A new Rb-Sr isotopic parameter for metasomatism, Δt, and its application in a study of pluri-fenitized gneisses around the Fen ring complex, South Norway

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Emplacement of the Fen peralkaline-carbonatitic ring complex 583 Ma ago in the c. 1105 Ma old Telemark gneisses caused mineralogical, chemical and Sr-isotopic changes, i.e., fenitization, in the country rocks. Fenitization involved at least two main phases of brecciation, creating pathways for the fenitizing fluids, and at least two main phases of metasomatic alteration. The initial phase was dry and at high temperature, inducing melting and hybridization, producing true fenites close to the contacts with magmatic textures and fenitized gneisses farther from the contact. The initial phase shows breakdown of biotite, hornblende and quartz to Na-pyroxene and alkali feldspar and formation of a fine-grained microcline and albite from original plagioclase and mesoperthite.

The subsequent phase of fenitization had a low-temperature, hydrothermal character. It also resulted in fenitization of the magmatic rocks of the Fen Complex. Mineralogically, it is characterized by the formation of Na-amphiboles, secondary biotite, stilpnomelane and carbonate minerals. Going outwards, the intensity of the brecciation and fenitization diminishes. Early fenitization occurred in an aureole up to 0.7 km wide. Subsequent fenitization extended up to at least 1.5 km from the core of the complex.

Fenitized gneisses show with increasing fenitization decreasing $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios. The $^{87}Sr/^{86}Sr$ plot of the fenite and fenitized gneisses against 1/total Sr is indicative of mixing of Sr of the Telemark gneisses with Sr of the fenitizing fluids, with a 'mantle-like' $^{87}Sr/^{86}Sr$ of about 0.703. Rb-Sr whole-rock ages were calculated for the fenitized rocks, using the initial $^{87}Sr/^{86}Sr$ of the Telemark gneisses.

The difference, Δt, between the calculated ages of the fenitized rocks and the age of the Telemark gneisses is used as a measure of the degree of 'total fenitization'. Fenitization in a Δt versus chemistry diagram is expressed in the form of chemical trends; negative trends in the case of depletion, positive trends in the case of enrichment. The major elements Si and Al show a negative trend and Fe, Mn, Mg, Ca, P, Na, K and LOI a positive trend. Correlation of chemistry and mineral content of fenitized rocks indicates that the trends for most major elements are realistic, e.g., for Si and Fe. The trends displayed by the trace elements are less definitive from the available data; trace elements cannot be correlated with mineral contents.

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Introduction

The Fen Complex, an intrusion in Mesoproterozoic gneisses in Telemark county, Southeast Norway, has a roughly circular outcrop of about 9 km^2 consisting of a central core of carbonate rocks enclosed by an incomplete ring of peralkaline silicate rocks (Figs. 1 and 2). The Complex, some 12 km west of the Late Palaeozoic Oslo Graben, became famous after publication of the classic monograph of Brøgger in 1921. Brøgger, one of the first proponents of carbonate magmas, called the Fen carbonate rocks "Karbonatite" (carbonatites). The metasomatism of the country rocks by the Fen Complex Brøgger named "fenitisierung" (fenitization) and the metasomatized gneiss "Fenit" (fenite). Fenite, the most intensively modified country rock, is an alkali syenite with a magmatic texture. In this paper fenite is used, in the sense of Brøgger, for rocks of alkali syenitic composition with a distinct magmatic texture (sometimes referred to as pulaskitic fenite). Fenite dykes intrude both the magmatic rocks of the Fen Complex and the surrounding country rocks. All metasomatized rocks that show palimpsest gneissose textures are designated as fenitized gneisses.

The country rock of the Fen Complex is predominantly a felsic, medium-grained, migmatitic gneiss, comprising quartz, perthitic microcline, oligoclase, dark-brown biotite and green hornblende, with subordinate opaques, apatite, allanite, titanite and zircon, interpreted as foliated granite and possibly metavolcanic rocks (Dahlgren 2004). Towards the margin of the Fen Complex the gneiss shows a gradual increasing brecciation and a gradual increasing replacement of the original biotite, hornblende and quartz by aggregates of Na-pyroxenes and Na-amphiboles. Microcline gives way to mesoperthite and chessboard albite aggre-

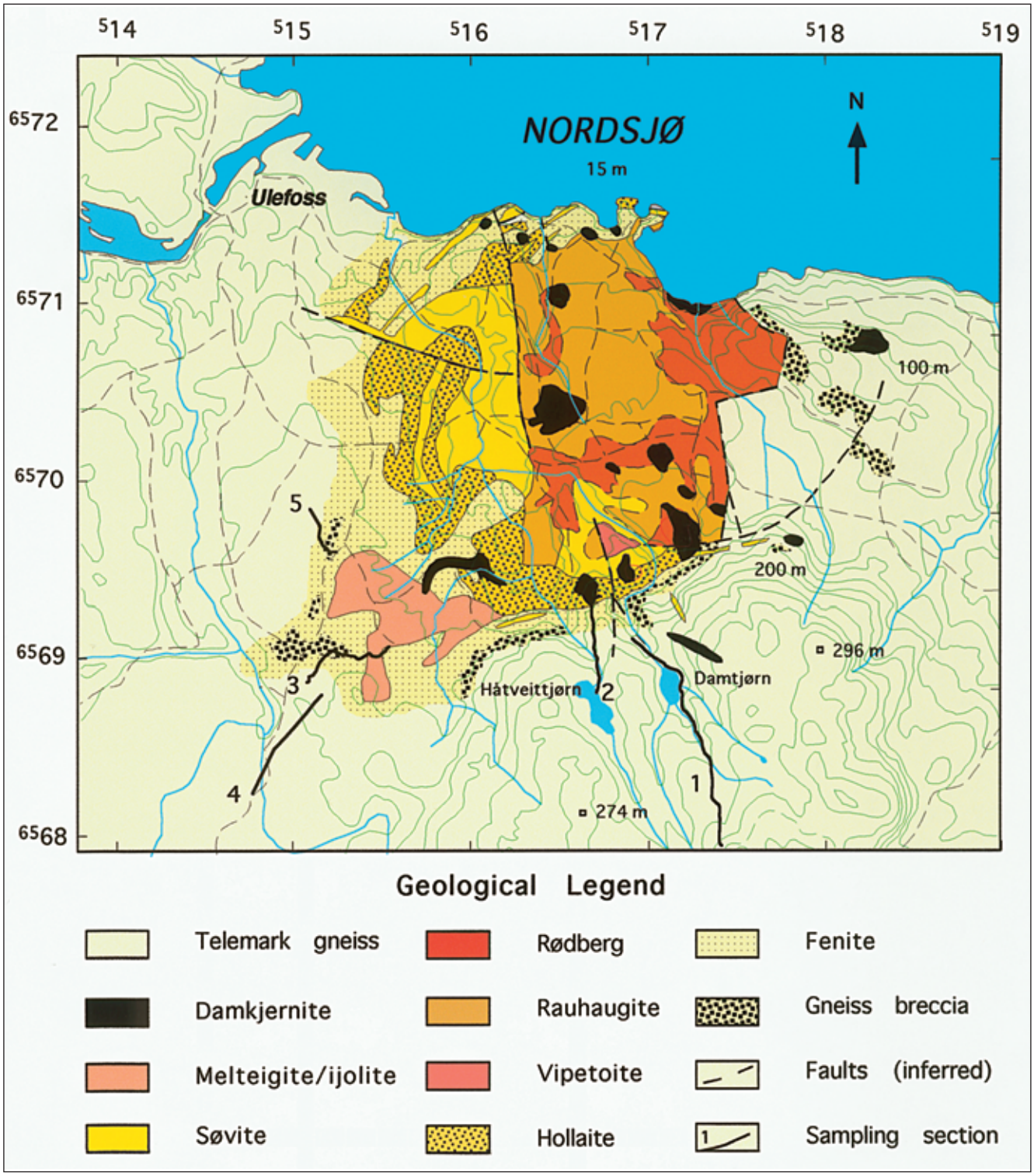


Fig. 1. Geological sketch map of the Fen Complex, after Sæther (1957); superimposed on part of the 5th NOR edition of the 1 : 50,000 topographical map-sheet UMT 1713 IV Nordagutu 1964 (contour interval 20 m; altitude Nordsjø + 15m). The five sampling sections are indicated. 1 The Damtjørn Section, 2 The Håtveittjørn Section, 3 The Mjølteig A Section, 4 The Mjølteig B Section, 5 The Holla Hagen-Tveitlåven Section.

gates. Plagioclase shows a gradual increasing saussuritization. Close to the rocks of the Fen Complex, plagioclase is replaced by clear aggregates of albite.

On petrographical grounds, Brøgger concluded that fenitization results in depletion of K and Si and enrichment of Na, Al and Ca. The complexity of fenitization was already observed by Brøgger (1921, p. 177), who described a fenitized gneiss in which aegirine was pseudomorphosed into

biotite and albite by "einer fortgezetsten Umwandlung" (a continued alteration) under "wesentlich niedrichen Temperaturen" (essentially low temperatures), accompanied by the formation of carbonate and cancrinite.

According to Brøgger (1921), Sæther (1957), Bergstøl (1960) and Dahlgren (1987), the fenitized zone around the Fen Complex has a maximum width of 200 m, sometimes only a few metres. However, outside this zone there are many occurrences of minerals typical for fenitization.

The gneisses in which the Fen Complex was emplaced cover a large part of the southern Norwegian Precambrian province. Originally known as the 'Telemark granite(s)', the more appropriate name 'Telemark gneisses' was suggested by Neumann (1960). The gneisses form part of the polyorogenetic Gothian-Sveconorwegian terrane of southern Scandinavia (e.g., Verschure 1985).

The protolith of the Telemark gneisses is considered to be essentially Gothian (1.7 to 1.5 Ga), reworked by Sveconorwegian (1.25 to 0.9 Ga) metamorphism and intruded by Late-Sveconorwegian (± 0.9 Ga) granites. The Sveconorwegian reworking resulted in Sr isotopic resetting (e.g., Priem et al. 1973, Verschure et al. 1990). The Telemark gneiss of the Kviteseid area, some 14 to 45 km west of the Fen area (Fig 2), yielded a Rb-Sr whole-rock age of 1105 ± 23 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7086 ± 0.0032 (Priem et al. 1973). Similar ages for the peak of Sveconorwegian metamorphism have been determined for many rocks in southern Norway (Kullerud & Machado 1991, Kullerud & Dahlgren 1993, Knudsen 1996, Knudsen et al. 1997).

Graphical reconstruction of the sub-Cambrian peneplain suggests a depth of 1 to 3 km for the now exposed level of the Fen Complex at the time of intrusion (Sæther 1957). Gravity investigations by Ramberg (1964, 1973) established that the various rocks outcropping in the Fen Complex form only a thin cap on top of a vertical cylindrical body at least 15 km long consisting of igneous material with a density of about 3.10 g cm^{-3}. This material was believed by Ramberg (1964, 1973) to be damkjernite, a phlogopite-bearing, ultramafic lamprophyre.

The mantle origin of the damkjernite is indicated by the presence of lherzolite nodules. The differentiation processes producing the damkjernite magma probably occurred at or below the base of the continental crust, which is now at least 33 to 34 km below the Fen area (Ramberg & Smithson 1971, Griffin 1973).

Brøgger postulated on geological grounds that the Fen Complex was not related to the magmatism of the Permian Oslo Graben but to an Early Cambrian volcanic event. Based on chemical-spectrographic Th-Pb age determinations on columbite, pyrochlore and zircon, Sæther (1957) reported that the Fen magmatism was of Early Cambrian age.

Meert et al. (1998), however, determined a $^{40}Ar/^{39}Ar$ age of 583 ± 10 Ma, using biotite and phlogopite separates from damkjernite and phonolite dykes. Presently, the 583 ± 10 Ma Vendian age is regarded the best estimate for the Fen magmatism.

The Fen Complex is the main centre of a great number of small satelite intrusions (e.g., Bergstøl & Svinndal 1960, Dahlgren 1987). Dahlgren (1984, 1987, 1994) called this region of about 1500 km^2 in southern Norway, with satellite intrusions, the 'Fen Province'.

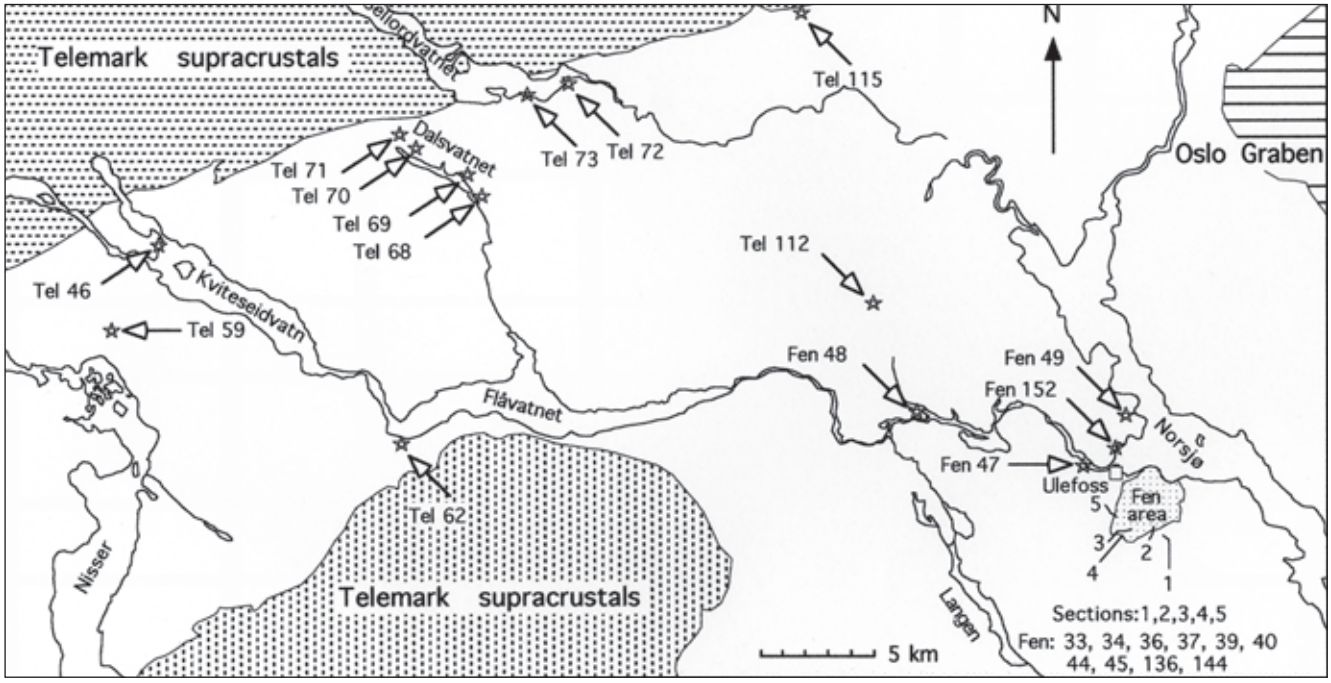


Fig. 2. Sketch map of central Telemark showing the locations of analysed Tel and Fen samples.

Scope of the present investigation

The objectives of this study were to investigate the petrographic, chemical and strontium isotopic modifications of the Telemark gneiss by fenitization. For this purpose, rock samples were collected from the fenitization aureole along 5 line traverses (the Damtjørn, Håtveittjørn, Mjølteig A, Mjølteig B and Holla Hagen-Tveitlåven Sections) and several places outside this aureole (Figs. 1 and 2). Details of the line sampling traverses of the Damtjørn, Håtveittjørn, Mjølteig A and B and Holla Hagen-Tveitlåven Sections can be obtained from the first author.

