Timing of Gothian structural evolution in SE Norway: A Rb-Sr whole-rock age study

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The polydeformed basement area in SE Norway is situated within the southwest border of the Baltic Shield. The investigated area covers the northern part of the Østfold segment (the Østfold Complex) and adjoining parts of the Median segment (the Romerike Complex). New Rb-Sr whole-rock age determinations are integrated with the structural evolution. The oldest rock unit is the Østfold–St. Le-Marstrand formation. During successive stages the supracrustal unit was intruded by major granitic bodies now forming the biotite gneiss (oldest), the augen gneiss and metatonalite/granite complexes (youngest). The emplacement of the granitic units was separated by orogenic deformation events, F_0–F_3, recognized by the development of large-scale regional folding accompanied by amphibolite facies metamorphism. Rb-Sr whole-rock age determinations indicate a maximum age for the biotite gneiss (pre-F_0) at 1.71 Ga; this age also marks the maximum age of the Gothian orogeny. Intrusion of the Nordstrand–Sørmarka metatonalite/granite complex, 1.58 ± 0.13 Ga, and the Østmarka metatonalite complex, 1.56 ± 0.04 Ga, around the F_2 deformation marks the end of the Gothian orogeny at ca. 1.57 Ga. A resetting age of the augen gneiss, 1.06 ± 0.17 Ga, is ascribed to the F_3 deformation; this age indicates a minimum age for the onset of the Sveconorwegian orogeny.

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Introduction

At the southwest border of the Baltic Shield the Proterozoic Østfold Complex (Berthelsen et al. 1996) is situated within the early Gothian domain (Windley 1992) in the eastern Sveconorwegian subprovince (Berthelsen 1980). The complex occupies the northern (Norwegian) part of the Østfold segment (Graversen 1984; Berthelsen 1980: Østfold slab) east of Oslofjord (Figs. 1 & 2). The Østfold Complex is separated from the Romerike Complex in the Median segment by the Sveconorwegian Ørje mylonite zone (Dalsland Boundary Thrust). To the west and northwest the Precambrian basement is delimited by the Cambro-Silurian sequence downfaulted into the Permian Oslo Graben.

The oldest rocks in the Østfold Complex are supracrustal gneisses belonging to the Østfold–St. Le-Marstrand formation. The supracrustal gneisses are intruded by granitic bodies and metabasic rocks. During regional folding episodes the granitic bodies were deformed and recrystallized into orthogneisses. Previous Rb-Sr whole-rock dating of rocks from the Østfold and Romerike Complexes yielded ages ranging from 1.7 Ga to 0.9 Ga, spanning the post-Svecofennian development during the Gothian and Sveconorwegian Orogens. The tectonic development and the orogenic evolution have been described by Pedersen et al. (1978), Berthelsen (1980, 1987), Hageskov (1980), Hageskov & Pedersen (1981, 1988), Skjernaa & Pedersen (1982), Graversen (1984) and Skjernaa (1997).

This paper presents new Rb-Sr whole-rock data from the orthogneisses in the Oslofjord–Øyeren area (Graversen 1984) to the north in the Østfold segment (Fig. 3). Discussion of the results is integrated with the structural evolution. Although resetting may have invalidated some results, the integrated approach helps to model the timing of regional folding phases during the Gothian orogeny. Together with data from Hageskov & Pedersen (1981, 1988) and Skjernaa & Pedersen (1982), a correlation between the orogenic evolution in the Østfold and Median segments in SE Norway is proposed (see Table 5).

Geology of the Oslofjord–Øyeren area

The following description gives a short account of the geology and structural evolution of the sampled units. For a more comprehensive description of the Oslofjord–Øyeren area, see Graversen (1984).

The Østfold–St. Le-Marstrand formation is composed of psammitic to semipelitic gneisses. No basement to the supracrustal unit has been reported. During successive stages the paragneisses were intruded by plutonic bodies now constituting the biotite gneiss (oldest), the augen gneiss, the metatonalite/granite complex and the Moss–Filtvet orthogneiss complex (youngest) (Hageskov & Pedersen 1981) (Fig. 3). The emplacement of the granitic units was separated by orogenic deformation events, F_0-F_3, recognized by large-scale regional folding accompanied by amphibolite facies metamorphism.

Analysed rock units

The biotite gneiss is a migmatitic microcline augen gneiss of granitic composition. Pegmatitic neosome veins, developed during the F_2 deformation, cut the folded biotite

