentary rocks (Touret, 1971a, 1972, 1985).

Table 2
Mineral ages constraining high grade metamorphism in four areas in the Bamble Sector, viz. the Tromøy-Arendal-Tvedestrand area, i.e. the granulite facies part of the transition zone, the Froland area, i.e. in the middle of the amphibolite facies part of the transition zone, the Nelaug area, i.e. the amphibolite facies stretch along the Porsgrunn-Kristiansand shear zone separating the Bamble Sector from the Telemark block, and, for comparison, the Risør-Kragerø amphibolite facies area in the northeast.

Mineral/method	Tromøy Arendal Tvedestrand	Froland	Nelaug	Risør Kragerø
Titanite, Pb-Pb	1103-1141		994, 1091	1104-1107
Allanite, Pb-Pb	1108-1128			
Monazite, U-Pb	1135-1145	1107-1134		1127
Zircon, U-Pb (incl. lower intercepts and overgrowths)	1105-1125	1097		
WR + minerals, Sm-Nd	1073-1107			1201

Data from: Kullerud and Machado (1991), Kullerud and Dahlgren (1993), Cosca et al. (1998), Knudsen and Andersen (1999), de Haas et al. (2002a), Graham et al. (2005), Bingen et al. (2008a).

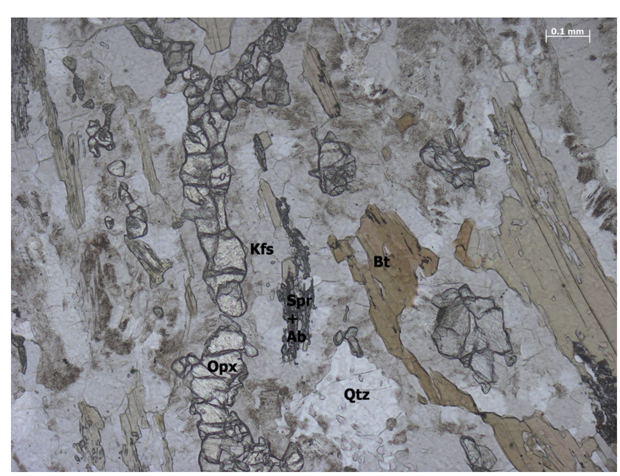

Figure 13. Microphotographs of orthopyroxene + K-feldspar rims between biotite + quartz and sapphirine + albite symplectites, both in response to brine-controlled formation of a 'granulite facies island' at Hauglandsvatn, well in the amphibolite facies part of the transition zone (Fig. 1) (Nijland et al., 1998a).

(Na,K)Cl brine inclusions also occur in orthopyroxene-bearing enderbitic rocks, where they are associated with prograde metamorphism and with CO_2 during granulite-facies peak metamorphism (Knudsen and Lidwin, 1996). Low H_2O activity (Na,K)Cl brines are proposed to be one of the mechanisms behind the formation of K-feldspar microveins (Harlov et al., 1998). Locally, their action in lowering the H_2O activity resulted in the formation of anhydrous assemblages in both the metasediments (Nijland et al., 1998a) and in the igneous rocks (Nijland and Touret, 2000).

6.2.2. Granulite-facies oxide-sulphide textures

Primary oxide minerals in the granulite-facies rocks from the Bamble Sector (especially Tromøy and Hisøy) include magnetite, titaniferous magnetite, ilmenite, and hemo-ilmenite (Harlov, 1992, 2000b). Titaniferous magnetite grains contain ilmenite in varying stages of exsolution (Fig. 14a, b) whereas the majority of the ilmenite grains (85%) contain hematite also in varying stages of exsolution (Fig. 14c). Titaniferous magnetite grains outnumber the ilmenite grains by at least 4 to 1, and more generally 8 to 1.

In thin section, the primary sulphide phase in the granulite-facies rocks is pyrrhotite (Harlov, 1992, 2000b,c). Pyrite also occurs, but in much lesser amounts; in some cases, pyrite may be secondary. Much more rarely, pyrrhotite can form close associations with discrete grains of chalcopyrite, ilmenite, pyrite, and (titaniferous) magnetite. Chalcopyrite is the common Cu-bearing phase and is almost always associated with isolated pyrrhotite grains in the form of either lamellae and/or as lenticular blebs within the body of the pyrrhotite grain (Fig. 14d). This would suggest that the chalcopyrite exsolved from the pyrrhotite with which it has a limited solid solution at temperatures between 700–900 °C at <100 bar (Harlov, 2000c).

Temperatures and oxygen fugacities were estimated for the granulite-facies rocks using the titaniferous magnetite-ilmenite thermometer/oxygen barometer of Ghiorso and Sack (1991), which is based on the exchange reaction: magnetite (Fe_3O_4) + ilmenite ($FeTiO_3$) = ulvöspinel (Fe_2TiO_4) + hematite (Fe_2O_3) (Harlov, 1992, 2000b). Two oxygen barometers were applied to the samples. The first is based on the oxidation reaction between the magnetite component in the titaniferous magnetite and the hematite component in the ilmenite: 6 hematite (Fe_2O_3) = 4 magnetite (Fe_3O_4) + O_2. The second oxygen barometer is internally consistent with the first (see discussion in Harlov, 1992, 2000b), and is based on the equilibrium between the ferrosilite component in orthopyroxene, the magnetite component in titaniferous magnetite and quartz: 2 magnetite (Fe_3O_4) + 6 quartz (SiO_2) = 3 ferrosilite ($Fe_2Si_2O_6$) + O_2.