The petrographic data of 69 hand-specimens collected along the traverses are summarized in Tables 1–5 and in Figs. 3–8. Additional samples ('Way Out' Fen Samples) are summarized in Table 6. Mineralogical data of these samples were obtained by estimating the quantity of the various minerals in thin-sections. It is realized that errors are inherent to the estimated numerical data but they are believed to be below 10%. Although these errors might appear to be large, in the light of the enormous changes in mineralogy by fenitization they do not invalidate the conclusions shown in Tables 1–5 and Figs. 3–7. Moreover, the most prominent fen-

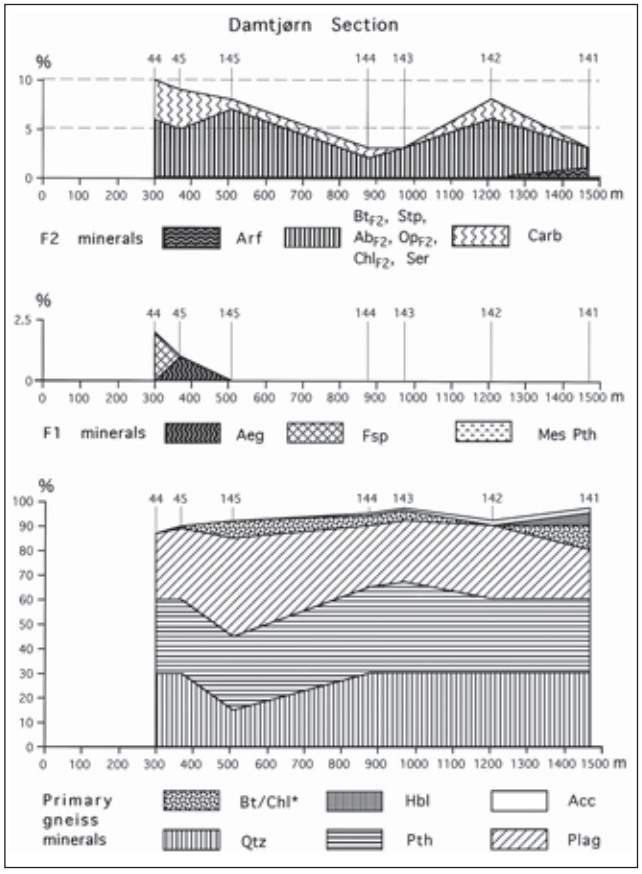


Fig. 3. Variations in mineralogy of fenitized gneisses (petrographical estimates, separately, of primary gneiss, Fenitization-1 and Fenitization-2) along the Damtjørn Section versus distance from the contact of the Intrusive Complex. Mineral abbreviations: Kretz (1983) and Carb = carbonate, Op = opaque, Pth = perthite, Mes Pth = mesoperthite, Ser = sericite. Chl* is chlorite probably not due to fenitization.

Table 1. Modal composition of samples from the Damtjørn Section (estimated percentages).

		Primary Gneiss										Fenitization-1 HT Dehydration				Fenitization-2 LT Hydration-Carbonation									Remarks
Sample	Distance m	Qtz	Pth	Plag	An %	Bt/ Chl*	Hbl	Op	Ap	Zrn	Aln	Ttn	Sum	Aeg	Fsp	Mes Pth	Sum	Arf	Bt F2	Stp	Ab F2	Op F2	Chl F2	Ser	Aln F2	Carb F2 disp	Carb F2 veins	Sum	
F 141	1470	30	30	20	15-20	10	5	1	acc	acc	acc	1	97	.	.	.	.	1	.	1	acc	1	.	acc	.	acc	.	3	Wf2 gneiss; along rims and cracks Hbl/Bt⇒Arf,Stp;f2Carb,Arf,Stp veins
F 142	1210	30	30	30	20-0	[]	acc	1	acc	acc	acc	1	92	.	.	.	.	.	.	3	acc	2	1	acc	.	.	2	8	Mf2 gneiss; Bt/Hbl⇒Stp,Ser±f2Chl,f2Op±f2Ab; Plag [large(y)]⇒Ser
F 143	970	30	37	25	10-0	4	[]	1	acc	acc	acc	acc	97	.	.	.	.	.	.	1	.	1	1	.	.	.	.	3	Wf2 gneiss; Bt/Hbl⇒f2Chl,Stp,f2Op
F* 144	880	30	35	25	0	4	.	1	acc	acc	.	.	97*	[?]	.	.	.	[?]	.	acc	.	1	1	acc	acc	1	.	3	Wf2-Wf1 gneiss; along veins [Aeg/Arf]⇒f2Op,f2Chl,f2Carb,f2Ab,f2Qtz
F 145	510	15	30	40	10-0	7	acc	.	acc	acc	.	.	92	.	.	.	.	.	.	5	.	1	1	.	.	1	.	8	Mf2 gneiss; Hbl⇒Stp,f2Chl,f2Op,f2Carb; [Bt/Hbl] coronas
F* 45	370	30	30	29	10-0	1	.	.	acc	acc	.	acc	90	1	.	.	1	acc	acc	acc	acc	3	1	1	.	3	1	9	Mf2-Wf1 gneiss; Bt/Hbl⇒f2Op,Ser,f2Carb,f2Ab,f2Qtz; [Bt/Hbl] coronas
F* 44	300	30	30	27	0	.	.	.	acc	.	.	.	87	[]	2	.	2	.	.	acc	acc	3	3	.	.	3	1	10*	Sf2-Wf1 gneiss; along coronas/veins' [Bt/Hbl]⇒[Aeg]⇒f2Chl,f2Op,f2Carb
Contact	0																												

Legend

Aeg	=	green Na clinopyroxene	[]	=	completely altered	vein	=	veins/veinlets	11*	=	including 1% apatite
Arf	=	blue or colourless Na amphibole	?	=	uncertain determination	/	=	and/or	97*	=	including 2% muscovite
Carb	=	carbonate group mineral	[?]	=	uncertain determination of completely altered mineral	F1	=	Fenitization-1			
Chl*	=	pre-fenitization chlorite pseudomorph	⇒	=	replaced by	F2	=	Fenitization-2			
Fsp	=	microcline-chessboard albite 'matrix'	disp	=	dispersed						
Kop	=	koppite	F*	=	sample used for: whole-rock chemistry	W	=	weak	[Sum F1 or Sum F2 = < 5]		
Mes Pth	=	mesoperthite			Rb-Sr isotope investigation	M	=	moderate	[Sum F1 or Sum F2 = 5 - 10]		
Op	=	opaque mineral	acc - **acc** - *acc*	=	accessory - major accessory - minor accessory	S	=	strong	[sum F1 or Sum F2 = > 10]		
Pth	=	perthite									
Ser	=	'sericite', colorless mica	Distance	=	inferred distance from contact country rocks - Fen Complex						

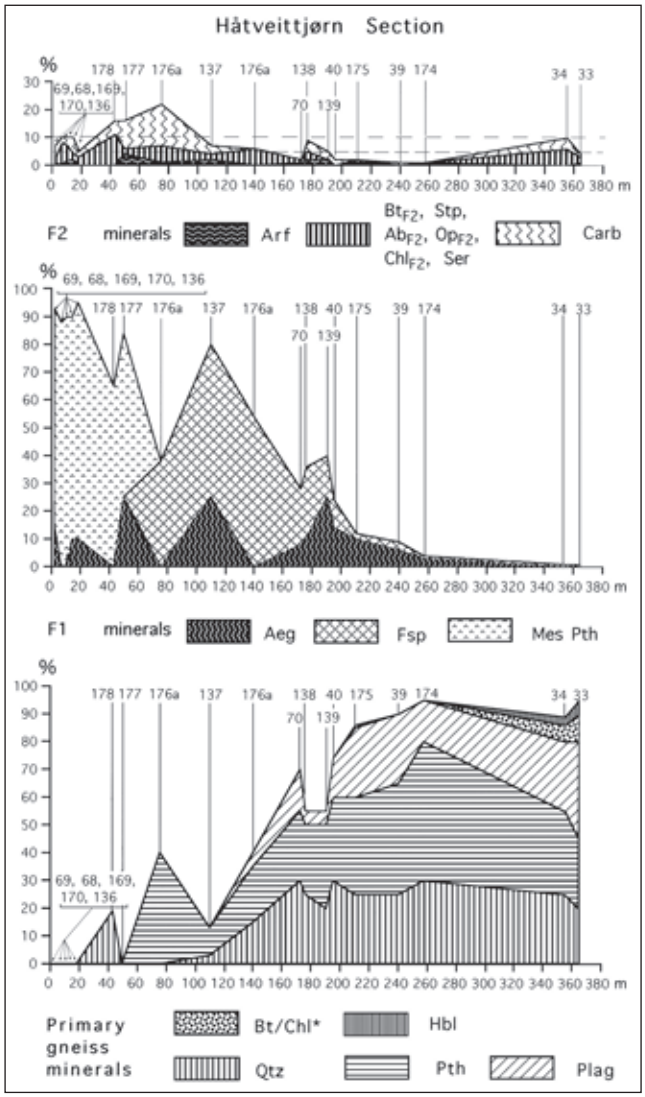


Fig. 4. Variations in mineralogy of fenitized gneisses and (pulaskitic) fenites (petrographical estimates, separately, of primary gneiss, Fenitization-1 and Fenitization-2) along the Håtveittjørn Section versus distance from the contact of the Intrusive Complex. Mineral abbreviations: Kretz (1983) and Carb = carbonate, Op = opaque, Pth = perthite, Mes Pth = mesoperthite, Ser = sericite. Chl* is chlorite probably not due to fenitization.

itization minerals: green pyroxene and blue amphibole are conspicuous enough to count amounts far below 1%.

Fourteen samples of about 15 kg were used for analysis of major and trace elements and Sr-isotope ratios. Three of these samples are from the Damtjørn Section (Fig. 3, Table 1), 5 from the Håtveittjørn Section (Fig. 4, Table 2), and 2 samples from the Mjølteig A and B Sections (Figs. 5 and 6, Tables 3 and 4). Four samples were taken from north and northwest of the Fen Complex ('Way Out Samples') (Fig. 2, Table 6). From these 14 samples, norm calculations were made that confirm the estimated modal analyses. The analytical results are compared with the analyses of 11 samples of the unfenitized Kviteseid Telemark gneiss collected some 14 to 45 km west to northwest of the Fen area (Fig. 2, Table 7) (Priem et al. 1973).

The petrographical modifications due to fenitization are compared and correlated with changes in chemical composition and in Rb-Sr isotope systematics. The latter have been used to create a parameter to quantify fenitization.

Petrography

Petrographic study of the rocks from Brøgger's (1921) 'classical' fenitization aureole and rocks outside this aureole indicates that fenitization encompassed at least two main phases of brecciation, creating pathways for the metasomatizing fluids and at least two main phases of metasomatic alteration. Fenitization at Fen was therefore called plurimetasomatism by Verschure & Maijer (1984).

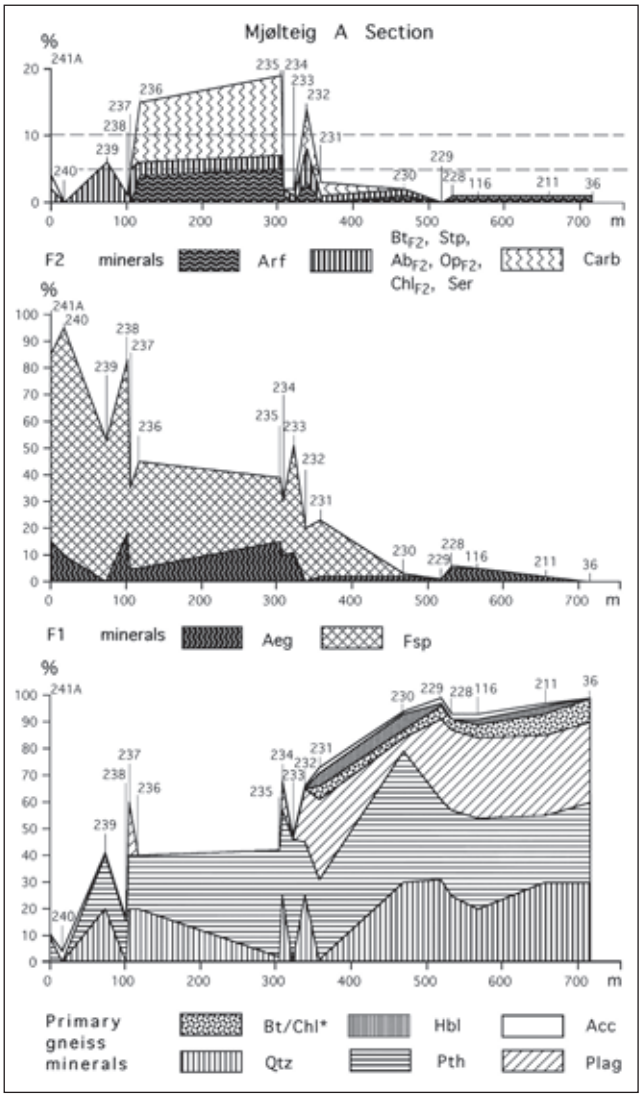


Fig. 5. Variations in mineralogy of fenitized gneisses (petrographical estimates, separately, of primary gneiss, Fenitization-1 and Fenitization-2) along the Mjølteig A Section versus distance from the contact of the Intrusive Complex. Mineral abbreviations: Kretz (1983) and Carb = carbonate, Op = opaque, Pth = perthite, Mes Pth = mesoperthite, Ser = sericite. Chl* is chlorite probably not due to fenitization.

Table 2. Modal composition of samples from the Håtveittjørn Section (estimated percentages).