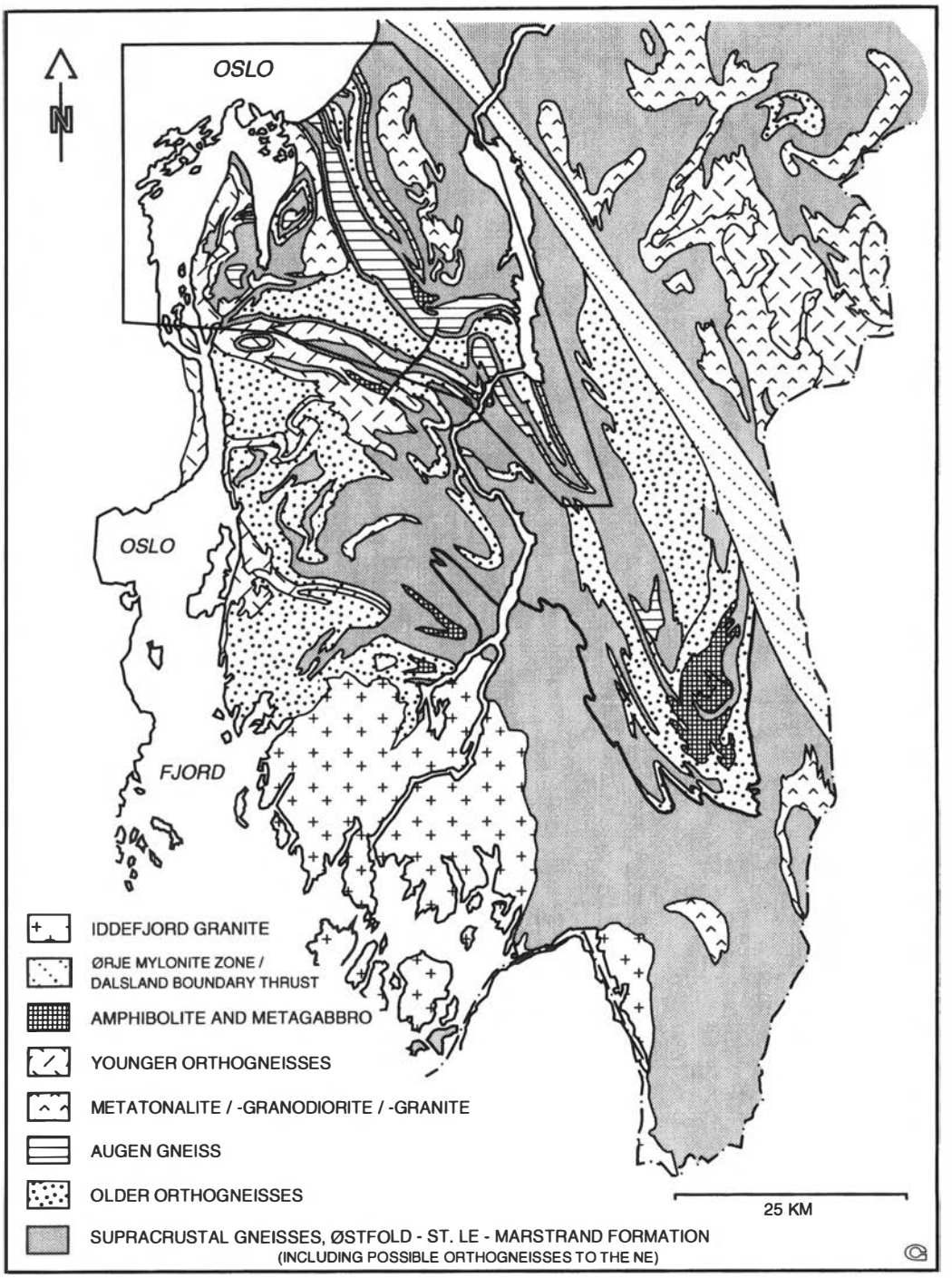

Fig. 1. Geological map of the of the Østfold area. The compilation is based on Berthelsen et al. (1996), Graversen (1984), Hageskov & Jorde (1980) and Skjernaa (1997). Insert frame indicates position of the Oslofjord–Øyeren area.

foliation and early migmatitic veins (S_1) developed during the F_1 deformation.

The augen gneiss is a foliated, migmatitic orthogneiss with microcline megacrysts (up to 2 × 5 cm) which may constitute about one-third of the rock. Individual augen may be composite or single microcline grains. The gneiss has an early migmatitic development displaying a layered or veined structure. During the F_3–F_3' deformation, the gneiss suffered retrogressive metamorphism under low amphibolite facies and greenschist-amphibolite transition facies.

Intrusions belonging to *the metatonalite/granite complex* are composed of medium-grained and usually weakly foliated, massive metatonalite and granite. In the Nordstrand–Sørmarka complex around the Gjersjø dome both tonalitic and granitic rocks occur, whereas only tonalitic–dioritic rocks are present in the Østmarka complex to the east (Fig. 3). The rocks were metamorphosed under

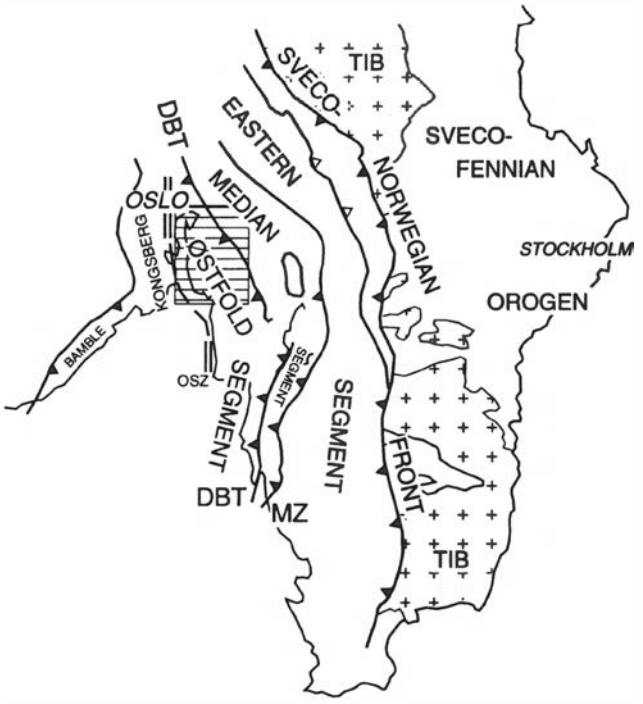

Fig. 2. Sveconorwegian tectonic units (eastern subprovince) along the Sveconorwegian front, SW Baltic Shield. OSZ: Oslofjord Shear Zone; DBT: Dalsland Boundary Thrust; MZ: Mylonite Zone; TIB: Transscandinavian Igneous Belt. Based on Berthelsen (1980) and Berthelsen et al. (1992). The Østfold area is indicated by insert cross-hatched frame.

amphibolite facies conditions with only scattered indications of migmatization.

Chemical analyses of the rock units are presented in Tables 6–9.

Age relationships

The relative ages of the orthogneiss units are established from field relations and structural analysis of large-scale map structures (Graversen 1984). The fold styles developed during the F_0-F_3' fold episodes indicate that changing tectonic regimes governed the subsequent events.

The *biotite gneiss* and the *augen gneiss* form stratiform units in the supracrustral gneiss and no crosscutting relationships are observed between them. Both units share the F_1-F_3' fold episodes while the biotite gneiss was also involved in the early F_0 deformation. This establishes the biotite gneiss as the oldest orthogneiss unit. Garnet amphibolite dykes are widespread in the supracrustal gneiss and the biotite gneiss, but are not encountered in the augen gneiss or other units. The dyke intrusion episode may indicate that the biotite gneiss and the augen gneiss were separated by an extensional anorogenic interval (see Fig. 8).

The bodies of the *metatonalite/granite complex* are intruded into various levels and display an overall discordant relationship with the stratiform sequence. The Nordstrand–Sørmarka complex cuts the contact between the supracrustal gneiss and the biotite gneiss, indicating the younger age of the metatonalite/granite complex. No crosscutting relationships have been observed between the augen gneiss and the metatonalite/granite complex. However, the metatonalite/granite complex was intruded between the F_1 and F_3 fold episodes. This indicates that the metatonalite/granite complex postdates not only the biotite gneiss but also the augen gneiss.

The age of the metatonalite/granite complex relative to the F_2 deformation is difficult to assess. In a number of cases, rocks belonging to the metatonalite/granite complex appear to have acted as competent bodies preventing the full development of F_2 structures. This indicates emplacement prior to or early during the F_2 deformation. The shape of other bodies, however, suggests that they intruded the supracrustal gneiss already structured by the interference between the F_1 and F_2 fold episodes, and this indicates an emplacement later than the F_2 deformation. It is therefore possible that intrusions grouped into the metatonalite/granite complex may include more than one intrusive unit that were emplaced at different times with respect to F_2.