Temperatures and titaniferous magnetite-ilmenite oxygen fugacities are plotted for granulite-facies samples from the islands of Tromøy and Hisøy (Fig. 15a) and the mainland (Fig. 15b), estimated using a mean pressure of 7.5 kilobars (cf. Harlov, 1992, 2000a). The large range of values cluster along the mean ulvöspinel isopleth for the titaniferous magnetite grains for all the samples. This strongly suggests that the large range in temperatures and oxygen fugacities is primarily caused by variability in the Fe_2O_3-component among the ilmenites, since independent variation in X_{Hm} causes movement along the X_{Usp} isopleth (cf. Frost et al., 1988; Lindsley et al., 1990; Harlov, 1992). This variability in the hematite component is also commonly seen among the ilmenite grains from just one sample (cf. Harlov, 1992). The reason why this variability occurs along the X_{Usp} and not the X_{Ilm} isopleth is that the titaniferous magnetite grains greatly outnumber the ilmenite grains. The extent to which the compositions of the titaniferous magnetite and

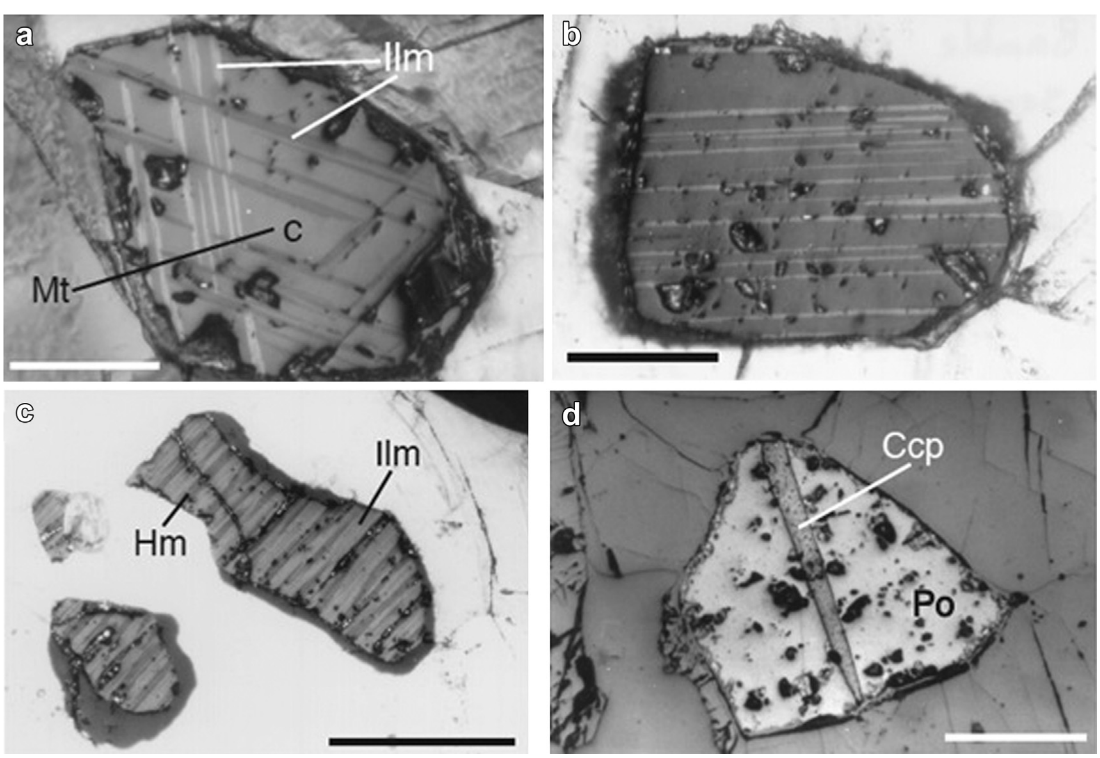

Figure 14. Examples of titaniferous magnetite grains from the granulite-facies rocks showing ilmenite (Ilm) in varying stages of exsolution in the magnetite host (Mt) including a trellis pattern of thin lamellae (a) and multiple horizontal, linear thin lamellae (b); the bar in each figure is 100 μm. (c) shows an ilmenite grain with hematite (Hm) exsolution lamellae in ilmenite (Ilm). The hematite lamellae contain secondary ilmenite exsolution lamellae; the bar is 200 μm. (d) shows a pyrrhotite grain with a chalcopyrite exsolution lamella. Both the oxide and sulphide grains are surrounded by plagioclase and quartz; the bar is 100 μm.

ilmenite grains change during re-equilibration, and hence the $T-\log_{10}fO_2$ trend followed, is governed by the relative proportions of the oxides present (cf. Frost et al., 1988). Since titaniferous magnetite grains are much more abundant than the ilmenite grains, the interoxide cooling trend follows the X_{Usp} isopleth with the ilmenites changing their composition, apparently in a variable manner, while the composition of the titaniferous magnetite grains changes relatively much less.

Orthopyroxene-titaniferous magnetite-quartz and titaniferous magnetite-ilmenite oxygen fugacities are plotted against titaniferous magnetite-ilmenite temperatures in Fig. 16c for all granulite-facies samples. Samples at high temperature and $\log_{10}fO_2$ show the best agreement in oxygen fugacity between both oxygen barometers. These are considered to preserve near-equilibrium compositions. For samples plotting below 725 °C, the oxygen fugacity estimated from titaniferous magnetite-ilmenite is always below that estimated from orthopyroxene-titaniferous magnetite-quartz. This increase in discrepancy is proportional with decreasing temperature, which is consistent with the inference that there is an increasing disequilibrium between the two assemblages with decreasing apparent temperature. It suggests a direct correlation between decreasing temperature and retrograde resetting of the oxide minerals, specifically ilmenite.