		Primary Gneiss												Fenitization-1 HT Dehydration				Fenitization-2 LT Hydration-Carbonation										Remarks
Sample	Distance m	Qtz	Pth	Plag	An %	Bt/ Chl*	Hbl	Op	Ap	Zrn	Aln	Ttn	Sum	Aeg	Fsp	Mes Pth	Sum	Arf	Bt F2	Stp	Ab F2	Op	Chl F2	Ser	Aln F2	Carb F2 disp	Carb F2 veins	Sum	
F* 33	365	20	25	35	10-0	10	5	acc	acc	acc	acc	.	95	1	.	.	1	1	.	1	.	1	.	.	.	.	1	4	W_{F2}-W_{F1} gneiss; Bt, Hbl, Aln with very fine-grained coronas
F* 34	355	25	30	25	0	6	3	[ ]	acc	acc	.	acc	89	[ ]	1	.	1	[ ]	1	acc	.	3	2	.	.	2	2	10	M_{F2}-W_{F1} gneiss; [Bt], [Aeg] with very fine-grained coronas
F 174	257	30	50	15	0	acc	.	[ ]	acc	acc	.	acc	95	3	1	.	4	1		.	.	acc	.	.	.	.	.	1	W_{F2}-W_{F1} gneiss; Bt (largely)⇒Aeg,Fsp,$_{F1}$Op coronas
F* 39	240	25	40	25	0	acc	.	.	acc	acc	.	.	90	6	3	.	9	acc	.	.	.	acc	.	.	.	1	.	1	W_{F2}-M_{F1} gneiss; Bt (largely)⇒Aeg,Fsp,$_{F1}$Op coronas
F 175	210	25	35	25	0	1	.	.	acc	acc	.	.	86	10	2	.	12	1	.	.	.	1	.	.	.	.	.	2	W_{F2}-S_{F1} gneiss; Bt (largely)⇒Aeg,Fsp,$_{F1}$Op coronas; Aeg veins
F* 40	195	30	30	14	0	acc	.	.	acc	acc	.	acc	74	14	10	.	24	acc	.	acc	.	.	.	.	.	2	.	2	W_{F2}-S_{F1} gneiss; (Bt largely)⇒Aeg,Fsp,$_{F1}$Op coronas; Aeg veins
F 139	190	20	30	5	0	[ ]	.	.	acc	.	.	acc	55	25	15	.	40	2	.	.	.	.	.	.	.	2	1	5	M_{F2}-S_{F1} gneiss; Aeg,Fsp coronas; Aeg veins; minor $_{F2}$Carb,Arf veins
F 138	176	25	25	5	0	[ ]	.	.	**acc**	acc	.	.	55	10	26	.	36	2	.	acc	.	3	.	.	.	3	1	9	M_{F2}-S_{F1} gneiss; various crosscutting veins: Aeg,$_{F2}$Carb,±Arf,$_{F2}$Op
Ma 70	175	30	25	15	10-0	[ ]	.	[ ]	acc	acc	.	.	70	8	20	.	28	1	.	acc	.	1	.	acc	.	.	.	2	W_{F2}-S_{F1} gneiss; Aeg,Fsp pseudomorphs after Bt; Aeg veins
F 176A	140	15	20	5	0	[ ]	.	.	acc	acc	.	.	40	[ ]	54	.	54	[ ]	.	1	.	4	1	.	.	acc	.	6	M_{F2}-S_{F1} gneiss; [Aeg]/[Arf]⇒$_{F2}$Op,$_{F2}$Chl,Stp;$_{F2}$Qtz,$_{F2}$Op veins
F 137	110	3	10	.	.	.	.	.	acc	.	.	acc	13	25	55	.	80	2	.	acc	acc	2	.	.	.	1	2	7	M_{F2}-S_{F1} gneiss; disp and veins Aeg; Aeg⇒Arf,$_{F2}$Op,$_{F2}$Carb,F2Bt; F2Carb,$_{F2}$Ab veins
F 176B	75	.	40	.	.	[ ]	.	.	acc	.	.	.	40	acc	38	.	38	1	3	acc	acc	3	.	.	.	12	3	22	S_{F2}-S_{F1} gneiss; Carb,$_{F2}$Qtz veins; Aeg⇒Arf,$_{F2}$Op,$_{F2}$Carb,$_{F2}$Bt; $_{F2}$Carb,$_{F2}$Ab veins
F 177	50	.	.	.	.	.	.	.	.	.	.	.	.	25	.	59	84	4	1	.	.	1	.	.	.	5	5	16	S_{F2} fenite; acc $_{F2}$Tnt,Ap,Aln; Aeg (partly)⇒Arf,$_{F2}$Carb,$_{F2}$Op
F 178	43	19	.		.	.	.	.	.	.	.	.	19	[ ]	.	65	65	[ ]	8	2	.	1	.	.	.	4	1	16	S_{F2} fenite; acc $_{F2}$Tnt,Ap; Aeg (complete)⇒$_{F2}$Bt,Stp,$_{F2}$Op,$_{F2}$Carb
F* 136	10	.	?	.	.	.	.	.	.	.	.	.	?	10	.	85	95	[ ]	.	1	acc	2	.	.	.	2	.	5	M_{F2} fenite; acc $_{F2}$Tnt,$_{F2}$Op,Carb,$_{F2}$Qtz; Aeg⇒[Arf]$_{F2}$Op,Stp,$_{F2}$Carb; Arf⇒$_{F2}$Op
F 170	10	.	?	.	.	.	.	.	.	.	.	.	?	10	.	80	90	2	.	.	.	2	.	.	.	4	2	10	M_{F2} fenite; acc $_{F2}$Tnt,Ap; along veins Aeg⇒$_{F2}$Carb,$_{F2}$Op,Arf
F 169	10	.	.	.	.	.	.	.	.	.	.	.	.	acc	.	90	90	2	.	1	.	1	3	.	.	3	.	10	M_{F2} fenite; acc $_{F2}$Tnt,Ap; most Aeg⇒Arf,$_{F2}$Chl,Stp,$_{F2}$Op,$_{F2}$Carb
Ma 68	10	.	.	.	.	.	.	.	.	acc	.	.	.	[ ]	.	88	88	[ ]	2	2	.	1	1	2	.	2	.	12*	S_{F2} fenite; acc Ap; $_{F2}$Op veins; Stp veins
Ma 69	10	.	?	.	.	.	.	.	.	.	.	.	?	15	.	78	93	1	acc	.	.	1	.	.	.	3	2	7	M_{F2} fenite; acc $_{F2}$Tnt,Ap; along veins Aeg⇒$_{F2}$Carb,$_{F2}$Op,Arf,$_{F2}$Bt
Contact	0																												

		Primary Melteigite											Fenitization-2 LT Hydration-Carbonation											Remarks
Sample	Distance m	Aeg	Pth	Neph	Plag	An%	Bt	Ttn	Ap	Carb	Op	Sum	Arf	Bt F2	Stp	Ab F2	Op F2	Chl F2	Ser	Carb F2 disp	Carb F2 veins	Sum	
F 140	-10	55	10	[ ]	.	.	.	5	2	2	1	. 75	5	3	acc	2	7	.	1	. 2	4	25*	S_{F2} 'melteigite'; along $_{F2}$Carb veins Aeg⇒$_{F2}$Op,Arf,$_{F2}$Bt;Ttn⇒Ant
F 140A	-30	70	[ ]	[ ]	.	.	5	1	2	2	2	. 82	.	3	acc	1	3	3	3	. 1	3	18*	S_{F2} 'melteigite'; up to 0.5 mm Aeg with CPX cores; Aeg⇒$_{F2}$Op,Arf,$_{F2}$Bt;Ttn⇒Ant

		Primary Carbonatite											Fenitization-2 LT Hydration-Carbonation										Remarks
Sample	Distance m	Carb	Bt	Ap	Op	Kop						Sum	Rt F2	Aln F2	Stp	Qz F2	Op F2	Chl F2	Ser	Carb F2 disp	Carb F2 veins	Sum	
F 59	-230	60	15	20	acc	.	.	.	.	.	.	95	acc	acc	acc	1	acc	4	.	acc	.	5	M_{F2} carbonatite; Bt⇒$_{F2}$Chl,$_{F2}$Qtz,$_{F2}$Carb rims
F 179	-230	85	2	10	1	acc	.	.	.	.	.	98	.	acc	acc	acc	acc	2	.	acc	acc	2	W_{F2} carbonatite; $_{F2}$Chl,Stp,$_{F2}$Qtz veins; Bt⇒$_{F2}$Qtz,$_{F2}$Carb lenses/rims/veins
Ma 72	-230	90	1	5	1	acc	.	.	.	.	.	97	acc	.	acc	acc	acc	3	.	acc	acc	3	W_{F2} carbonatite; $_{F2}$Chl,$_{F2}$Qtz,Stp veins; Bt⇒$_{F2}$Chl,$_{F2}$Qtz,$_{F2}$Carb rims/veins

Legend

Aeg	=	green Na clinopyroxene	[ ]	=	completely altered	vein	=	veins/veinlets		25*	=	including 1%F2Ant
Arf	=	blue or colourless Na amphibole	?	=	uncertain determination	/	=	and/or		18*	=	including 1%F2Ant
Carb	=	carbonate group mineral	[?]	=	uncertain, determination of completely altered mineral	F1	=	Fenitization-1		12*	=	including 2%F2Ttn
Chl*	=	pre-fenitization chlorite pseudomorph	⇒	=	replaced by	F2	=	Fenitization-2				
Fsp	=	microcline-chessboard albite 'matrix'	disp	=	dispersed							
Kop	=	koppite	F*	=	sample used for: whole-rock chemistry	W	=	weak	[Sum F1 or Sum F2 = < 5]			
Mes Pth	=	mesoperthite			Rb-Sr investigation	M	=	moderate	[Sum F1 or Sum F2 = 5-10]			
Op	=	opaque mineral	acc - **acc** - *acc*	=	accessory - major accessory - minor accessory	S	=	strong	[Sum F1 or Sum F2 = > 10]			
Pth	=	perthite										
Ser	=	'sericite, colourless mica	Distance	=	inferred distance from contact country rocks-Fen Complex							

Table 3. Modal composition of samples from the Mjølteig A Section (estimated percentages).

		Primary Gneiss												Fenitization-1 HT Dehydration				Fenitization-2 LT Hydration-Carbonation										Remarks
Sample	Distance m	Qtz	Pth	Plag	An %	Bt/ Chl*	Hbl	Op	Ap	Zrn	Aln	Ttn	Sum	Aeg	Fsp	Mes Pth	Sum	Arf	Bt F2	Stp	Ab F2	Op F2	Chl F2	Ser	Aln F2	Carb F2 disp	Carb F2 veins	Sum	
F* 36	716	30	30	30	15	9	.	acc	acc	acc	acc	acc	99	acc	.	.	.	1	.	acc	.	.	.	.	.	acc	.	1	W_{F2}-W_{F1} gneiss; Bt,⇒ Aeg⇒ Arf, Stp; fine-grained coronas; acc $_{F2}$Fsp
F 211	656	30	25	30	20	8	3	**acc**	acc	acc	acc	1	97	2	acc	.	2	1	acc	acc	.	.	.	.	.	acc	.	1	W_{F2}-W_{F1} gneiss; Bt/Hbl/Op/Aln⇒ Aeg⇒ Arf,Stp; fine-grained coronas; acc $_{F2}$Fsp
F 116	567	20	34	30	15-0	5	2	1	acc	acc	.	1	93	5	*acc*	.	5	1	1	acc	.	acc	.	.	acc	*acc*	.	2	W_{F2}-M_{F1} gneiss; Bt/Hbl/Op⇒ Aeg⇒ Arf,Stp; fine-grained coronas; acc $_{F2}$Fsp
F 228	532	25	32	30	15-0	4	acc	1	acc	acc	acc	1	93	5	1	.	6	1	acc	acc	.	acc	.	.	.	.	.	1	W_{F2}-M_{F1} gneiss; Bt/Hbl⇒ Aeg⇒ Arf,Stp; fine-grained coronas
F 229	518	31	30	30	15-0	5	1	1	acc	acc	acc	1	99	1	.	.	1	acc	acc	acc	.	acc	.	.	.	.	.	.	W_{F2}-W_{F1} gneiss; Bt⇒ Aeg⇒ Arf,Stp; fine-grained coronas; $_{F2}$Ab,$_{F2}$Op,$_{F2}$Qtz veins
F 230	468	30	49	5	0	3	6	.	acc	acc	*acc*	1	94	2	1	.	3	1	1	*acc*	.	1	.	.	.	.	.	3	W_{F2}-W_{F1} gneiss; Bt/Hbl⇒ Aeg⇒ Arf,Stp; fine-grained coronas
F 231	358	.	.	.	.	.	.	.	.	.	.	.	.	7	40	46	100*	.	acc	.	.	**acc**	.	.	.	.	.	.	W_{F2} fenite; 2 cm wide vein transsecting sample F 231
F 231	358	1	30	30	0	5	5	1	acc	acc	.	1	73	2	21	.	23	.	1	.	.	1	.	.	.	2	.	4	W_{F2}-S_{F1} gneiss; Bt/Hbl⇒ Aeg⇒ 2Bt, $_{F2}$Op; fine-grained coronas
F 232	338	25	20	20	10-0	.	.	.	.	.	.	1	66	acc	20	.	20	3	.	1	.	4	.	acc	.	4	2	14	S_{F2}-S_{F1} gneiss; Arf⇒Stp; Carb vein with Arf,$_{F2}$Op,$_{F2}$Bt/Stp
F 233	323	.	46	.	0	.	.	.	*acc*	.	.	1	47	11	40	.	51	acc	.	.	.	1	-.	.	*acc*	1	.	2	W_{F2}-S_{F1} gneiss; **acc** $_{F2}$Ap; $_{F2}$Op, Stp veins
F 234	308	25	32	10	.	.	.	.	.	.	.	1	68	10	20	.	30	1	acc	*acc*	.	1	.	.	.	.	.	2	M_{F2}-S_{F1} gneiss; along cracks Arf, Stp,$_{F2}$Op and Aeg⇒Arf,$_{F2}$Op
F 235	306	2	40	.	.	.	.	.	acc	acc	.	acc	42	15	24	.	39	5	.	.	acc	2	.	.	.	10	2	19	S_{F2}-S_{F1} gneiss; along cracks Carb and Aeg⇒Arf
F 236	117	20	210	.	.	.	.	.	acc	.	.	.	40	5	40	.	45	4	.	acc	.	2	.	.	.	6	3	15	S_{F2}-S_{F1} gneiss; along cracks Carb, Arf,$_{F2}$Op, Stp and Aeg⇒Arf,$_{F2}$Op
F 237	103	20	20	20	.	.	.	.	.	.	.	acc	60	5	30	.	35	acc	*acc*	3	.	2	acc	acc	.	acc	.	5	M_{F2}-S_{F1} gneiss; Aeg⇒Arf⇒Stp
F 238	103	.	15	.	.	.	.	.	.	.	.	1	16	18	65	.	83	*acc*	acc	.	acc	1	.	.	.	.	1	1	W_{F2}-S_{F2} gneiss; $_{F2}$Ap; Pth, Ttn xenocrysts; $_{F2}$Ab,$_{F2}$Op,$_{F2}$Qtz veins
F 239	73	20	20	.	.	.	.	.	.	.	.	1	41	.	53	.	53	.	.	1	.	3	2	.	.	.	.	6	M_{F2}-S_{F1} gneiss; in cracks and breccia zones $_{F2}$Op,Stp,$_{F2}$Chl
F 240	17	.	.	.	.	.	.	.	.	.	.	4	4	10	85	.	95	.	1	.	.	.	.	.	.	.	.	1	W_{F2}-S_{F1} gneiss; acc $_{F2}$Ap;
F 241A	0	.	10	[ ]	.	.	.	.	acc	acc	.	1	11	15	70	.	85	.	.	.	.	2	.	.	.	1	1	4	W_{F2}-S_{F1} gneiss; Pth,Ap,Zrn,Ttn xenocrysts
Contact	0																												

		Primary Melteigite												Fenitization-2 LT Hydration-Carbonation												Remarks
Sample	Distance m	Aeg	Kfsp	Neph	Plag	An%	Bt	Ttn	Ap	Carb	Op	Aln	Sum	Arf	Bt F2	Stp	Ep	Op F2	Chl F2	Ser	Ab	Carb F2 disp	Carb F2 veins	Sum	
F 241B	0	50	[ ]	[ ]	.	.	acc	5	1	.	1	acc	57	.	6	acc	7	.	.	25	5	.	.	43	S_{F2} melteigite; Ab,Prh,Ep vein; cracks with $_{F2}$Op,Stp; acc $_{F2}$Fsp
F 242	-94	69	.	[ ]	.	.	1	2	14	1	1	.	90*	.	.	.	.	acc	.	9	.	.	1	10	M_{F2} melteigite;
F 243	-114	63	.	[ ]	.	.	3	2	2	2	acc	.	75*	.	.	.	.	1	9	9	.	5	1	25	S_{F2} melteigite; coarse-grained zonal Aeg with Ti-Aug coronas

Legend

Aeg	=	green Na clinopyroxene	[ ]	=	completely altered	vein	=	veins/veinlets	100*	=	including 6% opaque and 1 % titanite
Arf	=	blue or colourless Na amphibole	?	=	uncertain determination	/	=	and/or	90*	=	including 2% melanite
Carb	=	carbonate group mineral	[?]	=	uncertain, determination of completely altered mineral	F1	=	Fenitization-1	75*	=	including 3% melanite
Chl*	=	pre-fenitization chlorite pseudomorph	⇒	=	replaced by	F2	=	Fenitization-2			
Fsp	=	microcline-chessboard albite'matrix'	disp	=	dispersed						
Kop	=	koppite	F*	=	sample used for: whole-rock chemistry	W	=	weak	[Sum F1 or Sum F2 = < 5]		
Mes Pth	=	mesoperthite			Rb-Sr investigation	M	=	moderate	[Sum F1 or Sum F2 = 5-10]		
Op	=	opaque mineral	acc - **acc** - *acc*	=	accessory - major accessory - minor accessory	S	=	strong	[Sum F1 or Sum F2 = > 10]		
Pth	=	perthite									
Ser	=	'sericite, colourless mica	Distance	=	inferred distance from contact country rocks-Fen Complex						

Table 4. Modal composition of samples from the Mjølteig B Section (estimated percentages).