Rb-Sr whole-rock isotope analyses

Sample weights

Large samples were collected in order to eliminate the effects of element and isotope migration during metamorphism and migmatization. From what follows, however, it will be evident that in this study large samples did not eliminate the effect of isotope migration due to secondary processes. Localities sampled for isotope dating are indicated in Fig. 3. The weights of individual samples are presented in Tables 6–9.

Analytical procedure

Rb/Sr ratios were determined by XRF at the Geological Institute, University of Copenhagen. G-2 was used as a standard, assigning a value of the Rb/Sr ratio of 0.355 (Pankhurst & O'Nions 1973). GSP-1, which was analysed at the same time, gave results within 0.3% of the Pankhurst & O'Nions (1973) value of 1.093. Errors in the Rb/Sr ratios are recorded in Tables 1–4. Sr isotope measurements were carried out on a VG Sector 54–30 mass spectrometer of the Danish Centre of Isotope Geology, University of Copenhagen. The errors on the isotope ratios in Tables 1–4 are 1SE obtained during the mass spectrometric analyses. 1σ errors used in the isochron calculation were 0.00005 for biotite-rich samples (augen gneiss and biotite gneiss), whereas samples without biotite (from the metatonalite complex) were assigned an error of 0.00001. Isochron calculations were carried out using the program by Williamson (1968). All errors of ages and isotope ratios are given at the 95% confidence level. Errors were calculated following the recommendation of Kalsbeek & Hansen (1989), which uses the square root of the MSWD as the error magnification factor. A decay constant for ^{87}Rb of 1.42×10^{-11} y^{-1} was used.

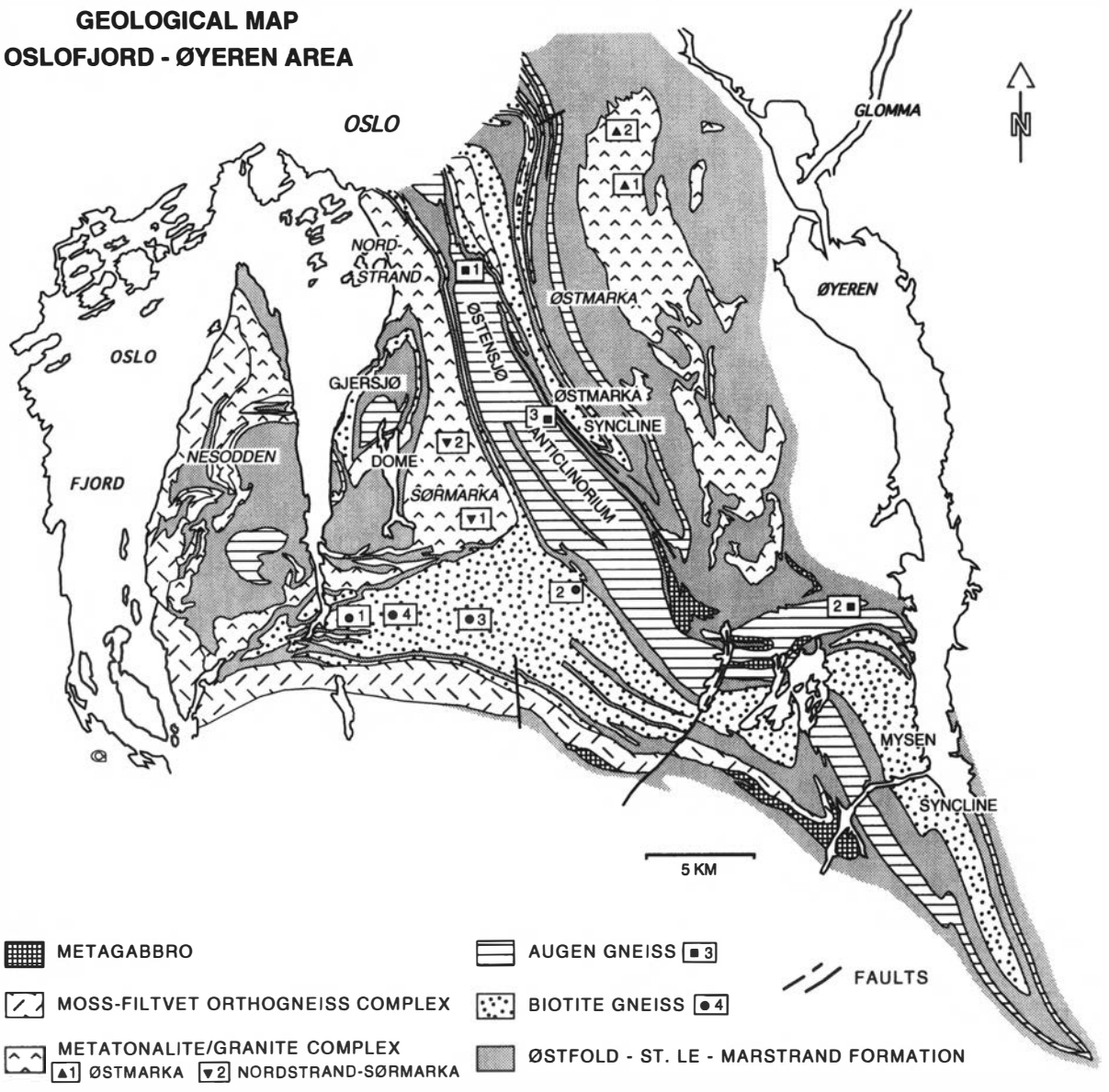

Fig. 3. Geological map of the Oslofjord–Øyeren area. Localities sampled for isotope dating are indicated by filled triangles (TO 1–2, TG 1–2), squares (AG 1–3) and circles (BG 1–4); numbers refer to Tables 1–4.

Results

Biotite gneiss. – The biotite gneiss yields an age of 1.71 ± 0.16 Ga, a SrIR of 0.7024 ± 0.0072 and an MSWD of 11.22 (Fig. 4, Table 1). The high MSWD does not qualify the age as an isochron age. However, the low SrIR indicates that an age of the biotite gneiss higher than 1.71 Ga is not probable. The obtained age is therefore interpreted as the maximum age of emplacement of the biotite gneiss.