Together, the linear combination of the equilibria magnetite + ilmenite = ulvöspinel + hematite and magnetite + quartz = ferrosilite + O_2 defines the so-called QUIlP equilibrium (cf. Lindsley et al., 1990; Harlov, 1992, 2000b) described by the following general expression: 2 quartz + 2 ulvöspinel = 2 ilmenite + ferrosilite. QUIlP represents the orthopyroxene analogue of the QUIlF equilibrium (quartz-ulvöspinel-ilmenite-fayalite) of Frost et al. (1988). QUIlP is defined in $\log_{10}fO_2-T$ space, for a specific pressure and activity of ferrosilite in orthopyroxene, as a series of temperatures calculated using the titaniferous magnetite-ilmenite thermometer for which there is perfect agreement between oxygen fugacities estimated from the titaniferous magnetite-ilmenite and orthopyroxene-titaniferous magnetite-quartz equilibria. An equilibrium temperature and oxygen fugacity for reset samples can be found from the intersection of the X_{Usp} isopleth for these samples with the QUIlP equilibrium (Frost et al., 1988; Lindsley et al., 1990; Harlov, 1992, 2000b). This entails conceptually increasing the hematite content of the ilmenite grain such that temperature and oxygen fugacity are shifted upward along the X_{Usp} isopleth until the QUIlP equilibrium point is reached. The mean QUIlP equilibrium temperature for reset samples from Tromøy and Hisøy is 830 ± 40 °C (Harlov, 1992) whereas oxygen fugacities range from $\log_{10}fO_2 = -11.0$ to -13.0. These results are in good agreement with QUIlP temperatures and oxygen fugacities (823 ± 6 °C (1σ); $\log_{10}fO_2 = -12.0$ to -14.0) estimated for the mainland enderbites along the coast (Harlov, 2000b).

Non-reset oxygen fugacities estimated both directly from the oxide-silicate data (Fig. 15c; also see above) and from QUILP indicate that carbon could only have been stable as CO_2 during granulite-facies metamorphism in the Bamble Sector. However, it should be noted that on a more local scale primary graphite can still be found in the granulite-facies rocks. For example, Broekmans et al. (1994) have documented primary graphite ± overgrowths in granulite-facies metapelites and fahlbands on the mainland. This suggests that the high oxidation state estimated from oxide-silicate assemblages was not uniform throughout the granulite-facies rocks but perhaps was limited to rocks whose protolith was igneous in origin as opposed to sedimentary.

Overall observations of a high oxidation states during granulite-facies metamorphism contradicts earlier studies of similar granulite-facies terranes utilizing titaniferous magnetite-ilmenite thermometery/oxygen barometery such as in the Adirondacks by Lamb and Valley (1985), who estimated substantially lower temperatures and oxygen fugacities implying that graphite was the stable carbon phase during granulite-facies metamorphism. However, since these oxygen fugacities are not compared isothermally with oxygen fugacities estimated from other internally consistent oxygen barometers such as ferrosilite-magnetite-quartz (see above), it is uncertain if they actually represent peak metamorphic conditions.

6.2.3. LILE depletion

The notion of LILE depletion as a regional feature of the lower continental crust, i.e. granulite-facies rocks, was put forward in the 1960s (e.g. Heier and Adams, 1963; Heier, 1965). Field and coworkers advocated the case of regional scale LILE depletion due to granulite-facies metamorphism in the Bamble Sector, defining the islands of Tromøy and Hisøy as a separate, high-grade, zone (Field et al., 1980, 1985; Lamb et al., 1986). As already noted by Moine et al. (1972), however, the actual relationships between whole rock chemistry and metamorphic grade in the area are complex, with K-poor ('hypopotassic') rocks and normal K-bearing rocks occurring in the granulite-facies area, e.g. on the island of Tromøy. Knudsen and Andersen (1999) showed that the gneisses that make up a large part of that island, the so-called Tromøy gneiss complex, dated at 1198 ± 13 Ma, represent a low-K, calcalkaline igneous complex with trondhjemitic affinities, whose trace element characteristics are explained by magmatic fractionation and post-emplacement anatexis, instead of regional metamorphic depletion (see Section 5.1 above).

6.2.4. Skarns

A special feature of the granulite-facies zone is the so-called skarns. In spite of their great economic importance in the past, these have obtained relatively little attention in geological research over the last decades. They are not skarns in the common sense, i.e. they are (at least in part) not clearly related to granitic intrusions (though, given the skarn formation is undated, the Tromøy igneous complex may be considered as such). The skarns are calcsilicate rocks, occurring in the area around Arendal and on the island of Tromøy, either as stratabound layers within the gneisses or as boudins of different size. The occurrences are known for a range of Ca- and Mg-silicates (andraditic and melanitic garnet, hedenbergite, tremolite, epidote, zoisite, forsterite, chondrodite, clinohumite, titanite, pumpellyite, vesuvianite, rhodonite; babingtonite, scapolite, apophyllite, phlogopite); borosilicates (axinite, datolite, tourmaline, okayamalite); zeolites (analcime, thomsonite, mesolite, scolectite, natrolite); sulphides (pyrite, chalcopyrite, tetrahedrite, molybdenite); oxides (magnetite, spinel, gahnite, rutile, anatase); hydroxides (groutite); phosphates (apatite); carbonates (calcite, dolomite, ankerite); borates (cahnite); and halides (fluorite) (Scheerer, 1845; Weibye, 1847; Kjerulf and Dahll, 1861; Vogt, 1910; J.A.W. Bugge, 1940, 1943, 1945, 1951, 1954, 1960; Neumann, 1985; Burns and Dyar, 1991; Broekmans et al., 1994; Nijland et al., 1998a; Olmi et al., 2000). Amphibolite-facies skarns occur in the southwesternmost tip of the Bamble Sector, around Kristiansand (Barth, 1928, 1963; Falkum, 1966).