		Primary Gneiss											Fenitization-1 HT Dehydration			Fenitization-2 LT Hydration-Carbonation									Remarks
Sample	Distance m	Qtz	Pth	Plag	An %	Bt/ Chl*	Hbl	Op	Ap	Zrn	Aln	Ttn	Sum	Aeg	Fsp	Mes Pth	Sum	Arf	Bt F2	Stp F2	Ab F2	Op F2	Chl F2	Ser F2	Aln F2	Carb F2 disp	Carb F2 veins	Sum	
F 93	1329	30	29	30	20	7	2	1	acc	acc	acc	acc	99	.	.	.	.	.	.	1	.	.	acc	.	.	.	.	1	Wf_2 gneiss; Bt with lenses of Tnt,Op,Aln; Bt/Hbl⇒Stp⇒f_2Chl; f_2Chl,Stp vein
F 218	1010	28	28	32	20	6	3	acc	acc	acc	.	acc	97	.	.	.	.	1	.	1	.	1	.	.	acc	.	acc	3	Wf_2 gneiss; Bt/Hbl⇒Arf, Stp,f_2Op coronas; Bt with f_2Aln lenses
F 217	890	30	32	30	0	1	.	.	acc	acc	.	.	93	.	.	.	.	[ ]	.	1	.	1	5	.	.	.	.	7	Wf_2 gneiss; [Arf]⇒f_2Chl; brecciation zones
F 216	820	32	30	30	20	6	2	2	acc	acc	acc	acc	100	.	.	.	.	acc	.	acc	.	.	.	.	.	.	.	.	Wf_2 gneiss; Bt/Hbl⇒Arf, Stp coronas
F 215	770	28	30	30	0	3	acc	acc	acc	acc	.	.	91	[ ]	1	.	1	[ ]	.	1	.	1	1	.	.	4	1	8	Mf_2-Wf_1 gneiss; Bt/Hbl⇒[Aeg]⇒[Arf]/Stp⇒f_2Chl,f_2Op,f_2Carb;coronas
F 214	695	25	35	30	15-20	3	2	acc	acc	acc	acc	acc	95	acc	.	.	.	2	.	.	.	.	.	1	acc	1	1	5	Mf_2-Wf_1 gneiss; Bt/Hbl⇒Aeg⇒Arf⇒f_2Op; coronas
F 213	620	30	30	30	0	acc	.	acc	.	.	.	acc	90	[ ]	acc	.	.	4	1	1	.	1	.	.	acc	1	1	10*	Mf_2-Wf_1 gneiss; [Aeg]⇒Arf/f_2Op,f_2Bt,f_2Chl,Ep; coronas; brecciation veins
F 212	540	20	35	25	0	.	.	.	**acc**	acc	acc	.	80	acc	2	.	2	9	.	1	.	3	.	.	.	2	3	18	Sf_2-Wf_1 gneiss;brecciation zones;f_2Qz,Carb,f_2Op veins
F 110	540	15	20	25	0	.	.	.	acc	acc	.	.	60	15	5	.	20	15	*acc*	*acc*	.	3	.	acc	.	2	.	20*	Sf_2-Sf_1 gneiss; Aeg⇒Arf⇒f_2Op;brecciation zones, relict corones
F* 37	± 500	30	30	30	20	7	.	acc	acc	acc	acc	acc	97	1	1		2	acc	*acc*	*acc*		1	.	.	.	acc	.	1	Wf_2-Wf_1 gneiss; Bt/Hbl/Op⇒Aeg⇒Arf,Stp coronas, Aln⇒Aeg⇒Stp coronas

Legend
[F* 37 was taken 250 m NW sample F 110]

Aeg	=	green Na clinopyroxene	[ ]	=	completely altered	vein = veins/veinlets	10* = including 1% epidote
Arf	=	blue or colourless Na amphibole	?	=	uncertain determination	/ = and/or	20* = including accessory Fl
Carb	=	carbonate group mineral	[?]	=	uncertain determination of completely altered mineral	F1 = Fenitization-1	
Chl*	=	pre-fenitization chlorite pseudomorph	⇒	=	replaced by	F2 = Fenitization-2	
Fsp	=	microcline-chessboard albite 'matrix'	disp	=	dispersed		
Kop	=	koppite	F*	=	sample used for: whole-rock chemistry	W = weak	[Sum F1 or Sum F2 = < 5]
Mes Pth	=	mesoperthite			Rb-Sr isotope investigation	M = moderate	[Sum F1 or Sum F2 = 5 - 10]
Op	=	opaque mineral	acc - **acc** - *acc*	=	accessory - major accessory - minor accessory	S = strong	[Sum F1 or Sum F2 = > 10]
Pth	=	perthite					
Ser	=	'sericite', colorless mica	Distance	=	inferred distance from contact country rocks - Fen Complex		

Fig. 6. Variations in mineralogy of fenitized gneisses (petrographical estimates, separately, of primary gneiss, Fenitization-1 and Fenitization-2) along the Mjølteig B Section versus distance from the contact of the Intrusive Complex. Mineral abbreviations: Kretz (1983) and Carb = carbonate, Op = opaque, Pth = perthite, Mes Pth = mesoperthite, Ser = sericite. Chl* is chlorite probably not due to fenitization.

Metasomatic alteration ascribed to the second phase overprinted the fenitized rocks of the first phase. Fenitization of the second fenitization phase is found in a much wider aureole around the Fen Complex (at least up to 1.5 km, possibly up to 10 km) than that of the first fenitization phase (up to 700 m). The second fenitization phase also affected the rocks of the intrusive Fen Complex and some country rocks that escaped the first phase.

The 'classical fenitization', or Fenitization–1, as well as the later hydration and carbonization phase (Fenitization-2), are both partly pervasive and partly channelled with concentrations of alteration along intergranular spaces, cracks and veinlets (Fig. 9). The amount of Fenitization-1 products increases to nearly 100% in rocks close to the contacts with

Table 5. Modal composition of samples from the Holla Hagen-Tveitlåven Section (estimated percentages).

		Primary Gneiss												Fenitization-1 HT Dehydration				Fenitization-2 LT Hydration-Carbonation										Remarks
Sample	Distance m	Qtz	Pth	Plag	An %	Bt/ Chl*	Hbl	Op	Ap	Zrn	Aln	Ttn	Sum	Aeg	Fsp	Mes Pth	Sum	Arf	Bt F2	Stp	Ab F2	Op F2	Chl F2	Ser	Aln F2	Carb F2 disp	Carb F2 veins	Sum	
F 210B	550	27	25	30	.	8	2	.	acc	acc	acc	acc	92	1	1	.	2	3	acc	1	.	.	.	.	.	1	1	6	MF2-WF1 gneiss; Bt/Hbl⇒Aeg,Arf, coronas; Hbl⇒F2Bt,Fsp;Aeg,F2Carb,Stp,Arf vein
F 210	519	25	36	30	20-0	2	.	.	.	.	acc	.	93	1	1	.	2	3	.	1	acc	.	.	.	.	.	1	5	MF2-WF1 gneiss; Bt/Hbl⇒Aeg,Arf, coronas; Aeg,F2Carb,Stp,Arf,F2Ab vein
F 209	499	26	23	32	0	3	1	.	acc	.	.	acc	85	5	3	.	8	2	2	.	acc	1	.	.	.	2	.	7	MF2-MF1 gneiss; Bt/Hbl⇒Aeg, Arf, vague coronas; Aeg,Carb,Stp,Arf,F2Ab vein
F 208	480	30	28	30	20-0	5	.	acc	acc	acc	.	acc	93	2	2	.	4	1	.	*acc*	acc	1	.	acc	.	1	.	3	WF2-WF1 gneiss; Bt/Hbl⇒Aeg⇒ Arf coronas; Plag⇒ F2Ab, Ser
F 207	460	30	30	27	20-0	1	.	.	acc	.	.	acc	88	6	4	.	10	1	.	.	acc	.	.	acc	.	1	.	2	WF2-MF1 gneiss; Bt/Hbl⇒Aeg ,Arf relict coronas; Plag⇒F2Ab,Ser; breccia vein
F 206	430	30	29	30	20	4	.	acc	acc	acc	acc	acc	93	acc	2	.	2	2	.	.	acc	1	.	acc	.	1	1	5	MF2-WF1 gneiss; Bt⇒[Aeg]⇒Arf,F2Op, F2Ab coronas
F 204	420	30	30	30	20-0	1	.	.	acc	acc	.	acc	91	1	2	.	3	1	acc	acc	acc	2	.	.	.	1	1	6	MF2-WF1 gneiss; Bt⇒[Aeg]⇒Arf,F2Op, F2Ab coronas; F2Carb, F2Op, F1 breccia vein
F 203	400	20	36	30	20	5	.	.	acc	acc	.	acc	91	2	2	.	4	1	acc	*acc*	acc	1	.	.	acc	1	2	5	MF2-WF1 gneiss; Bt⇒Aeg⇒Arf,F2Op, F2Ab,F2Ab coronas/vein
F 202A	380	30	30	28	20-0	6	.	.	acc	acc	.	acc	94	1	1	.	2	2	1	.	acc	1	.	.	acc	.	.	4	WF2-WF1 gneiss; Bt⇒Aeg⇒Arf,F2Op, F2Ab,F2Ab coronas/vein
F 202	360	30	30	30	20-0	3	.	acc	acc	acc	acc	acc	93	1	2	.	3	2	acc	acc	acc	1	-.	.	acc	1	.	4	WF2-WF1 gneiss; Bt⇒Aeg⇒Arf,F2Op, F2Ab,F2Ab coronas/vein
F 201	340	20	30	30	20-0	1	.	.	acc	.	.	acc	81	1	5	.	6	6	acc	acc	acc	3	.	.	.	2	2	13	SF2-MF1 gneiss; Bt⇒[Aeg]⇒Arf,F2Op, F2Ab,F2Ab VEIN; FEW coronas
F 200	320	25	25	20	0	.	.	.	acc	.	.	acc	70	10	16	.	26	1	.	.	.	acc	.	acc	.	1	2	4	WF2-MF1 gneiss; Aeg aggregates along F2Carb vein Aeg⇒Arf,F2Op
F 199	310	28	30	30	0	1	.	.	acc	acc	.	acc	89	5	5	.	10	1	.	.	.	acc	.	acc	.	.	.	1	WF2-MF1 gneiss; Aeg aggregates; Aeg,Fsp conoras; Aeg⇒Arf,Stp,F2Op; Plag,accF1
F 198	297	20	30	25	20	10	.	.	acc	.	.	acc	85	7	5	.	12	1	acc	.	.	1	.	.	.	1	acc	3	WF2-SF1 gneiss; Bt,[Hbl]⇒Aeg,fsp conoras; along F2Carb vein Aeg⇒Arf; Plag,accF1
F 197	235	25	30	25	20	2	.	.	acc	acc	.	acc	82	6	10	.	16	1	.	acc	.	acc	.	.	acc	1	.	2	WF2-SF1 gneiss; Bt⇒Aeg, Fsp conoras; along F2Carb vein Aeg⇒Arf; Plag,accF1
F 196	212	30	30	15	0	acc	.	.	acc	.	.	acc	75	5	20	.	25	**acc**	acc	acc	.	acc	.	*acc*	.	*acc*	.	.	WF2-SF1 gneiss; Aeg,Fsp conoras; Aeg aggregates/vein; Aeg⇒Arf
Contact	0																												

		Primary Melteigite									Fenitization-2 LT Hydration-Carbonation									Remarks
Sample	Distance m	Aeg	Bt	Neph	Ap	Ttn	Op	Carb	Prv	Sum	Fl	Ccn	Op F2	Prh	Bt F2	Prv	Carb F2 disp	Carb F2 veins	Sum	
F 105	-38	36	5	41	2	2	acc	1	acc	87	2	10	**acc**	acc	acc	acc	.	1	13	SF2 melteigite; contains Pth, Ab backvein, Ccn/F1/F2Carb/Pth/F2Bt/F2Op vein

Legend

Aeg	=	green Na clinopyroxene	[ ]	=	completely altered		vein	=	veins/veinlets	
Arf	=	blue or colourless Na amphibole	?	=	uncertain determination		/	=	and/or	
Carb	=	carbonate group mineral	[?]	=	uncertain, determination of completely altered mineral		F1	=	Fenitization-1	
Chl*	=	pre-fenitization chlorite pseudomorph	⇒	=	replaced by		F2	=	Fenitization-2	
Fsp	=	microcline-chessboard albite 'matrix'	disp	=	dispersed					
Kop	=	koppite	F*	=	sample used for:	whole-rock chemistry	W	=	weak	[Sum F1 or Sum F2 = < 5]
Mes Pth	=	mesoperthite				Rb-Sr investigation	M	=	moderate	[Sum F1 or Sum F2 = 5-10]
Op	=	opaque mineral	acc - **acc** - *acc*	=	accessory - major accessory - minor accessory		S	=	strong	[Sum F1 or Sum F2 = > 10]
Pth	=	perthite								
Ser	=	'sericite, colourless mica	Distance	=	inferred distance from contact country rocks-Fen Complex					

Table 6. Modal composition of 'Way out' Fen samples (estimated percentages).

		Primary Gneiss											Fenitization-1 HT Dehydration			Fenitization-2 LT Hydration-Carbonation								Remarks
Sample	Distance m	Qtz	Pth	Plag	An%	Bt/ Chl*	Hbl	Op	Ap	Zrn	Alh	Ttn	Sum	Aeg	Fsp	Mes Pth	Sum	Arf	Bt F2	Stp	Ab F2	Op F2	Chl F2	Ser	Aln F2	Carb F2 disp	Carb F2 veins	Sum	
F* 47	±2000	30	20	37	20	8		**acc**	acc	acc	*acc*	**acc**	100						?		?	acc?	?	?		acc			Wf_2 gneiss ?; Bt⇒f_2 ? Chl; Plag ⇒f_2 ? Ab,Ser
F* 48	±10000	35	35	[25]	20-10	5		*acc*	acc	acc		*acc*	100							?	?	acc?		?					Wf_2 gneiss ?; Bt⇒f_2 ? Chl; [Plag] ⇒f_2 ? Ab,Ser
F* 49	±2400	30	30	30	20	5		**acc**	acc	acc	*?*	**acc**	100						?	?		?		?		acc			Wf_2 gneiss?; Bt⇒f_2 ? Chl
F* 144	±1500	30	27	28	20	8	6	**acc**	acc	acc	*acc*	acc	99					acc	acc		acc	acc				1	acc	1	Wf_2 gneiss?; Bt⇒Arf,Ab;Hbl⇒Chl,Carb,Op

Legend

Aeg	=	green Na clinopyroxene	[ ]	=	completely altered	vein = veins/veinlets
Arf	=	blue or colourless Na amphibole	?	=	uncertain determination	/ = and/or
Carb	=	carbonate group mineral	[?]	=	uncertain determination of completely altered mineral	F1 = Fenitization-1
Chl*	=	pre-fenitization chlorite pseudomorph	⇒	=	replaced by	F2 = Fenitization-2
Fsp	=	microcline-chessboard albite 'matrix'	disp	=	dispersed	
Kop	=	koppite	F*	=	sample used for: whole-rock chemistry	W = weak [Sum F1 or Sum F2 = < 5]
Mes Pth	=	mesoperthite			Rb-Sr isotope investigation	M = moderate [Sum F1 or Sum F2 = 5 - 10]
Op	=	opaque mineral	acc - **acc**- *acc*	=	accessory - major accessory - minor accessory	S = strong [sum F1 or Sum F2 = > 10]
Pth	=	perthite				
Ser	=	'sericite', colorless mica	Distance	=	inferred distance from contact country rocks - Fen Complex	

Fig. 7. Variations in mineralogy of fenitized gneisses (petrographical estimates, separately, of primary gneiss, Fenitization-1 and Fenitization-2) along the Holla Hagen-Tveitlåven Section versus distance from the contact of the Intrusive Complex. Mineral abbreviations: Kretz (1983) and Carb = carbonate, Op = opaque, Pth = perthite, Mes Pth = mesoperthite, Ser = sericite. Chl* is chlorite probably not due to fenitization.