Augen gneiss. – An isochron calculation based on 11 samples of the augen gneiss results in an age of 1.47 ± 0.09 Ga, with an SrIR of 0.7087 ± 0.0042 and an MSWD of 2.58 (Fig. 5, Table 2). One sample falls clearly outside this trend and was omitted from the calculation. Considering the deviating sample as a result of secondary younger influence on the isotope system at this locality (AG-1), the remaining eight samples from two localities (AG-2, AG-3) yield a nearly identical age of 1.50 ± 0.10 Ga, an SrIR of 0.7073 ± 0.0049 and an MSWD of 2.53. The samples from locality AG-1 that could have been affected by secondary processes yield an age of 1.06 ± 0.17 Ga, an SrIR of 0.7278 ± 0.0049 and an MSWD of 1.67.

For the augen gneiss, the samples are all very large and the result fits an isochron. A conventional way of interpreting the age of 1.50 ± 0.10 Ga obtained at localities AG-2 and AG-3 would be that the age reflects the time of emplacement (also considering the low MSWD). However, the geological development and the structural model indicate that the augen gneiss was intruded as a large granite sheet prior to the intrusions of the metatonalite/granite complex (Graversen 1984). The age of the

Table 1. Rb-Sr isotope data of the biotite gneiss. Sample localities are indicated in Fig. 3.

Biotite gneiss	Sample no.	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 1SE$
Loc: BG-1	56114	3.61 ± 0.04	0.794901 ± 0.00007
	56115	4.02 ± 0.04	0.800596 ± 0.00007
	56116	4.08 ± 0.04	0.806103 ± 0.00008
	56117	4.15 ± 0.04	0.805590 ± 0.00007
Loc: BG-2	56118	3.10 ± 0.03	0.777811 ± 0.00005
	56119	2.67 ± 0.03	0.764160 ± 0.00007
	56120	3.04 ± 0.03	0.777527 ± 0.00007
	56121	2.27 ± 0.02	0.759827 ± 0.00007
Loc: BG-3	56122	2.91 ± 0.03	0.775984 ± 0.00004
	56123	3.32 ± 0.03	0.787827 ± 0.00007
	56124	3.18 ± 0.03	0.778534 ± 0.00009
	56125	2.58 ± 0.03	0.766696 ± 0.00005
Loc: BG-4	56149	4.34 ± 0.04	0.803730 ± 0.00008
	56150	3.65 ± 0.04	0.792790 ± 0.00007
	56151	3.22 ± 0.03	0.780977 ± 0.00005
	56152	3.49 ± 0.03	0.785240 ± 0.00006

Age calculations:
Localities BG-1 + BG-2 + BG-3 + BG-4 (n = 16):
Age: 1.71 ± 0.16 Ga, SrIR: 0.7024 ± 0.0072, MSWD: 11.22.

Table 2. Rb-Sr isotope data of the augen gneiss. Sample localities are indicated in Fig. 3.

Augen gneiss	Sample no.	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 1SE$
Loc: AG-1	56127	2.98 ± 0.03	0.773225 ± 0.000005
	56131	3.18 ± 0.04	0.776073 ± 0.000005
	56132	3.09 ± 0.03	0.784455 ± 0.000006
	56133	3.75 ± 0.04	0.773782 ± 0.000008
Loc: AG-2	56134	4.24 ± 0.04	0.796401 ± 0.000008
	56135	4.88 ± 0.05	0.811917 ± 0.000008
	56136	4.25 ± 0.04	0.799637 ± 0.000008
	56137	4.54 ± 0.05	0.805052 ± 0.000008
Loc: AG-3	56138	3.13 ± 0.03	0.775448 ± 0.000007
	56139	2.96 ± 0.03	0.768640 ± 0.000007
	56140	3.05 ± 0.03	0.773737 ± 0.000005
	56141	3.44 ± 0.04	0.780692 ± 0.000005

Age calculations: All samples (localities AG-1 + AG-2 + AG-3, except sample 56132)
Age: 1.47 ± 0.09 Ga, SrIR: 0.7087 ± .0042, MSWD: 2.58
Localities AG-2 + AG-3:
Age: 1.50 ± 0.10 Ga, SrIr: 0.7073 ± .0049. MSWD: 2.53
Locality AG-1:
Age:1.06 ± 0.17 Ga, SrIR: 0.7278 ± .0078, MSWD: 1.67
Locality AG-2:
Age:1.57 ± 0.44 Ga, SrIR: 0.702 ± .028, MSWD: 2.54
Locality AG-3:
Age:1.60 ± 0.59 Ga, SrIR: 0.703 ± .026, MSWD: 4.48.

augen gneiss should therefore be higher than the age of the metatonalite/granite complex (ca. 1.56–1.58 Ga, see below). Calculation of augen gneiss ages based on samples from individual localities does not solve the problem of the low augen gneiss age. When the two localities AG-2 and AG-3 are treated separately they give higher apparent ages in the order of 1.57 to 1.60 Ga (with large errors, Table 2). The individual calculations for these two localities yielded very low SrIR in the order of 0.702 and 0.703, indicating that an age in the order of 1.57–1.60 Ga may be the maximum age of this unit. If 1.57–1.60 Ga is the age of the unit, the 'common' age of 1.50 Ga for the two localities could be the result of combining two localities with different isotopic signatures (i.e. SrIR) in the isochron calculation. The deviating sample from locality AG-1 indicates a possible Sveconorwegian resetting at 1.06 ± 0.17 Ga.

Table 3. Rb-Sr isotope data of the Østmarka metatonalite complex. Sample localities are indicated in Fig. 3.

Østmarka complex	Sample no.	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 1SE$
Loc: TO1	56153	0.267 ± 0.006	0.709291 ± 0.000009
	56154	0.276 ± 0.006	0.709040 ± 0.000008
	56155	0.277 ± 0.006	0.709090 ± 0.000008
	56156	0.217 ± 0.004	0.707880 ± 0.000008
Loc: TO2	56157	0.028 ± 0.002	0.703570 ± 0.000007
	56158	0.021 ± 0.002	0.703330 ± 0.000007
	56159	0.030 ± 0.002	0.703660 ± 0.000008
	56160	0.034 ± 0.002	0.703640 ± 0.000008
	56161	0.149 ± 0.003	0.706220 ± 0.000007

Localities TO1 + TO2 (except 56153):
Age calculation:
Age: 1.56 ± 0.04 Ga, SrIR: 0.70291 ± .00006, MSWD: 1.12.

Table 4. Rb-Sr isotope data of the Nordstrand–Sørmarka metatonalite/granite complex. Sample localities are indicated in Fig. 3.