6.3. Sveconorwegian granulite-facies contact metamorphism

Contact aureoles (granulite-facies) occur along the contact between the granitic and charnockitic augen gneisses that intruded along the Porsgrunn-Kristiansand shear zone in the Nelaug-Ubergsmoen-Vegårshei area where they overprint regional amphibolite-facies metamorphism (Hagelia, 1989; Nijland and Senior, 1991). Geothermobarometry on granulite mineral assemblages in basic dikes in the contact aureole of the Ubergsmoen

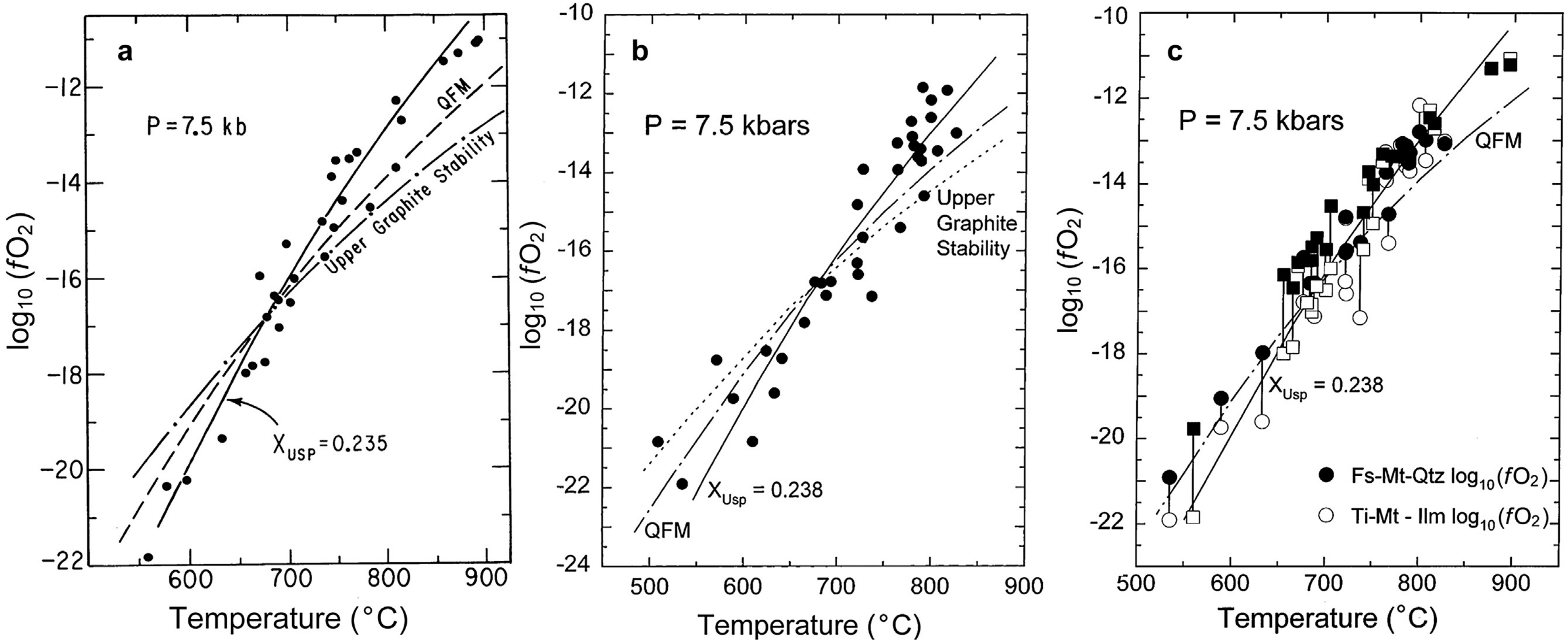

Figure 15. Plot of titaniferous magnetite-ilmenite temperatures and oxygen fugacities estimated for samples from Tromøy and Hisøy (a) and the mainland along the coast (b) using the titaniferous magnetite-ilmenite thermometer/oxygen barometer of Ghiorso and Sack (1991). The isopleth representing the mean molar fraction of ulvospinel in the samples ($X_{Usp} = 0.235$) (a) and ($X_{Usp} = 0.238$) (b) is shown for reference. The quartz-fayalite-magnetite oxygen buffer (QFM) (Berman, 1988) and the upper stability limit for graphite (Lamb and Valley, 1985) are also plotted. (c) shows a plot of magnetite-hematite (white circles) and ferrosilite-magnetite-quartz (black circles) oxygen fugacities connected by tie lines for samples from the mainland (Harlov, 2000b). Also plotted for comparison are magnetite-hematite (white squares) and ferrosilite-magnetite-quartz (dark squares) oxygen fugacities from titaniferous magnetite-ilmenite-orthopyroxene samples from Tromøy and Hisøy (Harlov, 1992).

Figure 16. Replacement of quartz in graphic intergrowths by actinolite + clinopyroxene, with simultaneous albitization of feldspars (Nijland and Touret, 2001).

augen gneiss indicate P-T conditions of ca. 750 °C and 870 MPa (Nijland and Senior, 1991).