the intrusive Fen Complex. The later fenitization products are subordinate and seldom exceed 10% of the total rock. The fenitization phenomena, especially of Fenitization-1, increase in intensity towards the contacts with the Complex. In the field, this is manifested by an increase in the number of veinlets, up to 5 mm wide, filled with very fine-grained, dark material. Microscopically, the succession of the brecciation and fenitization phases is best documented by cross-cutting relationships, e.g., Na-pyroxenes (varying from aegirine to aegirine-augite) of the Fenitization-1 phase transformed into Na-amphiboles (varying from magnesio-arfvedsonite to riebeckite and ferro-richterite) by the Fenitization-2 phase along carbonate/albite/quartz veinlets

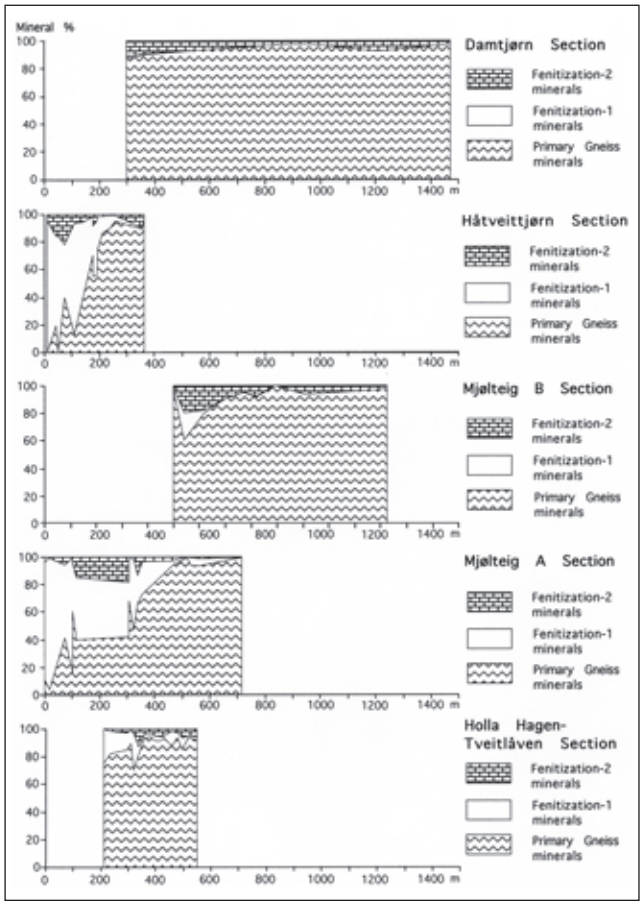


Fig. 8. Compilation of the Damtjørn, Håtveittjørn, Mjølteig A, Mjølteig B and Holla Hagen-Tveitlåven Sections of the same scale versus distance to the contact of the Intrusive Complex.

Fig. 9. Brecciated fenitized gneiss with dark veinlets containing of Na-amphibole and/or Na-pyroxene. Håtveittjørn Section at about 230 m north of Håtveittjørn. The diameter of the Norwegian 5 crown coin is 2.5 cm. Sample Fen 176A was taken here.

(e.g., Figs. 10 a and b). The increase in fenitization grade is accompanied by a gradual disappearance of the original mineralogy and texture of the Telemark gneiss.

Original country rocks

The Telemark gneiss into which the Fen Complex intruded is a fairly heterogeneous, medium-grained, migmatitic hornblende-biotite gneiss, with minor intercalations of amphibolite. The gneiss contains approximately equal amounts (about 30%) of quartz, perthitic microcline and acidic plagioclase (An10-20) and about 10% of mafic minerals, e.g., dark brown, iron-rich biotite in places accompanied by green iron-rich hornblende. The hornblende and biotite occasionally show chloritization features that are not due to fenitization but existed prior to the emplacement of the Fen Complex, as evidenced by chloritized hornblende and biotite in unfenitized Telemark gneiss of the Kviteseid area (Fig. 2). Accessories are opaque minerals, apatite, zircon, titanite and metamict allanite. The vague gneissosity is indicated by the parallel arrangement of biotite and hornblende crystals.

The mineralogy of 11 gneiss samples from the Kviteseid area, used as reference samples, is given in Table 7.

Fenitization-1

In rocks of the Telemark gneiss country rock, three degrees of increasing intensity of Fenitization-1 can be distinguished microscopically: weak, moderate and strong. These fenitized rocks still show a recognizable gneissose structure which can still be seen if the amount of primary gneiss minerals is not lower than about 40% of the total rock volume. The succession and intensities of alterations due to fenitization are visualized in tables of modal composition (Tables 1–5) and corresponding profiles of the sampled traverses (Figs. 3 - 8).

1. Weak Fenitization-1 is characterised by the breakdown of primary hornblende and biotite. Both minerals show incipient formation of fine-grained reaction coronas, with an outer zone of Na-pyroxenes and an inner zone of albite and/or microcline. The coronas occur only where hornblende and biotite crystals were in contact with quartz (e.g., Fig. 10 c), (this feature was described by McKie in 1966). Breakdown of hornblende is more complete than that of biotite. The primary feldspars, perthitic microcline and acidic plagioclase, remained largely unaltered, except for the development of turbidity by very fine-grained mineral matter. Metamict allanite disappears approximately 360 m from the contact (see the Håtveittjørn and Mjølteig A Sections, Tables 2 and 3). Allanite closest to the contact occasionally shows coronas of epidote (e.g., sample Fen 33 of the Håtveittjørn Section). The limit for a weakly fenitized-1 rock is taken at

⇨

Fig. 10. Photomicrographs of fenitized gneisses. (a) Fen 156: Na-pyroxene veinlet (Fenitization-1) transsected by a veinlet (Fenitization-2) of carbonate, blue Na-amphibole, clear albite and green biotite-F2 (not visible on this photomicrograph). Location of the sample: Kirkeruin, Økonomisk Kart Foreløpig Utgave 1971 (BV 030-5-2) coordinates: 141816-50665. (b) Fen 156: Detail of Fig. 10a, i. e., the transsection of the Fenitization-1 Na-pyroxene veinlet by the Fenitization-2 carbonate veinlet. This demonstrates in more detail the replacement and rimming of the Na-pyroxene crystals by blue Na-amphibole. In relation to Fig. 10a, this is rotated about 45° counterclockwise. (c) Ma 88: Biotite with reaction rim of massive Na-pyroxenes and alkali feldspar due to Fenitization-1. The rim was formed where biotite was in contact with quartz (clear) and not where biotite was in contact with feldspar (turbid). Other biotites within the same sample (not visible on this photomicrograph) appear stronger or even completely replaced. Location of the sample: Small quarry for road material near Steinsrud on road Holla-Steinsrud, Økonomisk Kart Foreløpig Utgave 1971 (BV 030-5-4) coordinates: 51502-656890.1. (d) Fen 125: Biotite replaced during Fenitization-2 by radiating needles of bluish Na-amphibole, subsequently partially replaced by fine-grained magnetite and hematite. The replacement occurred where biotite was in contact with quartz. Other biotites within the same sample appear unaffected or completely replaced. The sample was taken 1750 m south of the Fen Complex, far outside the zone of Fenitization–1. Location of the sample: HSP post M00059, Økonomisk Kart Foreløpig Utgave 1971 (BW 020-5-1) coordinates: 138965-51753. (e) Fen 116: Biotite-green hornblende aggregate with rim of Na-pyroxenes. The rim was initially formed by Fenitization-1 where the aggregate was in contact with quartz. The green hornblende was more intensely replaced than biotite. Small crystals in the rim of blue Na-amphibole (not visible on this photomicrograph) and green F2 biotite attest that the sample was also influenced by Fenitization–2. Location of the sample: Mjølteig A Section 567 m from the contact with the Fen Complex. (f) Fen 33‴: Biotite with a rim of a massive aggregate of blue Na-amphibole pseudomorphing Na-pyroxenes. Stilpnomelane (brown radiating flakes) occurs at the edge of the blue Na-amphibole aggregates. Location of the sample: Håtveittjørn Section 375 m from the contact with the Fen Complex.

a percentage of less than 5% of the rock volume for Fenitization-1 components.

2. Moderate Fenitization-1. This stage is characterised by the nearly complete breakdown of both hornblende and biotite by the formation of wide Na-pyroxene + albite-microcline reaction coronas. Na-pyroxenes also form irregular patches and vein-like aggregates. Primary plagioclase is partly replaced by fine-grained, clear aggregates of chessboard albite. Sæther (1957) called the formation of clear chessboard albite and microcline aggregates 'matrix formation'.
   Primary quartz and microcline perthite are still present. The limits for a moderate fenitized rock are taken at between 5 and 10% of the rock volume for the Fenitization–1 components.

3. Strong Fenitization–1. This stage is characterised by a major reduction in the amount, or nearly complete disappearance, of primary quartz and primary microcline perthite and the complete disappearance of primary plagioclase. Coronas of Na-pyroxene are no longer present, but Na-pyroxene occurs as veins and irregular aggregates. The original gneissose texture, however, is still recognizable in places. The strongly fenitized-1 rocks also contain clear, euhedral alkali feldspar crystals forming a matrix of chessboard albite and microcline without preferred orientation. The limit for a strongly fenitized rock is taken at more than 10% of the rock volume for the Fenitization-1 components.

Close to the Fen Complex, a maximum 50 m-wide zone only rarely contains quartz, plagioclase or orthoclase/microcline. These rocks – fenites in the sense of Brøgger (1921) and probably similar to Kresten's (1988) contact fenites – are mainly made up by aggregates of Na-pyroxene in a matrix of sub- to euhedral mesoperthite (in places with Carlsbad or Baveno twinning) with discontinuous intergranular rims of exsolved albite. The texture of these rocks is magmatic. In various places, dykes of fenite with similar texture are found that intrude fenitized country rock gneisses (e.g., sample Fen 231 of the Mjølteig A Section, Table 3) and rocks of the Fen Complex. Such igneous fenites, or pulaskitic fenites, as found in the Håtveittjørn Section, where the Fen Complex consists of carbonatite and damkjernite (apart from a few tens of metres of melteigite, Table 2), are absent in the Mjølteig A Section, where the rocks of the Fen Complex consist only of melteigite (compare Figs. 4 and 5, Tables 2 and 3).

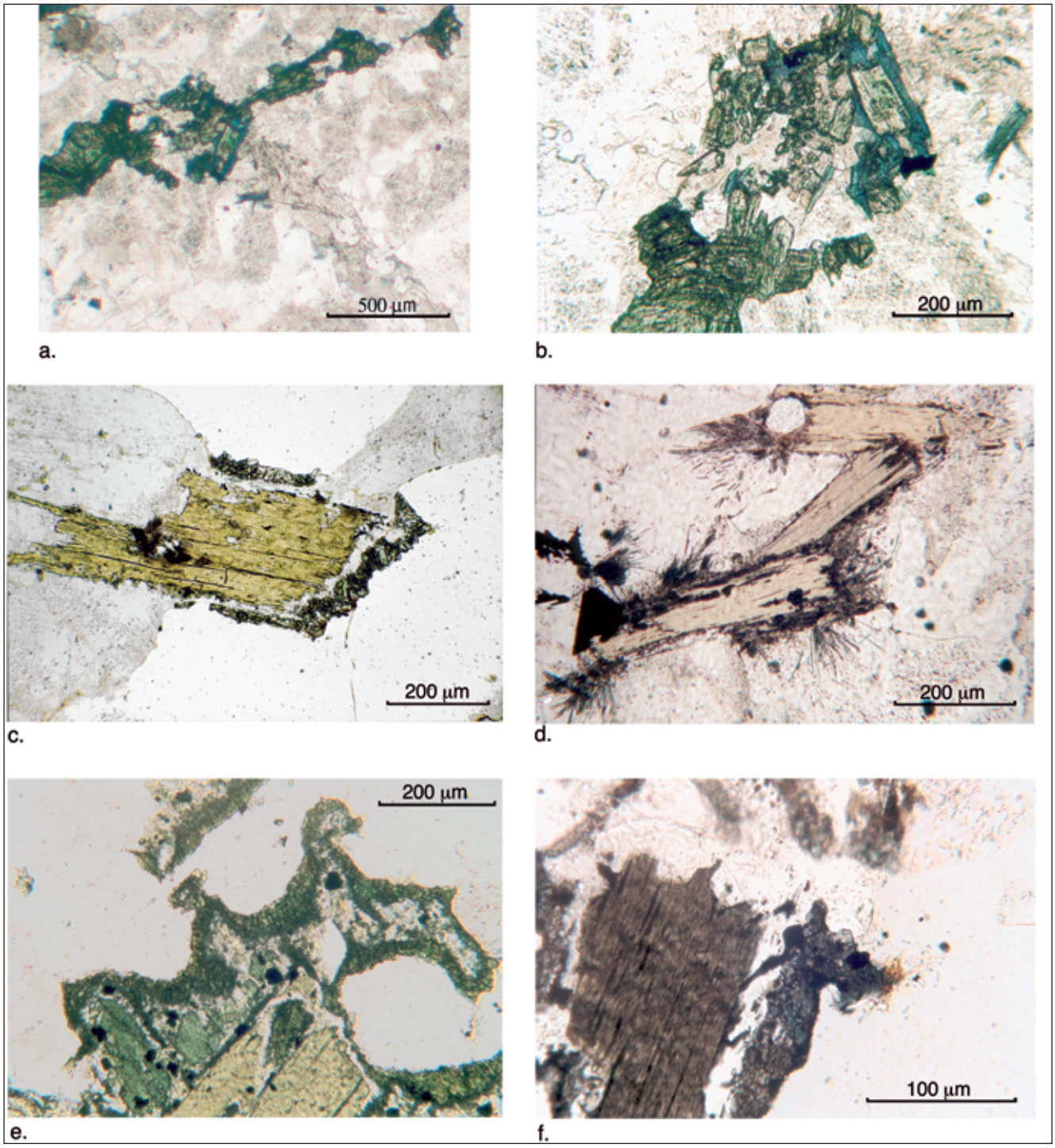
Table 7. Modal composition of samples from the Telemark gneisses (estimated percentages).

Sample	Qtz	Pth	Plag	An %	Bt/ Chl	Hbl	Op	Ap	Zrn	Aln	Ttn	Fl	Sum
T*46	32	25	38	12	4	1	acc	acc	*acc*	acc	**acc**		100
T*59	34	25	30	18	8	2	*acc*	**acc**	acc	acc	1	*acc*	100
T*62	41	30	27	15	2		*acc*		*acc*	*acc*	*acc*	*acc*	100
T*68	36	25	35	15	4			*acc*	*acc*	acc	acc	*acc*	100
T*69	37	25	35	15	3		acc	acc	acc	acc	acc		100
T*70	42	30	25	10	3		acc	*acc*	acc	acc	acc		100
T*71	40	32	25	10	3		acc	*acc*	acc	**acc**	**acc**		100
T*72	32	27	33	15-18	4	3		acc	acc	acc	1		100
T*73	35	32	30	10	3			acc	*acc*		*acc*	**acc**	100
T*112	33	23	36	18	5	3	acc	acc	acc		acc		100
T*115	39	20	28	10	3(Bt+Ms)				acc			*acc*	100

Legend
Op = opaque mineral, mainly magnetite with titanite rim
Pth = microcline perthite
Aln = mainly strongly metamict
T* = sample used for: whole-rock chemistry and Rb-Sr investigation
acc - **acc** - *acc* = accessory - major accessory - minor accessory

Fenitization-2

Fenitization-2 is a late hydrothermal process resulting in the replacement of Fenitization-1 minerals, primary



gneiss minerals and also minerals of the Fen Complex. Fenitization-2 produced low-temperature crystallization of hydrous minerals (Na-amphiboles, new greenish biotite, new chlorite, sericite and stilpnomelane), carbonates, quartz and opaque minerals. Fenitization-2 minerals are fine grained and seldom exceed 10% of the total rock volume. Fenitization-2 comprised several successive stages as indicated by mineral replacement relationships and various vein types showing cross-cutting relationships. In Tables 1–5, the Fenitization-2 minerals are grouped together, because the succession of Fenitization–2 mineral growth is not always certain, impossible to assess, or seemingly controversial. It is probably an indication of the gradual cooling of successive pulses of fenitizing fluids. The new minerals form veinlets and occur dispersed through intergranular spaces in fenitized gneisses and gneisses outside the Fenitization-1 aureole and also in rocks of the Fen Complex. The fine-grained aggregates of opaque phases (magnetite, hematite) are late products, palimpsestically replacing fibrous aggregates of Na-pyroxene and/or Na-amphibole (Fig. 10 d). Probably, the formation of the majority of the economically important minerals, i.e., hematite and pyrochlore in carbonatitic rocks

of the Fen Complex, took place during Fenitization-2 (Bjørlykke & Svinndal 1960).