Nordstrand–Sørmarka complex	Sample no.	$^{87}Rb/^{86}S$	$^{87}Sr/^{86}Sr \pm 1SE$
Loc: TG-1	56126	0.776 ± 0.008	0.717771 ± 0.000011
	56128	0.550 ± 0.012	0.716416 ± 0.000008
	56129	0.515 ± 0.010	0.715049 ± 0.000008
	5613	0.610 ± 0.009	0.716502 ± 0.000006
Loc: TG-2	56142	1.535 ± 0.015	0.741599 ± 0.000008
	56143	1.632 ± 0.016	0.739152 ± 0.000007
	56144	1.872 ± 0.019	0.747200 ± 0.000007
	56145*	4.09 ± 0.04	0.798442 ± 0.000010
	56146*	3.05 ± 0.03	0.777970 ± 0.000007
	56147*	2.70 ± 0.03	0.766229 ± 0.000007
	56148*	3.04 ± 0.03	0.773091 ± 0.0000015

*Granitic component
Age calculations:
Locality TG-2 (except 56143):
Age: 1.58 ± 0.13 Ga, SrIR: .7061 ± .0043, MSWD: 10.49.

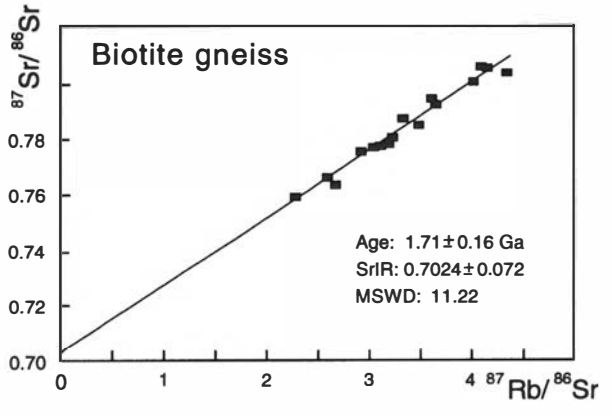

Fig. 4. Isochron diagram: biotite gneiss.

Metatonalite/granite complex. – The Østmarka metatonalite complex yields a well-defined isochron age of

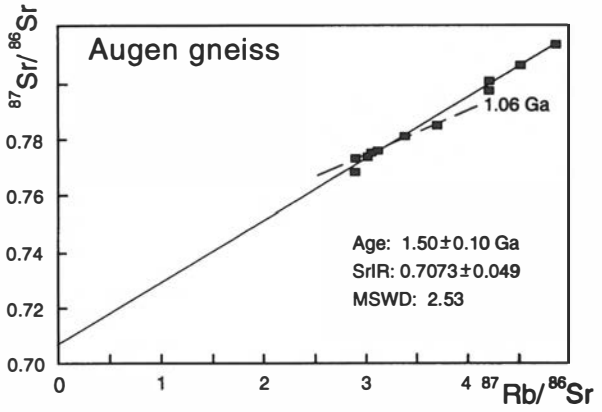

Fig. 5. Isochron diagram: Augen gneiss. The full line is the isochron for the localities AG-2 and AG-3 (1.50 ± 0.10 Ga), and the broken line is the isochron for locality AG-1 (1.06 ± 0.17 Ga).

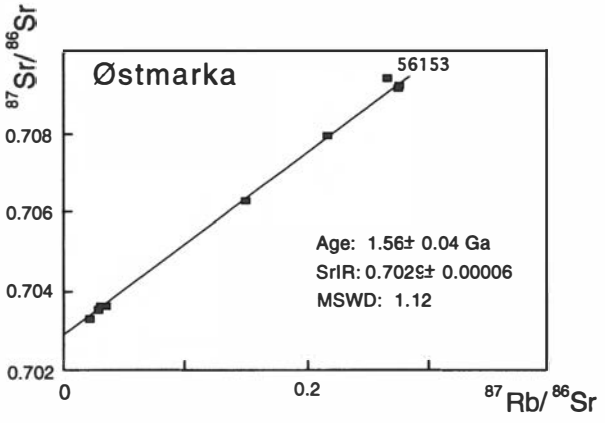

Fig. 6. Isochron diagram: Østmarka metatonalite complex.

1.56 ± 0.04 Ga, an SrIR of 0.70291 ± 0.00006 and an MSWD of 1.12. All but one out of nine samples fall on the isochron (Fig. 6, Table 3).

Samples from the Nordstrand-Sørmarka metatonalite/granite complex were collected at two localities. The southern locality (TG-1) has metatonalitic rocks only with a narrow range in Rb/Sr ratios. No age calculation based on this locality has been performed. The northern locality (TG-2) includes samples of both tonalitic and granitic compositions. When choosing six of the seven samples, an age of 1.58 ± 0.13 Ga, an SrIR of 0.7061 ± 0.0043 and an MSWD of 10.49 were obtained (Fig. 7, Table 4). The high SrIR of 0.7061 ± 0.0043 from locality TG-2, and the fact that data from the two localities of the Nordstrand–Sørmarka complex are distributed on two different lines, may indicate that the complex suffered resetting of the isotope system after emplacement, or the rocks may have somewhat different ages and/or initial ratios. If we consider 0.7028 as a possible SrIR for locality TG-2 at the time of formation, a maximum time of emplacement of 1.67 Ga can be calculated for these rocks.

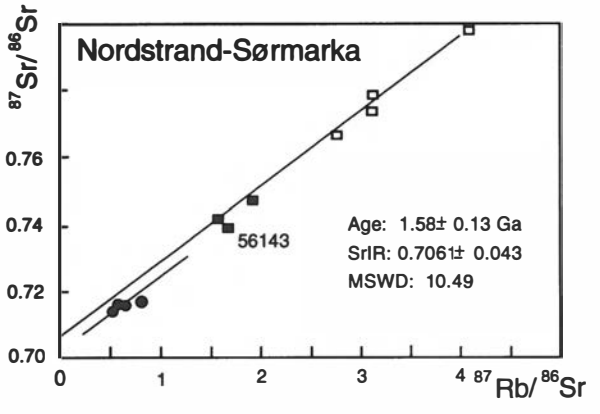

Fig. 7. Isochron diagram: Nordstrand–Sørmarka metatonalite/granite complex. Filled circles: metatonalites, locality TG-1. Filled rectangles: metatonalites, locality TG-2. Open rectangles: metagranites, locality TG-2.