6.4. Sveconorwegian regional retrograde metamorphism

Except directly adjacent to the Porsgrunn-Kristiansand shear zone (Fig. 1), the post-peak metamorphic evolution of the Bamble Sector is characterized by a typical P-T path with an onset of isobaric cooling followed by near isothermal decompression and subsequent near isobaric cooling (Fig. 12). This is documented by mineral assemblages (Visser and Senior, 1990; Nijland et al., 1993b; Sørensen, 2007) and fluid inclusion isochores (Touret and Olsen, 1985). In the Froland corundum-bearing rocks (in the middle of the amphibolite-facies zone), the peak metamorphic assemblage of sillimanite + plagioclase + biotite + corundum (ca. 750 °C, 700 MPa) was replaced by kyanite + muscovite + chlorite, which reflects isobaric cooling (600–700 °C, 700 MPa). This was followed by decompression, which is reflected by the formation of margarite + corundum (500–570 °C, 300–700 MPa). Retrograde evolution occurred in two stages. The first stage involved the development of muscovite, biotite, and epidote (ca. 400 °C, 200–400 MPa). The second stage was characterized by the development of prehnite, pumpeleyite, scapolite, and tourmaline (175–280 °C, 200–300 MPa) (Nijland et al., 1993b). Phase modelling of the successive assemblages by Sørensen (2007), taking into account solution models and corrected H_2O activities, implies that the entire uplift path has to be shifted lower by about 100 °C.

In the cordierite-orthoamphibole bearing rocks, retrogression is reflected by the breakdown of gedrite to cordierite + anthophyllite + magnetite at 527–560 °C and 300–600 MPa (Visser, 1992) and the subsequent formation of talc + kyanite + quartz and kyanite + andalusite + chlorite + quartz assemblages at 350–600 °C and 600–700 MPa, and 420–530 °C and 300–400 MPa, respectively (Visser et al., 1990; Visser and Senior, 1990). This stage also involved the development of retrograde borosilicate assemblages with dumortierite + muscovite + chlorite + quartz and rare grandidierite (Michel-Lévy and Lacroix, 1888; Visser and Senior, 1991). In the original paper by Visser and Senior (1991), the dumortierite assemblages were limited to the inland zone along the Porsgrunn-Kristiansand shear zone, suggesting a regional trend. However, dumortierite has since also been identified in similar rocks on Tromøy.

The formation of new muscovite porphyroblasts in rocks of suitable composition, (quartzites, granitic gneisses), has been recognized by several authors. This prompted Maijer (1990) to propose the notion of a north-facing, retrograde muscovite-in isograd. Muscovite porphyroblasts, however, also occur in the granitic sheets (similar to those studied by Field and Råheim, 1979) on the island of Tromøy and elsewhere along the coast. Along the Porsgrunn-Kristiansand shear zone, the formation and recrystallization of deformed muscovite porphyroblasts have been dated by the ^{40}Ar-^{39}Ar method at 891 ± 3 and 880 ± 3 Ma (Mulch et al., 2005). Here, oxygen and hydrogen isotopic data indicate (final) equilibration between muscovite and infiltrating meteoric water at 320 ± 30 °C (Mulch et al., 2005).

Though the retrograde fluids were obviously H_2O-rich, in many cases several retrograde assemblages show the action of localized CO_2-rich fluids, as in the case of the breakdown of gedrite in cordierite-orthoamphibole rocks at Blengsvatn (Visser, 1992). Brines documented at high-grade conditions (see above) are also documented in retrograde assemblages, where they stabilize more anhydrous assemblages at lower temperatures (Sørensen, 2007).

6.5. Regional albitization and scapolitization

Both in the central part of the Bamble Sector and the Kragerø area (Fig. 1), so-called albitites or albite-actionolite-quartz (AAQ) rocks occur (Brøgger, 1934a; A. Bugge, 1965; Elliott, 1966; Nijland and Touret, 2001; Engvik et al., 2008). Similar lithologies occur in the Kongsberg Sector (Jøsang, 1966; Munz et al., 1994, 1995). The term albitites is confusing in the sense that, in the Bamble Sector, it is used for both metasomatically altered rocks and apparently magmatic albitite pegmatites (cf. Bodart, 1968; Morshuis, 1991). Considering the close spatial and temporal relationship between both rock types and the experiments of Keppler and co-workers (Shen and Keppler, 1997; Bureau and Keppler, 1999) on the transition between albite melts and fluids, differences in the genesis of the magmatic and metasomatic albitites may be relatively small.

Metasomatic albitization affected both the metagabbros and the sediments. For example, in the Blengsvatn gabbro at the Snøløsvatn or at the margin of the Jomåsknutene gabbro near Uvatn, albitization of the metagabbro starts with the formation of rims of albite around laths of igneous plagioclase. Subsequently, the individual igneous plagioclases are replaced by albite-oligoclase. The laths grow to stringers and veinlets of albite, giving the rock a brecciated outlook. Meanwhile, ferromagnesian minerals are replaced by what is initially patchy actinolite ± clinopyroxene. Continuing metasomatism results in the formation of veinlets of actinolite ± clinopyroxene, (which enhances the brecciated appearance), and/or large aggregates of these minerals. Comparable to episyenitization, quartz is removed during the process. This is illustrated by the Mjåvatn pegmatite, where feldspar and quartz in graphic intergrowths are replaced by albite and actinolite-clinopyroxene intergrowths, respectively, whilst macroscopically preserving the graphic texture (Nijland and Touret, 2001; Fig. 16). Here, metasomatism is estimated to have occurred at 350–450 °C and 200–400 MPa. At least part of the albitization, however, occurred at higher temperatures. TEM observation of actinolite from albitized rock in the Jomås area show the presence of cummingtonite exsolution lamellae in actinolite that have been affected by two phases of deformation after exsolution (ter Haar, 1988). Depending on Fe/Mg, the presence of these cummingtonite exsolution lamellae in the actinolite implies a temperature of formation above 600–700 °C at P_{H_2O} of 200 MPa (Cameron, 1975).