The main minerals formed by Fenitization–2 comprise, in approximate order of crystallization:

1. Bluish to colourless Na-amphiboles replace the earlier green Na-pyroxenes of Fenitization-1, but also relict biotite inside pyroxene coronas. Outside the zone of Fenitization-1, the genuine effect of Fenitization-2 can be seen. Here, the replacement of biotite starts with clusters of radiating blue Na-amphibole needles, again where biotite was in contact with quartz. Progressive replacement produces aggregates of blue Na-amphiboles + albite + opaques pseudomorphing original biotite or hornblende (Fig. 10 f).
2. Fine-grained greenish biotite and colourless mica ('sericite'), the former preferentially replacing primary green hornblende.
3. New formed chlorite and/or golden brown ferri-stilpnomelane (Fig. 10 f).
   The chlorite replaces hornblende, in places in combination with carbonate. Stilpnomelane forms rims of tiny, often 'bushy' crystal aggregates around hornblende and biotite.
4. Iron oxides, hydroxides and sulphides comonly form grains or clusters of radiating needles. The latter are regarded as replacements of Fenitization-1 Na-pyroxenes or Fenitization-2 Na-amphiboles.

Clear (chessboard) albite, microcline, quartz and carbonate minerals are partly formed together with the minerals of Fenitization-2. The carbonate minerals occur both in disseminated form and as veinlets (Figs. 10 a and b).

From the above petrographic descriptions, summarized in Figs. 3–8 and Tables 1–7, it is clear that fenitization, and especially Fenitization-1, increases towards the contacts with the Fen Complex. However, the amount of breakdown and replacement reactions varies considerably from tiny reaction rims to complete replacement even within one sample. Therefore, distance from the contact cannot be taken as a straightforward parameter of fenitization.

Strong Fenitization-1, is found within about 210 m of the contact along the Håtveittjørn Section (Fig. 4, Table 2), within about 320 m along the Holla Hagen-Tveitlåven Section (Fig. 7, Table 5), about 360 m along the Mjølteig A Section (Fig. 5; Table 3) and, in places, up to 540 m from the contact in the Mjølteig B Section (Fig. 6, Table 4).

Weak Fenitization-1 effects are seen up to 365 and 370 m from the contact along the Håtveittjørn and Damtjørn Sections respectively (Figs. 3 and 4, Tables 1 and 2), at least up to 550 m along the Holla Hagen-Tveitlåven Section (Fig. 7, Table 5), and up to 770 m from the contact along the Mjølteig Sections (Figs. 5 and 6, Tables 3 and 4).

The width of the Fenitization-2 aureole is not exactly known. Fenitization-2 effects are found at least up to 1320 m (Mjølteig B Section, Fig. 6, Table 4) and up to 1470 m (Damtjørn Section, Fig. 3, Table 1) from the contact. Further, the effects of (known and unknown) satellite intrusions may explain Fenitization-2 effects at greater distances from the contact. For the distribution of satellite intrusions, see Bergstøl & Svinndal (1960). Possible traces of Fenitization-2 effects are even found in sample Fen 48, collected some 10 km WNW of the Fen Complex (Fig. 2). It is uncertain if these effects are an indication of the size of the Fenitization–2 aureole, or the result of near-surface satellite intrusions.

Isotope geology

An isochron diagram of the Fen Rb-Sr data is given in Fig. 11 together with Rb-Sr data of the Telemark gneiss samples from the Kviteseid area (Fig. 2) investigated by Priem et al. in 1973. Both are recalculated to 583 Ma which is taken as the age of the Fen magmatism (Meert et al. 1998). Microscopically, the Telemark gneiss samples show no trace of fenitization.

It is striking that on the 583 Ma isochron diagram the Rb-Sr datapoints of the Fen samples, especially those representing the higher grades of Fenitization-1, give the impression of having 'fallen off' Priem et al.'s (1973) Telemark gneiss isochron. The Fen datapoints are crowding near the lower left corner of the isochron diagram (Fig. 11), with low $^{87}Sr/^{86}Sr$ and low $^{87}Rb/^{86}Sr$. One could argue that these Fen samples have undergone a decrease of their original $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$, if the Fen gneisses were similar to the Kviteseid samples prior to fenitization.

The linearity of the plot of 1/total Sr versus $^{87}Sr/^{86}Sr$ recalculated to 583 Ma for the Fen country rock gneisses (Fig. 12) probably indicates that during the emplacement of the Fen Complex, mixing took place between Sr from the original country rock gneisses, represented by the 11

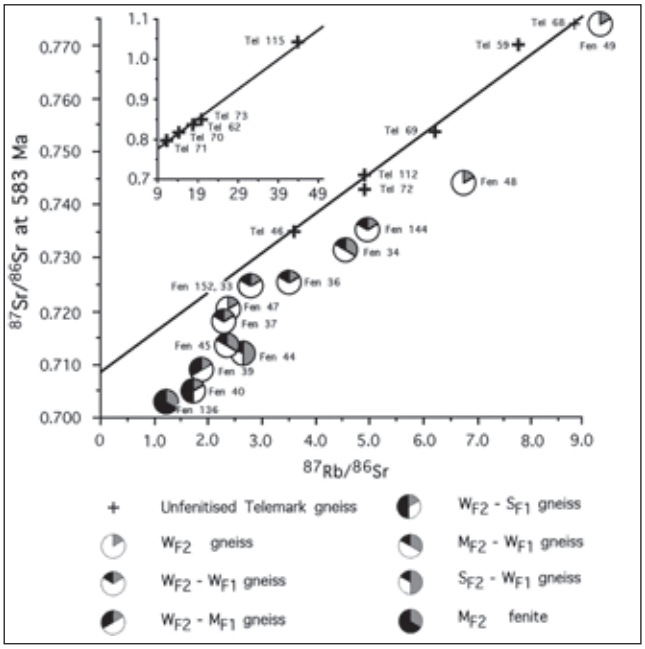


Fig. 11. Isochron plot of 11 Telemark gneisses (data from Priem et al 1973) at 583 Ma, 13 fenitized gneisses and fenite Fen 136. The petrographically estimated grade of fenitization of the Fen samples is indicated graphically.

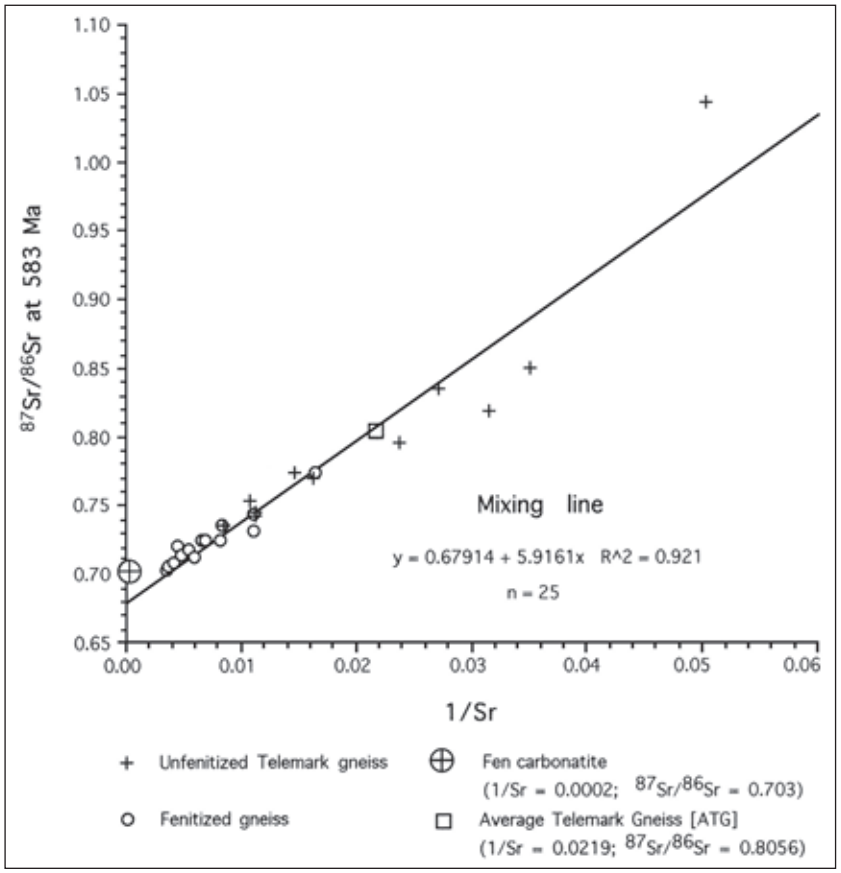


Fig. 12. Mixing line 1/total Sr versus 87Sr/86Sr at 583 Ma with unfenitized Kviteseid gneisses, fenitized gneisses and pulaskitic fenite Fen 136. The average Telemark gneiss, ATG, and average Fen carbonatite are added.

Table 8. Whole-rock Rb-Sr data of fenitized Fen gneisses and non-fenitized Telemark gneisses.

Sample nr	Rb [ppm Wt]	Sr [ppm Wt]	$^{87}Rb/^{86}Sr$ at present	$^{87}Rb/^{86}Sr$ at 583 Ma	$^{87}Rb/^{86}Sr$ at present	$^{87}Rb/^{86}Sr$ at 583 Ma
			Fen whole-rock samples			
Fen 33	115.5	121.5	2.754	2.777	0.74744	0.72455
Fen 34	138.5	89.5	4.494	4.531	0.76864	0.73128
Fen 36	172.5	145.0	3.460	3.489	0.75397	0.72521
Fen 37	142.5	182.0	2.266	2.285	0.73682	0.71798
Fen 39	153.0	239.0	1.858	1.873	0.72436	0.70891
Fen 40	156.5	267.5	1.693	1.707	0.71933	0.70526
Fen 44	149.0	165.5	2.615	2.737	0.73380	0.71206
Fen 45	166.0	207.5	2.316	2.235	0.73282	0.71357
Fen 47	179.5	221.5	2.355	2.375	0.74014	0.72056
Fen 48	205.0	89.5	6.694	6.750	0.79949	0.74384
Fen 49	189.5	60.6	9.182	9.258	0.85009	0.77376
Fen 136	119.0	285.5	1.206	1.216	0.71315	0.70312
Fen 144	200.5	119.0	4.918	4.959	0.77610	0.73522
Fen 152	143.0	152.0	2.734	2.756	0.74754	0.72481
			Telemark whole-rock samples			
Tel 46	143	117.0	3.56	3.59	0.7646	0.7350
Tel 59	161	61.2	7.70	7.76	0.8340	0.7700
Tel 62	218	36.9	17.6	17.7	0.9818	0.8355
Tel 68	203	68.3	8.71	8.78	0.8461	0.7737
Tel 69	195	92.8	6.14	6.19	0.8047	0.7537
Tel 70	152	31.7	14.2	14.3	0.9360	0.8180
Tel 71	160	42.1	11.2	11.3	0.8881	0.7950
Tel 72	147	88.6	4.84	4.88	0.7831	0.7429
Tel 73	188	28.5	19.7	19.9	1.0130	0.8492
Tel 112	147	88.2	4.84	4.88	0.7857	0.7455
Tel 115	281	19.9	43.7	44.1	1.4060	1.0427

Telemark gneiss samples (Table 8), and Sr from the Fen intrusions with much higher Sr contents (Table 9). Such mixing could have increased the Sr content of the Fen country rocks and decreased their $^{87}Sr/^{86}Sr$.

Equally, mixing of Rb from the original country rock gneisses (e.g., the Telemark gneiss) and the Fen intrusions with lower Rb contents (Table 11) has probably led to a decrease of Rb in the Fen country rock gneisses. Such changes in Rb and especially Sr contents and $^{87}Sr/^{86}Sr$ explains the position of the Fen samples 'off the isochron line' (Fig. 9). It also demonstrates that the disturbance of the Rb-Sr isotope system in the Fen aureole increases with increasing fenitization.

It will be clear that the change of the Rb and Sr contents and the Sr-isotope ratio will influence the calculated ages of the fenitized rocks. The combined effects of a reduction in Rb content and an increase in Sr content would reduce $^{87}Rb/^{86}Sr$ and therefore result in 'older' calculated ages, while a decrease in Sr-isotope ratios would result in 'younger' calculated ages. The positions of the fenitized rocks in Fig. 11 show younger apparent ages, indicating that the effect of the decrease of Sr-isotope ratio due to mixing with 'mantle' Sr is stronger than the effects of increase of total Sr and reduction of total Rb. It is likely that both Fenitization-1 and Fenitization-2 played a role in lowering their original ages, but their relative contributions could not be quantified. Fen samples that microscopically show lower grades of 'total fenitization' yield dates not much different from the age of the Telemark gneiss. Fen samples that microscopically show higher grades of total fenitization give dates that severely deviate from the age of the Telemark gneiss. The age difference, Δt, between the 1105 Ma age of the Telemark gneiss and the calculated ages of the Fen samples, using the Kviteseid Telemark gneiss initial $^{87}Sr/^{86}Sr$ ratio of 0.7086 (Priem et al., 1973), is a measure of the grade of fenitization.

To illustrate the use of Δt, plots of Δt versus the Rb and Sr contents are given in Figs. 13 and 14 .

These figures show a scatter of 9 datapoints for values of $\Delta t < 300$, i.e., with weak fenitization. It looks as if the 5 data-

points at values of Δt > 300 have a more or less linear trend. For Sr, this trend (Fig. 14) is clearly positive, as would be expected with regard to the lower Sr values of the country rock gneisses and the higher Sr values of the intrusive Fen rocks (Table 11). For Rb, the trend (Fig. 13) is less clear.

Table 9. Average Rb and Sr contents, and Sr-isotope ratios of Telemark gneisses and Fen intrusions.

Rock type	Rb-contents Average	n	Sr-contents Average	n	$^{87}Sr/^{86}Sr$ at 583 Ma	Source of data
Telemark gneiss	181 ± 42	11	61 ± 32	11	0.8056	this study
Fen carbonatite	20.8 ± 30.4	13	4821 ± 1923	23	~0.703	Mitchel & Crocket 1972, Andersen 1987 and Kresten 1994.
Fen melteigite	109 ± 89	10	1691 ± 981	10		
Fen damkjernite	68	1	1028	1		

Table 10. Major and trace elements, element ratios and Δt values of Fen gneisses.