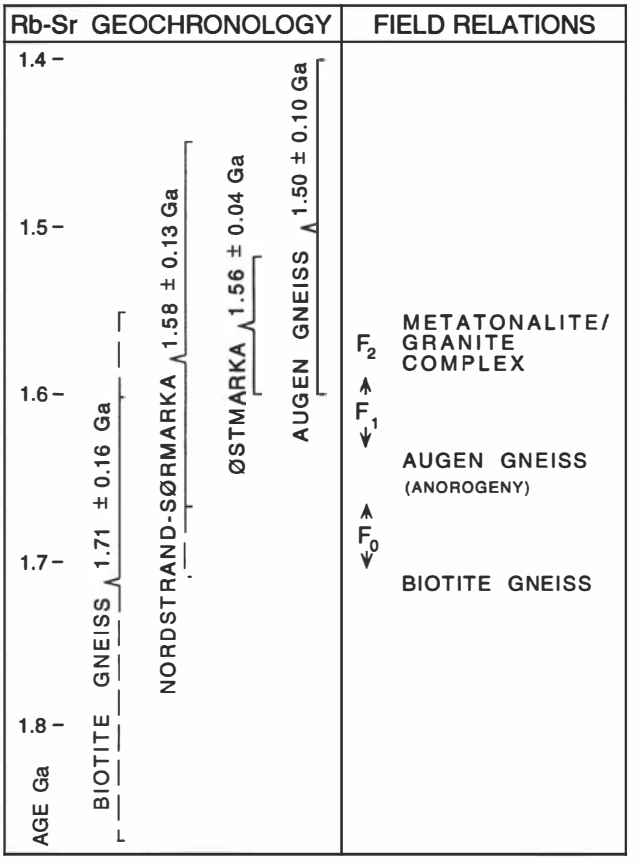

Fig. 8. Summary diagram and correlation between Rb-Sr whole-rock geochronology and field relations (Graversen 1984) of the Oslofjord–Øyeren area.

The errorchron age from the northern locality in the Nordstrand–Sørmarka metatonalite/granite complex of 1.58 ± 0.13 Ga is of the same order as the isochron age of 1.56 ± 0.04 Ga for the Østmarka metatonalite complex. It is therefore concluded that metatonalite/granite complexes of the Oslofjord–Øyeren area were intruded around 1.56–1.58 Ga.

Table 5. Correlation of the orogenic development of the Østfold segment and the Median segment in SE Norway. ØMZ/DBT: Ørje Mylonite Zone/Dalsland Boundary Thrust. 1) Pedersen et al. (1978); 2) Hageskov & Pedersen (1981, 1988); 3) Graversen 1984; 4) Skjernaa & Pedersen (1982); 5) Åhäll & Daly 1989.

	SE Norway	
	Østfold segment: Østfold Complex	Median segment: Romerike Complex [4]
Post-SN granites	Iddefjord granite 923 Ma [1]	Seterdalen granite 0.93 Ga
Sveconorwegian orogeny >1.16-0.97 Ga	*west* [2] / *east* [3] Fjordzone ductile shear deformation 1015 Ma F_3' fold episode W axes F_3 fold episode 1.06 Ga	ØMZ / DBT D_{SN4} shearing and thrusting 1.0-0.97 Ga D_{SN3} N-S axes D_{SN2} E-W axes D_{SN1} regional foliation
Anorogeny	Moss-Filtvet orthogneiss complex 1.32±0.02 Ga Røyken granites 1.38 Ga Kattsund-Koster dykes 1.42±0.03 Ga	Runddelen orthogneiss 1.16 Ga Red orthogneiss complex 1.28 Ga Light grey granodioritic orthogneisses 1.4 Ga
Gothian orogeny 1.7 - 1.57 Ga	F_2 fold episode some migmatization metatonalite/granite complex 1.56-1.58 Ga	Folding and metamorphism, some migmatization Grey tonalitic orthogneiss 1.63 Ga
	F_1 fold episode amphibolite facies, migmatization Augen gneiss (metagranite) -age? Garnet amphibolites (metadolerites) -age? F_0 fold episode	Metamorphism and migmatization One or two fold episodes
	Biotite gneiss 1.71 Ga [early metagranites]	Augen gneiss 1.71 Ga
	Østfold - St. Le - Marstrand formation 1.76 Ga [5]	

Tectonic evolution of the Oslofjord-Øyeren area

In the present study the isochron age of the Østmarka metatonalite complex (1.56 ± 0.04 Ga) is of fundamental importance since the ages obtained from the biotite gneiss, the augen gneiss and the Nordstrand–Sørmarka complex indicate disturbance of their isotope systems. A summary diagram of the geochronology and the tectonostratigraphy of the Oslofjord–Øyeren area is shown in Fig. 8.

The starting-point for correlation between geochronology and tectonostratigraphy is based on the age of the metatonalite/granite complex and its emplacement associated with the F_2 deformation. Based on the ages of the Østmarka metatonalite complex (1.56 ± 0.04 Ga) and the Nordstrand–Sørmarka metatonalite/granite complex (1.58 ± 0.13 Ga), the F_2 fold episode is thought to date from ca. 1.57 Ga (Fig. 8). The oldest age for the structural evolution is set by the maximum age of the biotite gneiss (1.71 Ga, based on the low SrIR 0.7024). The F_0 fold episode therefore postdates 1.71 Ga.

According to the structural model of the regional fold structures (Graversen 1984), the augen gneiss (1.50 ± 0.10 Ga) should be older and not younger than the metatonalite/granite complex (ca. 1.56–1.58 Ga) and should also precede the F_1 fold episode. Since the datapoints of the augen gneiss define an isochron, it is possible that the structural model for the regional structures may be invalid. However, the mesoscopic structures and neosome formation indicate that the augen gneiss participated in both the F_1 and F_2 fold episodes. This discrepancy has not been resolved.

The age of the metatonalite/granite complex (ca. 1.56–1.58 Ga) sets the lower limit to the Gothian orogeny. The F_2 and F_3 fold episodes are separated by the intrusion of the

Table 6. Chemical analyses of the biotite gneiss.