Albitization is associated with the formation of pipes of very pure quartz intergrown with up to 1 m long needles of actinolite (*strahlstein*). The albitized rocks are often enriched in Ti-minerals, particularly titanite and rutile. The latter have been termed *kragerøite* in the past (Johanssen, 1937; Force, 1991). Ti-enrichment reflects strong enhancement in Ti-solubility due to the presence of a Na-silicate component in the fluid (Antignano and Manning, 2008; Hayden and Manning, 2011). The AAQ rocks can be apatite-rich, and associated with apatite-actinolite rocks. One example occurs at the margin of a boudin from the Blengsvatn gabbro at Håvatn (Brøgger, 1934a). It has a diameter of several tens of metres, and has been mined in the past (C. Bugge, 1922). Light green F-OH apatite is intergrown with dark green actinolites. Accessory titanite and calcite also occur (Nijland and Maijer, 1991).

Detailed 1:5000 scale mapping has shown that the regional distribution of AAQ rocks indicates the presence of a regional scale irrigation network that came into existence during the collapse of the Sveconorwegian orogen (Nijland and Touret, 2001). As part of this network the AAQ rocks occur along a late joint system, which is also manifest in the geomorphology of the area, and along gabbro - country rock contacts. The exact timing of the formation of this network is unclear. Munz et al. (1994) obtained a U-Pb titanite age of 1080 $\pm$ 3 Ma for similar albitized rocks from the Kongsberg Sector. Such an age seems to be relatively old for the Bamble Sector, as it would be within the error range of the U-Pb zircon lower intercept and overgrowth ages (Kullerud and Machado, 1991; Knudsen et al., 1997) and the Sm-Nd mineral + whole rock isochron ages for granulites from the area (Kullerud and Dahlgren, 1993). Magmatic albite pegmatites differ from the AAQ rocks by apparent magmatic textures and sharp cross-cutting relationships with the surrounding country rocks.

In addition to albitization, scapolitization is locally widespread, most notably affecting metagabbroic bodies e.g. the Hiåsen gabbro in the Søndeled area (Frodesen, 1968, 1973); the Jomåsknutene gabbro in the Froland area (de Haas, 1992); and the Ødegården gabbro in the Bamble municipality (Hysingjord, 1990; Korneliussen and Furuhaug, 1993; Engvik and Austrheim, 2010; Engvik et al., 2011), amongst many others (Fig. 1). Locally, almost pure Cl-scapolite rocks with minor rutile and Na-phlogopite formed at Ødegårdens Verk (Lieftink et al., 1993) and was denominated *sand rock* by Brøgger (1934a). These rocks are associated with Cl-apatite + enstatite + phlogopite veins (Lieftink et al., 1994; Engvik et al., 2009). These veins, most probably, are of metasomatic origin, deriving from an ilmenite-bearing precursor (Austrheim et al., 2008). After their formation, the veins underwent new hydrous alteration, involving replacement of Cl-apatite by F-OH-apatite and accompanying formation of monazite and xenotime (Lieftink et al., 1994; Harlov et al., 2002; Engvik et al., 2009). The latter process is probably more widespread than previously recognized, also occurring in (non-metasomatized) granite pegmatites such as Gloserheia (Åmli, 1975, 1977; Harlov, 2012a).

7. Geotectonic genesis and evolution of the Bamble Sector

In a regional geotectonic context, the evolution of the Bamble Sector has been discussed in terms of different models that may be generalized (ultimately) either in terms of a continental collisional setting in which southern Norway collided with southern Sweden, or in terms of a translateral model, where southern Norway was originally positioned together with Southwest Sweden along the same continental margin, and subsequently displaced along a major shear zone. It is not the purpose of this review to discuss either model or their peculiarities in full, as far as the Southwest Scandinavian Domain as a whole is concerned. Instead, we will limit ourselves to the discussion of some points most directly related to the Bamble Sector.

The last version of the continental collision model was developed by Bingen et al. (2008b), whom reviewed the available geochronological data for the Southwest Scandinavian Domain. This model proposed a four stage model for the Sveconorwegian orogeny, involving one parautochtonous terrane and four displaced terranes. The parautochtonous terrane is identical to the eastern segment (in SW Sweden) of Berthelsen (1980; Fig. 2). The four allochtonous terranes include, besides the Bamble and Kongsberg Sectors, two composite terranes, which consist of the Idefjorden terrane and the Telemarkia block introduced by the authors (Bingen et al., 2008b). The latter is the starting point of the model by Bingen et al. (2008b). This Telemarkia block is composed of the Telemark Sector proper, Rogaland-Vest-Agder, and Hardanger-Ryfylke with Suldal. The Ideforjden terrane groups together the sectors or segments previously denoted as the Median segment, Ostfold, and Stora-Le Marstrand (Berthelsen, 1980; Fig. 2). The evaluation of geochronological data also demonstrates the presence of significant pre-Sveconorwegian activity in all four allochtonous terranes. The Sveconorwegian orogeny itself has been divided into four stages, viz. thee Arendal (1140–1080 Ma), Agder (ca. 1050 and 1035–980 Ma), Falkstad (980–970 Ma), and Dalane stage (970–940 Ma and 940–900 Ma). The Bamble Sector was mainly affected by the Arendal stage, with ages related to peak amphibolite- to granulite-facies metamorphism clustering over two periods, 1140–1125 and 1110–1080 Ma. Both dates can occasionally be found in one sample (Bingen et al., 2008a).

A model involving major translateral displacement of southern Norway along a shear zone, nowadays obscured by the Permian Oslo rift, was first proposed by Torske (1977, 1985) and Park et al. (1991). It may involve a setting analogous to that of the present day Canadian Cordillera (e.g. Umhoefer, 1987; Samson and Patchett, 1991). Varieties of the model, mainly based on geochemical data, have been proposed since by various authors, e.g. Andersen et al. (2004, 2009), Pedersen et al. (2009), and most recently by Slagstad et al. (2013).