	Fen 33	Fen 34	Fen 36	Fen 37	Fen 39	Fen 40	Fen 44	Fen 45	Fen 47	Fen 48+	Fen 49	Fen136	Fen 144	Fen 152
%														
SiO_2	70.55	73.20	73.15	72.73	69.69	65.20	72.24	71.90	72.66	75.80	75.76	63.80	72.74	70.35
TiO_2	0.42	0.31	0.14	0.31	0.29	0.33	0.29	0.25	0.39	0.15	0.14	0.24	0.23	0.50
Al_2O_3	13.49	12.25	13.53	12.66	11.57	10.98	11.73	12.23	12.97	12.40	12.53	15.45	13.50	12.62
Fe_2O_3	3.95	2.97	1.53	2.39	3.63	5.54	3.00	2.70	2.92	1.29	1.63	3.12	2.20	4.45
MnO	0.07	0.04	0.03	0.04	0.14	0.26	0.08	0.08	0.06	0.02	0.02	0.12	0.03	0.08
MgO	0.40	0.46	0.20	0.36	0.60	1.32	0.34	0.17	0.57	0.23	0.11	0.57	0.34	0.36
CaO	1.10	1.08	1.25	1.39	2.28	3.58	1.56	1.54	1.87	0.59	0.83	2.83	1.07	1.84
Na_2O	4.90	3.75	3.87	3.73	4.82	4.48	3.50	3.74	3.67	2.86	3.45	6.24	3.53	3.25
K_2O	3.86	4.57	4.81	4.71	4.73	5.53	5.03	5.38	3.56	5.75	4.86	5.91	5.03	5.24
P_2O_5	0.06	0.05	0.04	0.07	0.07	0.25	0.09	0.04	0.10	0.02	0.02	0.19	0.06	0.10
LOI	0.55	0.99	0.55	0.82	1.42	1.65	1.44	1.11	0.51	0.20	0.31	1.43	0.97	0.72
Sum	99.35	99.67	99.10	99.21	99.24	99.12	99.30	99.14	99.28	99.31	99.66	99.90	99.70	99.51
ppm														
Sc**	7.14	5.20	1.81	3.75	4.06	4.46	4.25	2.83	5.54	1.47	1.49	4.39	3.13	5.44
V	18	18	8	17	34	64	13	12	29	3	6	55	19	21
Cr**	65	65	14	85	66	65	66	73	171	82	90	15	38	59
Co**	2.01	1.24	1.19	2.49	1.49	2.57	1.10	1.58	3.63	1.34	1.22	2.13	2.06	3.50
Ni	4	4	3	5	4	6	5	6	6	3	5	4	5	5
Zn	228	228	29	47	112	220	81	99	67	21	11	55	30	78
Ga	26	26	23	18	24	25	25	26	21	14	18	28	20	23
Rb*	115.5	138.5	172.5	142.5	153.0	156.5	149.0	166.0	179.5	205.0	189.5	119.0	200.5	143.0
Sr*	121.5	89.5	145.0	182.0	239.0	267.5	165.5	207.5	221.5	89.5	60.6	285.5	119.0	152.0
Y	85	82	23	32	26	18	37	58	38	28	30	18	35	61
Zr	640	375	110	215	315	288	338	381	184	111	125	182	159	469
Nb	22	20	9	10	23	32	22	23	10	24	7	46	32	19
Cs**	2.94	1.16	2.61	2.50	1.10	1.35	1.56	2.64	6.88	1.87	1.70	0.57	2.18	4.60
Ba	1046	628	375	649	660	728	675	991	653	240	180	697	457	687
La**	65	49	33	69	30	21	34	50	25	40	33	19	39	35
Ce**	160	127	74	122	44	39	57	122	64	107	90	40	98	92
Nd	67	52	32	45	34	28	35	52	34	21	36	30	36	48
Sm**	13.3	10.7	8.9	7.4	4.0	6.9	5.1	9.6	4.3	8.1	6.1	2.5	8.3	8.8
Eu**	3.85	2.41	0.87	1.15	1.07	1.04	1.43	2.43	1.01	1.16	0.40	1.25	1.04	1.83
Tb**	5.52	4.25	1.35	1.83	1.28	1.01	1.78	3.60	1.56	2.01	1.09	1.51	1.75	2.98
Yb**	9.4	9.0	1.7	3.7	5.1	5.7	4.8	6.0	3.50	3.40	2.50	2.10	3.50	4.80
Lu**	12	1.01	0.24	0.37	0.78	0.90	0.65	0.97	0.42	0.27	0.56	0.30	0.48	0.73
Hf**	19.9	12.3	4.1	6.8	8.1	8.6	8.4	11.2	5.3	5.7	4.4	4.6	5.4	12.4
Ta**	1.46	1.43	0.52	0.47	0.67	0.70	0.75	0.82	0.71	0.42	0.46	0.72	0.73	0.53
W	5	6	1	4	1	4	7	5	3	5	3	2	2	5
Pb	54	23	42	32	21	12	22	44	31	25	26	7	48	26
Th**	16.9	17.8	35.4	12.2	11.0	37.9	13.2	15.7	8.9	23.8	15.7	6.2	43.2	12.2
U**	2.4	2.0	20.2	1.4	1.9	2.3	1.1	1.8	1.6	1.5	1.2	0.4	7.6	1.1
A/CNK	0.95	0.94	0.98	0.92	0.67	0.55	0.84	0.83	0.98	1.04	1.01	0.71	1.02	0.88
A/NK	1.10	1.10	1.17	1.13	0.89	0.82	1.05	1.02	1.31	1.14	1.15	0.93	1.20	1.15
FeO#	0.90	0.85	0.87	0.86	0.84	0.79	0.89	0.93	0.82	0.83	0.93	0.83	0.85	0.92
K/Rb	277.44	273.92	231.48	274.39	258.98	293.34	280.25	269.05	164.64	232.85	354.89	412.29	208.26	304.20
Rb/Sr	0.95	1.55	1.19	0.78	0.64	0.59	0.90	0.80	0.81	2.29	3.13	0.42	1.68	0.94
La/Yb	6.9	5.4	19.4	18.6	5.9	3.7	7.1	8.3	7.1	11.8	13.2	9.0	11.1	7.3
Th/U	7.0	8.9	1.8	8.7	5.8	16.5	12.0	8.7	5.6	15.9	13.1	15.5	5.7	11.1
Zr/Hf	32.2	30.5	26.8	31.6	38.9	33.5	40.2	34.0	34.7	19.5	28.4	39.6	29.4	37.8
Δt	119	170	188	233	510	660	430	372	168	155	28	841	145	109

Legend

** INAA * Analyses SIGO + Analyses ECN and SIGO

FeO# = %wt $\frac{FeO}{FeO+MgO}$ A/CNK [alumina index] = mol $\frac{AL_2O_3}{CaO+Na_2O+K_2O}$ A/NK [alkalinity index] = mol $\frac{AL_2O_3}{Na_2O+K_2O}$

Table 11. Major and trace elements, element ratios and Δt values of Tel gneisses.

	Tel 46+	Tel 59	Tel 62	Tel 68	Tel 69	Tel 70	Tel 71	Tel 72	Tel 73+	Tel 112	Tel 115
%											
SiO_2	70.70	76.05	77.81	75.98	76.18	79.16	77.98	73.51	76.50	72.91	77.11
TiO_2	0.48	0.12	0.11	0.14	0.17	0.11	0.12	0.32	0.13	0.44	0.10
Al_2O_3	13.20	12.30	11.22	12.18	11.56	11.14	11.06	12.53	11.70	11.55	11.26
Fe_2O_3	4.35	1.46	1.43	1.47	1.66	1.35	1.42	2.83	1.52	3.83	1.36
MnO	0.06	0.03	0.02	0.03	0.04	0.02	0.02	0.04	0.01	0.07	0.02
MgO	0.42	0.12	0.05	0.17	0.17	0.06	0.05	0.24	0.05	0.36	0.03
CaO	1.72	0.79	0.55	0.91	1.05	0.45	0.55	1.16	0.56	1.77	0.53
Na_2O	3.86	3.53	2.93	3.62	3.81	3.04	3.08	3.63	3.30	3.46	3.23
K_2O	4.21	4.58	4.97	4.36	4.12	4.74	4.75	4.73	5.27	4.24	4.72
P_2O_5	0.13	0.03	0.01	0.03	0.04	0.02	0.02	0.05	0.01	0.09	0.01
LOI		0.28	0.22	0.22	0.31	0.23	0.20	0.20		0.57	0.26
Sum	99.13	99.29	99.32	99.11	99.11	100.32	99.25	99.24	99.05	99.30	98.63
ppm											
Sc**	5.64	1.18	3.57	1.72	2.42	1.69	1.35	4.21	2.11	6.94	1.53
V		8	2	7	11	3	5	15		24	4
Cr**	111	114	92	105	118	107	310	71	122	110	132
Co**	4.08	1.35	0.83	1.90	2.47	0.91	1.13	2.29	0.98	3.97	0.86
Ni		7	5	6	5	5	6	5		6	6
Zn		6	16	13	22	7	10	32		64	23
Ga		17	18	17	18	18	18	20		21	19
Rb*	143	161	218	203	195	152	160	147	188	147	281
Sr*	117.0	61.2	36.9	68.3	92.8	31.7	42.1	88.6	28.5	88.2	19.9
Y		25	59	34	27	38	33	46		69	68
Zr	221	100	121	99	119	121	130	292		336	115
Nb		5	10	7	7	6	7	11		13	13
Cs**	6.84	2.94	1.29	3.50	4.93	2.34	3.20	3.36	3.10	4.24	7.70
Ba		208	262	152	261	213	245	631		523	127
La**	49	19	35	19	20	45	47	37	39	53	39
Ce**	94	50	97	46	59	105	113	94	106	100	102
Nd		25	40	25	29	35	39	44		52	37
Sm**	8.5	2.7	6.3	3.3	3.3	5.8	4.9	6.8	6.5	9.2	8.5
Eu**	1.83	0.31	0.48	0.29	0.57	0.47	0.75	1.42	0.44	1.65	0.33
Tb**	2.87	0.82	1.91	0.98	1.12	1.47	1.35	2.18	1.73	3.10	1.80
Yb**	7.50		4.80	3.10	2.60	2.60	3.40	5.00	5.10	6.70	7.80
Lu**	0.91		0.49	0.20	0.46	0.54	0.50	0.51	0.70	0.86	0.94
Hf**	10.9	4.1	5.4	4.7	5.0	4.0	5.5	8.7	5.9	11.0	5.6
Ta**	0.64	0.40	0.95	0.76	0.73	0.46	0.65	0.58	0.87	0.89	1.20
W		4	5	3	3	4	2	4		5	6
Pb		24	30	24	23	21	21	22		19	30
Th**	7.9	13.1	16.1	15.8	15.2	12.6	15.4	11.8	16.8	12.0	22.1
U**	2.6	2.1	2.5	2.9	2.3	1.9	1.7	2.5	6.0	3.4	4.1
A/CNK	0.93	1.01	1.00	0.99	0.91	1.02	0.99	0.95	0.97	0.86	0.99
A/NK	1.21	1.14	1.10	1.14	1.08	1.10	1.08	1.13	1.06	1.12	1.08
FeO#	0.90	0.92	0.96	0.89	0.90	0.95	0.96	0.91	0.96	0.90	0.98
K/Rb	244.40	236.16	189.26	148.03	175.40	258.88	246.45	267.12	232.71	239.45	139.44
Rb/Sr	1.22	2.63	5.89	2.97	2.10	4.79	3.80	1.66	6.60	1.67	14.12
La/Yb	6.5		7.3	6.1	7.7	17.3	13.8	7.4	7.6	7.9	5.0
Th/U	3.0	6.2	6.4	5.4	6.6	6.6	9.1	4.7	2.8	3.5	5.4
Zr/Hf	20.3	24.4	22.4	21.1	23.8	30.25	23.6	33.6	13.7	30.5	20.5
Δt	6	-33	20	2	11	-14	-15	29	25	-8	-10

Legend

** INAA * Analyses SIGO + Analyses ECN and SIGO

$$\text{FeO\#} = \%\text{wt}\ \frac{FeO}{FeO+MgO} \qquad \text{A/CNK [alumina index]} = \text{mol}\ \frac{Al_2O_3}{CaO+Na_2O+K_2O} \qquad \text{A/NK [alkalinity index]} = \text{mol}\ \frac{Al_2O_3}{Na_2O+K_2O}$$

In this paper, Δt will be used as the parameter to indicate the grade of fenitization.

Chemistry

Quantification of chemical changes in the country rock of the Fen Complex due to fenitization is difficult owing to the inhomogeneity of the Telemark gneiss. Brøgger (1921) and Sæther (1957) attempted chemical quantification of fenitization mostly on the basis of petrography because, at that time, only one single chemical analysis of a country rock gneiss was available. Brøgger (1921) considered this analysis as not representative for the average composition of the country rock.

Kresten (1988) based his chemical study of fenitization on the average composition of five gneiss samples near the Fen Complex, which he called AWR (Average Wall Rock). AWR comprises Brøgger's sample 36 and four samples from various places near the Fen Complex (Kresten's samples Fen 1, 2, 25 and 26). Kresten considered these samples to be "almost unaffected" by fenitization. However, Kresten & Morogan (1986) labelled samples Fen 1 and 25 as "low-grade fenites" while Kresten (1994, Table 1) labeled samples Fen 1 and 26 as "protolith/low grade".

Microscopical investigation of rocks collected for the present study close to Kresten's gneiss samples showed weak fenitization; e.g., Fen 218, collected close to Kresten's Fen 25, is a weakly fenitized gneiss (Table 4) with 3% of Fenitization-2 minerals. Moreover, Kresten's five AWR samples show a considerable spread in chemical composition, e.g., Figs. 13, 14 and 15. Therefore, it is unwarranted to base quantification of chemical changes by fenitization in the Fen area on the average composition of inhomogeneous gneisses not devoid of the effects of fenitization. Mass transfer estimates for metasomatized rocks are critically dependent on "a knowledge of the original composition" as Rubie stated in 1982. Determining the chemical rock composition of the Fen country rock gneisses prior to fenitization must be deemed illusory, and calculations concerning mass transfer by metasomatism (e.g., Gresens 1967 and Grant 1986), on the basis of the country rocks exposed at Fen, aimless.

In Fig. 15, diagrams are presented in which the chemical compositions of various major elements of 14 samples from the fenitization aureole (Table 10) are shown against increasing Δt. At the right side of these diagrams the aver-

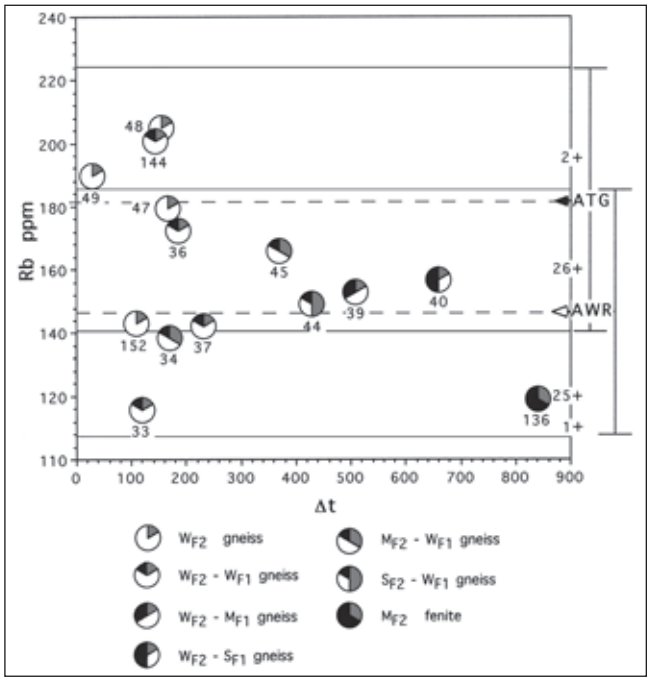


Fig. 13. Plot of Rb contents of fenitized gneisses and pulaskitic fenite Fen 136 versus Δt. The petrographically estimated grade of fenitization of the Fen samples is indicated graphically. Rb contents of average Telemark gneisses, ATG, and of Kresten's (1988) average whole rock, AWR, both with range of standard deviations.