Biotite gneiss Sample no.	56114	56115	56116	56117	56118	56119	56130	56121	56122	56123	56124	56125	56149	56150	56151	56152
SiO2	70.99	71.34	71.54	71.49	69.18	70.27	70.43	70.82	70.08	71.68	70.04	70.84	70.48	71.58	67.92	66.63
TiO2	0.50	0.51	0.47	0.45	0.66	0.57	0.53	0.53	0.54	0.43	0.51	0.53	0.57	0.46	0.56	0.64
Al203	13.47	13.51	13.60	13.63	14.10	13.71	13.73	13.81	13.85	13.54	13.75	13.67	13.72	13.46	14.84	15.23
Fe203	0.23	0.23	0.22	0.32	0.48	0.66	0.24	0.17	0.70	0.19	0.32	0.33	1.58	0.45	0.94	0.94
FeO	3.20	3.46	3.28	3.07	4.06	3.22	3.41	3.32	3.19	2.93	3.35	3.07	2.63	2.97	3.19	3.60
MnO	0.06	0.06	0.06	0.07	0.07	0.05	0.07	0.05	0.05	0.07	0.05	0.05	0.07	0.07	0.05	0.05
MgO	1.05	1.07	1.00	0.98	1.39	1.17	1.13	1.10	1.18	0.92	1.05	1.11	1.22	0.98	1.24	1.42
CaO	1.80	1.80	1.78	1.76	1.94	1.95	2.03	2.09	2.03	1.61	1.66	1.99	1.83	1.89	1.86	1.84
Na20	2.39	2.60	2.58	2.56	2.80	2.90	2.67	2.58	2.64	2.72	2.94	2.90	2.45	2.57	2.71	2.73
K20	4.38	4.19	4.19	4.48	4.12	4.36	4.34	4.12	3.75	4.21	4.30	3.76	4.19	4.01	4.77	4.98
P205	0.21	0.18	0.19	0.21	0.13	0.19	0.20	0.19	0.17	0.21	0.17	0.20	0.19	0.21	0.23	0.21
LOI	1.32	1.00	0.63	0.56	0.40	0.48	0.40	0.62	1.17	0.96	1.23	1.06	0.71	0.81	1.06	1.34
Total	99.60	99.95	99.54	99.58	99.33	99.53	99.18	99.40	99.35	99.47	99.37	99.51	99.64	99.46	99.37	99.61
Feo*/MgO	3.24	3.42	3.47	3.43	3.23	3.26	3.21	3.15	3.24	3.37	3.47	3.04	4.14	4.46	3.25	3.13
Weight (kg)	6.0	9.0	8.0	10.5	12.0	12.0	12.0	18.5	13.0	6.5	10.5	13.5	15.5	15.0	14.0	15.5

Table 7. Chemical analyses of the augen gneiss.

Augen gneiss Sample no.	56127	56131	56132	56133	56134	56135	56136	56137	56138	56139	56140	56141
SiO2	69.11	69.97	67.51	68.22	69.32	70.94	70.62	70.60	69.65	68.52	68.94	69.07
TiO2	0.70	0.68	0.72	0.66	0.70	0.55	0.58	0.63	0.65	0.75	0.74	0.69
Al203	13.36	13.31	13.85	13.76	13.29	13.31	13.07	13.22	13.14	13.15	13.29	13.58
Fe203	0.89	0.87	1.49	0.73	1.34	0.62	0.64	0.52	1.47	0.72	0.91	1.00
FeO	3.89	3.67	4.07	4.30	3.89	3.03	3.35	3.60	3.27	4.72	4.43	3.75
MnO	0.08	0.08	0.08	0.07	0.08	0.06	0.07	0.07	0.09	0.08	0.09	0.08
MgO	0.77	0.73	0.91	0.85	0.81	0.67	0.69	0.74	0.70	0.83	0.81	0.72
CaO	2.56	2.50	2.28	2.30	2.29	1.88	2.03	2.03	2.59	2.36	2.60	2.51
Na20	2.22	2.46	2.30	2.39	2.48	2.36	2.55	2.40	2.28	2.19	2.13	2.51
K20	4.52	4.56	4.95	4.80	4.73	5.18	4.76	4.89	4.42	4.45	4.48	4.97
P205	0.26	0.26	0.22	0.22	0.24	0.19	0.21	0.20	0.31	0.27	0.28	0.30
LOI	0.93	0.99	1.22	1.05	0.96	0.57	0.84	0.70	1.03	1.36	0.93	0.73
Total	99.29	100.08	99.60	99.35	100.13	99.36	99.41	99.60	99.60	99.40	99.63	99.91
FeO*/MgO	6.09	6.10	5.95	5.84	6.28	5.76	5.68	5.50	6.56	6.48	6.47	6.46
Weight (kg)	28.5	19.5	20.5	14.0	28.5	24.5	21.5	24.5	34.0	33.5	33.5	23.5

Table 8. Chemical analyses of the Østmarka metatonalite complex.

Tonalite, Østmarka Sample no.	56153	56154	56155	56156	56157	56158	56159	56160	56161
SiO2	57.85	58.36	58.88	58.85	57.11	57.36	54.87	59.24	55.80
TiO2	1.01	1.03	1.04	1.02	0.92	0.86	0.96	0.85	0.87
Al203	17.33	16.69	16.74	16.97	16.86	17.32	17.59	16.99	17.65
Fe203	1.73	2.00	1.19	0.73	1.11	2.19	1.74	0.45	2.01
FeO	5.46	5.55	6.22	6.46	6.77	5.23	6.54	6.43	5.44
MnO	0.10	0.11	0.10	0.10	0.13	0.12	0.13	0.10	0.15
MgO	3.30	3.21	3.11	3.07	4.05	3.80	4.27	3.51	3.72
CaO	6.30	6.26	6.28	6.32	6.96	7.38	7.76	6.74	7.31
Na20	3.56	3.33	3.44	3.47	3.64	3.66	3.80	3.69	3.87
K20	1.30	1.38	1.32	1.28	0.46	0.57	0.67	0.61	0.86
P205	0.29	0.28	0.27	0.27	0.27	0.26	0.30	0.26	0.27
No determination of LOI									
Total	98.23	98.20	98.59	98.54	98.28	98.75	98.63	98.87	97.95
FeO*/MgO	2.13	2.29	2.34	2.32	1.92	1.89	1.90	1.95	1.95
Weight (kg)	13.0	13.0	9.5	11.0	8.0	11.0	8.5	7.5	5.0

anorogenic Moss–Filtvet complex at 1.32 ± 0.02 Ga (Hageskov & Pedersen 1981). The resetting age of the augen gneiss at 1.06 ± 0.17 Ga may thus be related to the F_3 deformation during the Sveconorwegian orogeny. In this case it suggests a minimum age for the onset of the Sveconorwegian orogeny (Table 5).

Gothian evolution in SE Norway

The Proterozoic chronological development of the Østfold Complex in the Østfold segment and the Romerike Complex in the Median segment is compared in Table 5. Although the correlation of the incorporated areas is still

Table 9. Chemical analyses of the Nordstrand–Sørmarka metatonalite/granite complex.