Critical to any model are a few issues concerning the Bamble Sector. The first of these is the relationship between the suite of granitic to charnockitic augen gneisses, whose magmas were intruded over a considerable period, 1.19–1.12 Ga, and are traditionally considered to be related to the Sveconorwegian orogeny. They represent one of the several recurrent pulses of A-type granitic magmatism in the Southwest Scandinavian Domain, and reflect one of a series of anatectic melting events in the deep crust (Andersen et al., 2007, 2009). Only the latest part of this period of magmatism overlaps with the first stage of the Sveconorwegian orogeny as defined by Bingen et al. (2008b). They considered it to be a phase of Pre-Sveconorwegian magmatism. While all together occurring over 70 Ma, on the basis of field relationships and whole rock chemistry, these intrusions have generally been considered as belonging to one phase of synkinematic and synmetamorphic magmatic activity (e.g. Touret, 1967a, 1968; Milne and Starmer, 1982; Hagelia, 1989; Nijland and Senior, 1991; Andersen et al., 1994). Whether this magmatism is part of the early Sveconorwegian orogeny or not is crucial to interpretation of the Sveconorwegian orogeny. If different from the Sveconorwegian orogeny proper, it implies two major events in the Bamble Sector prior to the Arendal phase of the Sveconorwegian orogeny. Phase one would involve intrusion of magmas from the augen gneiss suite. An older phase two would involve two phases of deformation and migmatization prior to their intrusion, possibly during the ill-defined Gothian orogeny.

The second issue critical to any interpretative model is the (tectonic) relationship between the Bamble Sector and other terranes. In the collisional model proposed by Bingen et al. (2008b), two hypothetical scenarios are considered. The first scenario involves subduction of Fennoscandia (with the Idefjorden terrane at its margin, in the nomenclature of these authors) below an unidentified continent (Amazonia?), from which the Telemarkia block was derived during pre-Sveconorwegian times (1220–1140 Ma). In this scenario, the Bamble and Kongsberg Sectors were trapped between the Telemarkia block and Fennoscandian terrane during the Arendal phase of the Sveconorwegian orogeny (1140–1080 Ma). The second scenario involves collision between the Telemarkia block and the Idefjorden terrane, starting in pre-Sveconorwegian times (1220–1140 Ma) and coming to a halt during the Arendal phase of the Sveconorwegian orogeny (1140–1080 Ma). In this scenario, the Bamble and Kongsberg Sectors were also mangled between the Telemarkia block and the Idefjorden terrane. In either scenario, the origins of the Bamble and Kongsberg Sectors are unclear. In both scenarios, the Bamble Sector represents a tectonic wedge upthrusted against the so-called Telemarkia block during the first Arendal stage of the Sveconorwegian orogeny in response to continental collision.

Geochemical data, including Pb, Hf, Sr, and Nd isotope data for igneous rocks from all over southern Norway, show that the Telemark, Bamble, and Kongsberg Sectors have an identical geochemical signature and imply they may have been part of the same Fennoscandian continental margin prior to 1.6 Ga (Andersen et al., 2001b, 2002a, 2004, 2009). A discontinuity, such as a fossil suture, would likely be expected to be manifest in the isotopic data (Andersen et al., 2009). This argues against an exotic Telemarkia block. The second scenario does not explain why the east-west sequences within both southern Norway and Sweden show considerable similarities, whilst they are currently positioned after each other such that they form one single east-west traverse (Berthelsen, 1980, 1987).

However, a prolonged, subduction related, destructive margin scenario, followed by continental collision during the Sveconorwegian orogeny, can be supported by several observations. Pesonen and Torsvik (1990) deduced from palaeomagnetic data that, after a period of strongly increased plate drift velocity between ca. 1.4 and 1.3 Ga, rather slow plate drift velocities occurred between 1.27–1.23 Ga. This can be interpreted to reflect a change from an overall extensional to a collisional setting. At ca. 1.2 Ga, the Tromøy igneous complex shows geochemical characteristics that have been interpreted as the remant of an oceanic island arc (Smalley et al., 1983; Knudsen and Andersen, 1999; Andersen et al., 2002a, 2004), i.e. a subduction related setting. Evidence for an oceanic basin, however, has not been found yet. It is unclear to what extent older ductile precursors (shear zones) exist for the late brittle faults between Tromøy and Hisøy and between Tromøy and the mainland, and what this would imply for the interpretation of the relationship between Tromøy and the mainland. Other indications of a closed oceanic basin in the Bamble Sector (or elsewhere) are, however, lacking. High pressure subduction related rocks (eclogites) have not been encountered in the Bamble Sector, but occur elsewhere in the Sveconorwegian belt. These include late Sveconorwegian high pressure granulites and eclogites in SW Sweden (Johansson et al., 1991; Möller, 1998) and 1.08 Ga eclogites at Glen Elg, Scotland (Sanders et al., 1984; Sanders, 1989). These rocks are, however, much younger and belong to a later phase of the Sveconorwegian orogeny.