Tonalite/granite, Nordstrand-Sørmarka Sample no.	56126	56128	56129	56130	56142	56143	56144	56145	56146	56147	56148
SiO2	65.19	67.83	67.24	63.56	63.64	63.01	64.56	73.71	73.23	72.79	72.84
TiO2	0.86	0.81	0.82	0.98	1.08	1.13	1.06	0.33	0.31	0.37	0.32
Al203	14.92	14.47	14.34	15.35	15.16	15.20	15.23	13.11	13.65	13.15	13.25
Fe203	0.82	0.77	0.58	1.65	0.00	0.97	1.26	0.22	0.22	0.39	0.08
FeO	4.85	4.26	4.54	5.13	6.77	6.11	5.15	2.02	1.90	2.07	2.14
MnO	0.09	0.08	0.09	0.11	0.11	0.11	0.09	0.03	0.04	0.05	0.05
MgO	1.59	1.45	1.45	1.87	1.89	1.97	1.78	0.50	0.42	0.51	0.46
CaO	3.26	2.95	3.19	3.95	3.33	3.45	3.39	1.47	1.42	1.47	1.60
Na20	3.94	3.92	3.76	3.95	3.26	3.36	3.36	3.08	2.97	2.85	3.03
K20	1.94	1.46	1.79	1.64	2.44	2.48	2.36	4.49	5.11	4.85	4.65
P205	0.28	0.11	1.51	0.37	0.13	0.14	0.08	0.10	0.11	0.14	0.10
No determination of LOI											
Total	97.74	98.11	99.31	98.56	97.81	97.93	98.32	99.06	99.38	98.64	98.52
FeO*/MgO	3.52	3.41	3.49	3.53	3.58	3.54	3.53	4.43	5.00	4.74	4.78
weight (kg)	9.0	15.0	13.0	11.0	6.5	5.0	6.5	8.0	8.5	8.0	5.5

under debate, the radiometric ages published in Hageskov & Pedersen (1981, 1988), Skjernaa & Pedersen (1982) and the present paper have enabled a compilation of the orogenic evolution incorporating both tectonic segments across the Ørje mylonite zone (Dalsland Boundary Thrust). The early orogenic evolution in SE Norway can be ascribed to the Gothian orogeny within the 1.75–1.55 Ga interval reviewed by Gaál & Gorbatschev (1987).

The main part of the Østfold–St. Le-Marstrand supracrustals outcrops in the Østfold segment and adjoining parts of the Median segment (Larsson 1956; Berthelsen 1980; Skjernaa & Pedersen 1982; Skjernaa 1997). The lower age limit of orogenic evolution in SE Norway is therefore established by the age of the Østfold–St. Le-Marstrand supracrustal gneisses dated by Åhäll & Daly (1989) at ca. 1.76 Ga (Sm-Nd errorchron age: 1758 ± 78 Ma, MSWD: 9.4), and by the age of the oldest orthogneisses intruded into the supracrustal complex. These are the biotite gneiss intruded into the Østfold segment at ca. 1.71 Ga (maximum age, this paper) and the augen gneiss intruded into the Median segment also at ca. 1.71 Ga (Skjernaa & Pedersen 1982). Åhäll et al. (1998) have recently obtained a Pb-Pb single grain zircon age of 1.579 ± 0.019 Ga for the Stora Le-Marstrand Formation. However, this age is within error similar to the age of the Rönnäng tonalite (1.587 ± 0.003 Ga), which intruded into the Stora Le-Marstrand Formation in Sweden, and to the Østmarka and the Nordstrand–Sørmarka metatonalites, which intruded into the Stora Le-Marstrand Formation in Østfold (this paper). Prior to intrusion of the (meta-) tonalites, the Stora Le-Marstrand Formation was folded and underwent migmatization under amphibolite facies conditions during one event in SW Sweden (Åhäll & al. 1998) and during two events in Østfold (Graversen 1984, this paper). These relations indicate that the geological consequences of the clustering of the obtained ages regarding the Stora Le-Marstrand host rocks and the tonalite intrusions needs further clarification. The new Stora Le-Marstrand age of 1.579 ± 0.019 Ga is therefore not included in the present summary and Table 5.

During the early orogenic evolution, rocks of the Median segment were folded and metamorphosed during one or two fold episodes prior to intrusion of the youngest Gothian unit, the grey (tonalitic) orthogneiss complex dated at 1.63 ± 0.05 Ga (Skjernaa & Pedersen 1982). The early folding in the Median segment may thus be correlated with the F_0 and F_1 fold episodes of the Østfold segment. If this correlation is valid, the F_1 fold episode should precede 1.63 ± 0.05 Ga. The grey orthogneiss complex was folded and metamorphosed under amphibolite facies conditions prior to the intrusion of sill-like layers of granodioritic orthogneiss dated at ca. 1.4 Ga (Skjernaa & Pedersen 1982). This deformation may correlate with the F_2 fold episode in the Østfold segment (Table 5), whereas the 1.4 Ga age indicates the upper limit of the Gothian orogeny in the Romerike Complex.

Although the timing of individual Gothian events in the Østfold and Median segments cannot be decisively correlated, there are no age constraints that indicate a separate and independent evolution of these tectonic units (see also Berthelsen 1987). The Østfold and Romerike Complexes are therefore considered to belong to one and the same Gothian terrane, and the Sveconorwegian Ørje mylonite zone (Dalsland Boundary Thrust) does not reflect a Gothian terrane boundary. The suggested correlations indicate that the Gothian orogeny in SE Norway started at ca. 1.7 Ga and terminated with the F_2 fold episode at ca. 1.57 Ga.

Conclusions

The present study is focused on the development of the Oslofjord–Øyeren area in the northernmost part of the Østfold segment. The Rb-Sr whole-rock age determinations have been integrated with the established geological history and tectonostratigraphy (Graversen 1984). Although the errors of some ages are large and resetting may invalidate some of the results, the integrated approach has helped to limit the time of emplacement of major

orthogneiss bodies and to model the timing of regional fold phases during the Gothian orogeny.

The lower limit of the Gothian orogeny is indicated by the emplacement of the biotite gneiss not earlier than ca. 1.71 Ga. This was followed by the early Gothian F_0 deformation.

The late Gothian folding and amphibolite facies metamorphism is bracketed by the ages of the metatonalite/granite complexes, ca. 1.56–1.58 Ga, emplaced around the F_2 deformation (i.e. the interval ranging between the F_1 and F_2 fold episodes and post-F_2 deformation). The age of the Østmarka metatonalite complex, 1.56 ± 0.04 Ga, thus marks the upper limit of the Gothian orogeny while the F_2 deformation is indicated at ca. 1.57 Ga.

Based on the tectonochronology of the Oslofjord–Øyeren area a common Gothian and Sveconorwegian evolution has been established for SE Norway (Table 5). This suggests that the Norwegian part of the Østfold and Median segments belongs to one and the same Gothian terrane. A resetting age of 1.06 ± 0.17 Ga may be correlated with the early Sveconorwegian F_3 deformation, and this date (1.06 ± 0.17 Ga) thus indicates a minimum age for the onset of the Sveconorwegian orogeny. A maximum age is indicated by the pre-Sveconorwegian Runddelen orthogneiss intruded into the Median segment at 1.16 Ga (Skjernaa & Pedersen 1982).

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