A third crucial aspect in any geotectonic model involving the Bamble Sector orogeny is the question concerns when the Bamble and Telemark Sectors were joined together. Did the Bamble and Telemark Sectors already amalgate prior to the Sveconorwegian orogeny or not? Some authors have argued that the two sectors were joined only during the late Sveconorwegian (e.g. Andresen and Bergundhaugen, 2001). Interpretation of the nature of the granitic to charnockitic augen gneisses and their relationship with the Porsgrunn-Kristiansand shear zone is crucial with respect to answering this question. Members of this magmatic suite (the Gjerstad augen gneiss and Morkheia monzonite suite) intrude within this shear zone on the border between the Telemark Sector and the Bamble Sector, as may clearly be seen on the geologic map of Starmer (1987) as well as in more detail in Starmer (1990). The Gjerstad augen gneiss cuts older structures in the Telemark gneisses (Starmer, 1990). Given the intrusive ages of these granitic to charnockitic magmas (1.19–1.12 Ga; see above), and their synkinematic and synmetamorphic nature, this shear zone was already active, and the Bamble Sector and Telemark Sector joined together, prior to the Arendal phase of the Sveconorwegian orogeny.

The accretionary model for the Sveconorwegian orogeny in the Southwest Scandinavian Domain proposed by Slagstad et al. (2013) depends on three crucial observations, viz. the timing of 1050–1025 Ma calcalkaline, subduction related magmatism (called the Sirdal magmatic belt by the authors); the observation that it preceeds high grade metamorphism; and the observed peak metamorphic temperatures, which are higher than normally attained in collisional orogens. The last two key observations also apply for the Bamble Sector. However, the timing of metamorphism in the Bamble Sector is much older than in the westernmost part (Rogaland-Vest Agder) of the Southwest Scandinavian Domain. The model involves subduction of oceanic crust below the west of Fennoscandia, which is assumed by these authors to be identical to the so-called Idefjord terrane of Bingen et al. (2008b). Remains of this oceanic crust have not been identified yet. The position of the Bamble and Kongsberg Sectors in this model is unclear.

Any proposed cause for granulite-facies metamorphism depends on the geotectonic setting. The different clockwise and anticlockwise PT paths found by Visser and Senior (1990) on the mainland and by Knudsen (1996) on the off shore islands have so far hampered any interpretation. A Sveconorwegian granulite-facies event, superimposed on an already high grade migmatitic gneiss terrane, is clear from the geochronological data (Table 2). The already high-grade nature of the rocks may form an example of metamorphic preconditioning as proposed by Caddick (2013). The cause of this granulite-facies metamorphism is, however, still subject to debate. Though intimately associated with granulite-facies rocks in the area, the 1.2 Ga Tromøy igneous complex predates peak metamorphism by about 100 Ma (Knudsen and Andersen, 1999), implying that the igneous complex could not have acted as a heat source. However, Sveconorwegian metamorphism did affect a high-grade gneiss terrane, that had already been deformed and migmatized prior to 1.19–1.12 Ga (see above). The presence of carbonic and saline fluids appears to have exerted a strong local control on the development of H_2O-poor, high-grade mineral assemblages in the granulite-facies zone as well as in the granulite-facies islands in the amphibolite-facies zone (e.g. Touret and Nijland, 2012). A possible heat source for granulite-facies metamorphism could either have been thermal doming due to the elevation of asthenosphere magmas below an overriding plate, or thinned lithosphere due to attempted rifting (Nijland and Maijer, 1993).

No definitive evidence exists to definitively confirm any of these hypotheses. Starmer (1985, 1990, 1991) distinguished five major phases of deformation in the Bamble Sector. Three predated the intrusion of the granitic-charnockitic augen gneisses, and four postdate them. The latter phases are tentatively correlated with the Sveconorwegian orogeny in the sense of Bingen et al. (2008b). The period between the 5th and 6th phases of deformation was considered by Starmer (1985, 1990, 1991) as an '*anorogenic phase of crustal extension*', in which coronitic gabbros ('*main hyperites*') and granitic magmas intruded. They were subsequently metamorphosed and deformed mainly along their margins. This caused him to suggest elevated heat flow due to rifting as the cause of metamorphism in this period, comparable to Hercynian metamorphism in the Pyrenees (cf. Wickham and Oxburgh, 1985). In this respect, it is noteworthy that on a larger scale, palaeomagnetic data indicate the break up and mutual rotation of amalgated Laurentia-

Fennoscandia between 1.10 and 1.05 Ma. This occurred after a pre-Sveconorwegian configuration in which Laurentia and Fennoscandia were in close proximity with their internal tectonic lineaments in alignment until about 1250 Ma (Piper, 2009).

8. Conclusions

The importance of the discovery of CO_2 in granulite-facies rocks from the Bamble Sector by Jacques Touret and its relevance with regard to the lower continental crust was grasped within a few years. Since then, the role of (Na,K)Cl brines as the other agent in granulite genesis has been recognized in the Bamble Sector and elsewhere (e.g. Newton et al., 1998; Harlov and Förster, 2002; Hansen and Harlov, 2007; Harlov, 2012b; Aranovich et al., 2013; see also discussion in Touret and Nijland, 2012). However, in a geotectonic context the development of an amphibolite- to granulite-facies transition zone in the Bamble Sector is a regional phenomenon. How this transition zone formed in an already high-grade gneiss terrane is still unclear.

As will be clear from the brief discussion provided above, understanding the geological evolution of the Bamble Sector and the causes of formation behind the regional amphibolite- and granulite-facies zones would benefit from modelling based on the integration of geochronological, geochemical, structural, and field geological data. Topics that need to be considered to substantiate any large-scale concepts include the elucidation of the actual position of the granulite-facies islands of Tromøy and Hisøy relative to the granulite-facies areas on the mainland. These include any displacements by the brittle faults identified in the sounds between the islands (chiefly Tromøy and Hisøy) and the mainland (and possible older ductile deformation zones currently obscured by these faults); the relationship between the intrusion of the granitic to charnockitic augen gneisses and the ductile precursor of the Porsgrunn-Kristiansand shear zone; and the relationship between synkinematic and synmetamorphic magmatism in the Bamble Sector and the Sveconorwegian orogeny.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.gsf.2014.04.008.

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