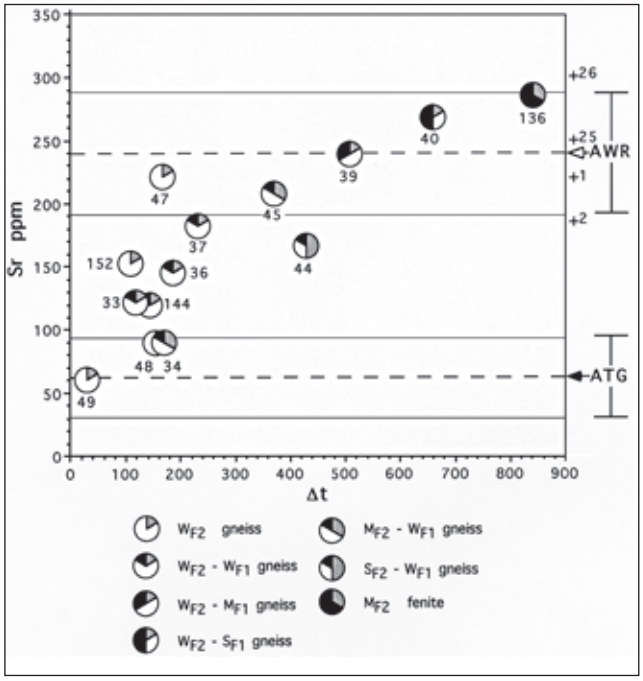


Fig. 14. Plot of Sr contents of fenitized gneisses and pulaskitic fenite Fen 136 versus Δt. The petrographically estimated grade of fenitization of the Fen samples is indicated graphically. Sr contents of average Telemark Gneiss, ATG, and of Kresten's (1988) average whole rock, AWR, both with range of standard deviations are added for comparison.

age composition of 11 Telemark gneiss samples, Average Telemark Gneiss, ATG, is also given, as well as Kresten's (1988) average wall rock composition, AWR, both with their standard deviations.

The Kviteseid Telemark gneisses (Table 11), studied by Priem et al. 1973, are free from fenitization and therefore considered more representative for the original Telemark gneiss of the Fen area than Kresten's AWR samples. The diagrams show that the ATG, and the AWR differ considerably in their major elements. At best, there is overlap in the range shown by both series as indicated by the standard deviations of the average values.

Chemical trends

In the plots of Δt versus variation in chemistry of the fenitized rocks (Fig.15), the majority of all elements show variations similar to those of Sr and Rb (Figs. 13 and 14). Best-fit lines are added in an attempt to visualize the overall chemical changes in these rocks. It is tempting to consider that the best-fit lines of nearly all analysed elements are not accidental, but indicate trends of qualitative metasomatic effects of fenitization. This is substantiated because:

(a) Most of the best-fit lines of major elements and their element ratios show correlation coefficients, $R > 0.7$.
(b) In most cases, the best-fit lines have either a clear positive or a clear negative slope. The best-fit lines of major elements and some trace elements are in accordance with expectations on account of differences in amounts of these elements in rocks of the Fen Complex compared to those of the country rock gneisses.
(c) Chemically related elements exhibit comparable trends of best-fit lines, e.g. Fe, Mn and Mg; Na and K.

A negative trend is suggestive of transport out of the gneisses and into the intrusion, (e.g., SiO_2 and Al_2O_3), and a positive trend is suggestive for transport from the intrusion into the gneisses, (e.g., Na_2O, K_2O, CaO, Fe_2O_3, MgO and LOI).

The scatter of datapoints within weakly fenitized rocks ($\Delta t < 300$) is, for most elements, in the same order of magnitude as for the Kviteseid Telemark gneiss. Therefore, the scatter is regarded as a relic of the original Fen country rock gneisses before fenititization. In these weakly fenitized rocks chemical changes due to fenitization must have been small, in agreement with their mineral composition, which deviates by less than 12 vol.% (on average < 5 vol.%) from the original mineral composition of these samples (Tables 1–5).

The pulaskitic fenite, Fen 136, with a $\Delta t = 810$, is a special case, because it was an ultra-metasomatized, molten country rock and therefore not completely comparable with fenitized gneisses. In Fig. 15, Fen 136 clearly deviates from the inferred trends of the best-fit lines for several elements, e.g., Al_2O_3, confirming its different origin. Therefore, the chacterization of the best-fit lines of only 13 fenitized gneisses, excluding fenite Fen 136, with their correlation coefficient, R, are given in Fig. 15.

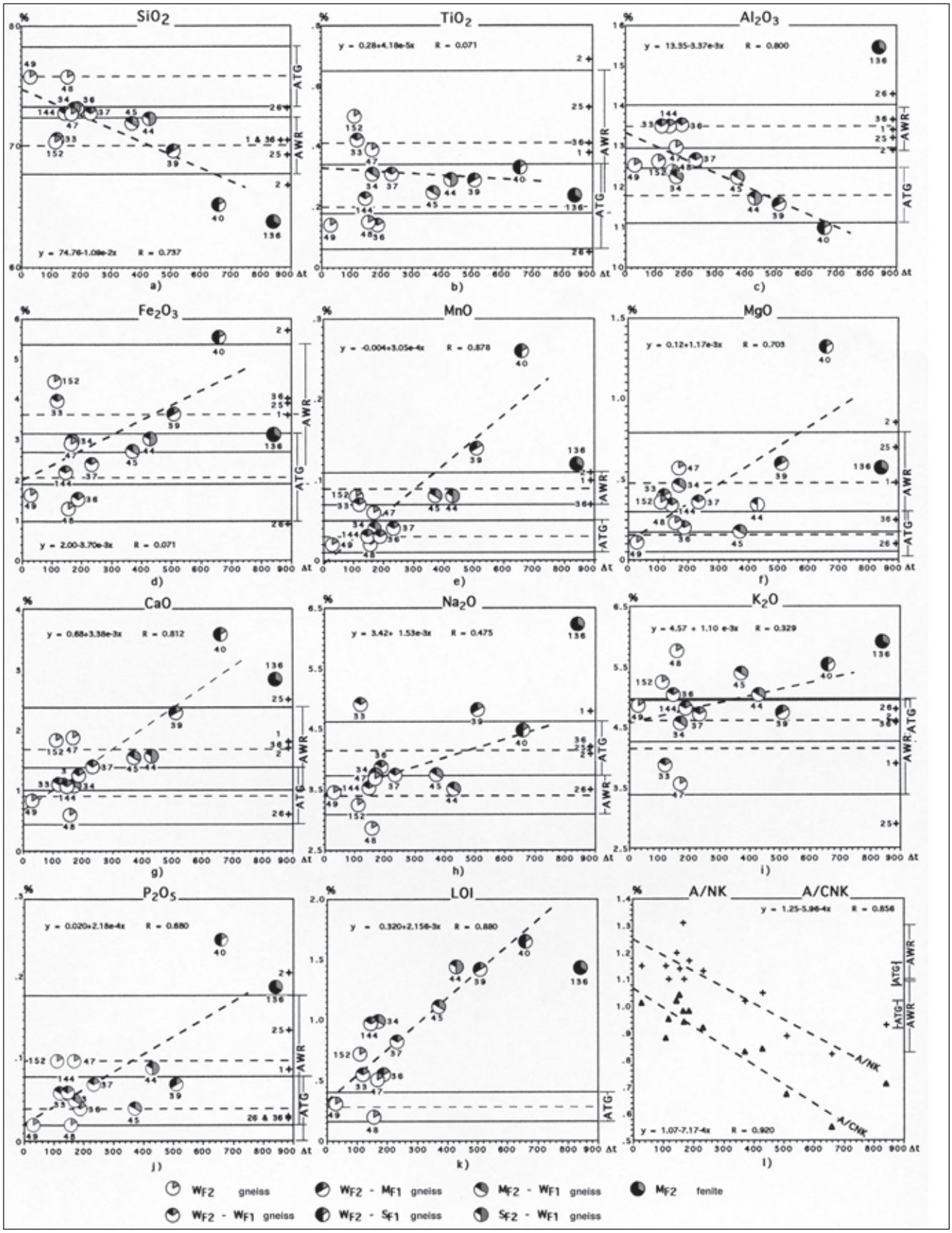


Fig. 15. Plots of major elements of fenitized gneisses and pulaskitic fenite Fen 136 versus Δt. The petrographically estimated grade of fenitization of the Fen samples is indicated graphically. Best-fit lines of fenitized gneisses with correlation coefficients are added. Values of average Telemark gneiss, ATG, and Kresten's (1988) average whole rock, AWR, both with standard deviations, are added on the right side of each figure. a = SiO_2, b = TiO_2, c = Al_2O_3, d = Fe_2O_3, e = MnO, f = MgO, g = CaO, h = Na_2O, i = K_2O, j = P_2O_5, k = LOI and l = A/NK + A/CNK.

Major elements

SiO_2: A decrease of SiO_2 during fenitization was already postulated by Brøgger (1921). It is supported by our data (Fig. 15 a) and in good agreement with petrography. The lowest SiO^2 content (65 wt.%) is recorded in the strongly fenitized gneiss, Fen 40, but this sample still contains c. 74 vol.% of primary gneiss minerals, including c. 30 vol.% quartz (Table 2). Therefore, it is assumed that other strongly fenitized gneisses with lower contents of primary gneiss minerals will have SiO_2 contents lower than 65 wt.%. Kresten (1988) reports a SiO_2 content down to 58.4 wt.% for a medium grade 'aureole fenite'. In general, SiO_2 contents of strongly fenitized gneisses are thought to vary roughly between 60 and 65 wt.% SiO_2.

TiO_2: Neither a positive nor a negative trend can be seen (Fig 15 b). The TiO_2 content of nearly all fenitized gneisses lies within the standard deviation range of ATG, suggesting immobility of TiO_2 with fenitization.

Al_2O_3: The clear negative trend of Al_2O_3 in Fig. 15 c is probably a misrepresentation. Al_2O_3 is largely incorporated in feldspars and to a minor extent in biotite and hornblende. Of the 24 strongly fenitized gneisses (with a Fenitization–1 mineral content > 10 vol.%, Tables 2 - 5), Fen 40 is among the lowest in feldspar content (54 vol.%), much lower than the average feldspar content (66.5 vol.%; range 50 to 85 vol.%). As a consequence, strongly fenitized gneisses would show a considerable spread in Al_2O_3 content. Calculated with a relevant Al_2O_3 content of feldspars, biotite and hornblende, the Al_2O_3 content of 24 strongly fenitized gneisses is estimated, on average, as 13.3 wt.%, ranging roughly between 10 and 16 wt.%. As a consequence, the negative slope of the best-fit line for Al_2O_3 in Fig. 15 c is questionable. However, the higher content of Al_2O_3 in true fenites (Fig. 15 c) than in fenitized gneisses is probably realistic. The feldspar content of 7 fenites (Table 2) ranges roughly from 60 to 90 vol.% and is, on average, 78 vol.%, leading to a Al_2O_3 content ranging roughly from 12 to 18 wt.% with an average of 15.6 wt.%, i.e., close to Fen 136 in Fig.15 c.

Fe_2O_3 (Fig. 15 d), MnO (Fig. 15 e) and MgO (Fig 15 f): These oxides show positive trends, except for the pulaskitic fenite Fen 136. The positive trends of Fe_2O_3, MnO and MgO strongly depend on the high content of these elements in the strongly fenitized gneiss Fen 40. These high contents of Fe_2O_3, MnO and MgO result mainly from the high content of aegirine (c. 14 vol.%). However, comparison with other strongly fenitized gneisses (Tables 2, 3, 4 and 5) reveals that 14 vol.% of aegirine is not at all exceptional, the aegirine content varying from accessory to 25 vol.%. This variation implies a strong variation in the content of Fe_2O_3 (and MnO and MgO) – both with higher and lower values than in Fen 40 – in strongly fenitized gneisses (with a Fenitization–1 mineral content > 10 vol.%). The resulting trend lines for Fe_2O_3, MnO and MgO are supposed to be not fundamentally different from the ones calculated and presented in Figs. 15 d, e and f. Total iron contents of 5.5 wt.% or more are not uncommon in medium- or high-grade fenitized gneisses (Kresten 1988).

Strongly fenitized gneisses may also vary in their contents of CaO (Fig. 15 g), Na_2O (Fig. 15 h) and K_2O (Fig. 15 i), but such variations cannot easily be deduced from their mineral contents. These elements are incorporated in various minerals, many of them of inprecisely known compositions. However, the clear positive trend of CaO and the less clear positive trends of Na_2O and K_2O are thought to be realistic. Increase of alkalis is generally considered as a common feature of fenitization. There is often an inverse relationship between Na_2O and K_2O in weakly to moderately fenitized rocks: those richer in Na_2O are poorer in K_2O and vice versa, e.g., compare Fen 33 and 48 in Figs. 15 h and i.

P_2O_5 (Fig. 15 j): The positive trend is questionable because it is largely determined by the high P_2O_5 content of Fen 40. The trend cannot be coupled with a high content of apatite in this sample, nor with high contents of apatite in strongly fenitized gneisses in general (Table 2–5), because of inaccurate estimates of the apatite contents.

LOI (Fig. 15 k): A clear positive trend is considerd to be related to the increase of H_2O and/or CO_2 with fenitization, in particular with Fenitization-2.

The fenites, of which only one sample Fen 136, has been analysed, will also probably vary considerably in the content of most elements. This can easily be deduced from their variation in mineralogy. e.g., the aegirine content of true fenites varies from accessory to c. 25 vol.% (Table 2). As a consequence, this Fe_2O_3 content will vary considerably (with the analysed sample, Fen 136, more or less in the centre of the spread of Fe_2O_3 values) as well as most other elements, although possibly to a lesser extent.

With the modifications of the chemical composition due to fenitization, the country rocks of the Fen Complex change in character. The alumina-index A/CNK (Table 11, Fig. 15 l) of the Telemark gneiss varies around 1.0 (average 0.97 ± 0.05; n = 11), being slightly > 1.0 in some rocks, or slightly < 1.0 in others. In these rocks, the alkalinity-index A/NK (Table 11) in all samples is > 1.0 (average 1.12 ± 0.04).

Of the Fen country rocks, the weakly fenitized samples still have A/CNK around 1.0 and A/NK is clearly > 1.0; but in the strongly fenitized samples and fenite (Fen 39, 40 and 136), A/CNK is << 1.0 (Table 10) and they are peralkaline (A/NK < 1.0). Both the alumina-index A/CNK and the alkalinity-index A/NK show clear negative trends (Fig. 15 l).

Of the metasomatic changes that took place during fenitization, the reduction in SiO_2 is by far the largest change in absolute terms. The SiO_2 content of the strongly fenitized gneiss, Fen 40, at $\Delta t = 660$ is 9% lower than the average SiO_2 content of fenitized gneiss, extrapolated to $\Delta t = 0$, i.e., a reduction of roughly 12%. In relative terms, the changes of some other elements are higher, e.g., MnO and to a lesser extent possibly MgO, CaO and Fe_2O_3, but more chemical analyses of strongly fenitized gneisses are needed to substantiate the percentage of change.

In summary, it is realized that the quantitative importance of the best-fit lines of major elements is restricted, in regard to the limited number of analyzed samples, especially of moderately and strongly fenitized rocks. However,

most of these best-fit lines do not seem to be unrealistic (e.g., SiO_2, Fe_2O_3, A/CNK and A/NK), whereas others are questionable (e.g., Al_2O_3 and possibly P_2O_5).

Trace elements

Twenty-eight trace elements have been analysed in fenitized and unfenitized gneisses (Tables 10 and 11). All trace elements of the fenitized gneisses scatter – just as the major elements – at low-grade fenitization ($\Delta t < 300$). Again, the effect of chemical changes of (most) trace elements due to weak fenitization might be smaller than the inhomogeneity of the precursor granitic gneisses. Several of the measured trace elements show a scatter also at higher grades of fenitization ($\Delta t > 300$).

The trends of the majority of trace elements, however, are less clear than those of the major elements. Of the 33 trace elements and trace element ratios only 5 show variation with Δt with R values > 0.5, viz. positive trends for Sr (R = 0.804), V (R = 0.708) and Nb (R = 0.507), negative trends for Rb/Sr (R = 0.610) and Ce (R = 0.598).

Moreover, trace elements cannot, or hardly, be correlated with mineral contents (as for major elements, Fe_2O_3, MnO and MgO contents correlate with aegirine content, and Al_2O_3 content with feldspar content in strongly fenitized gneisses). Even for the element Zr, which is incorporated mainly in zircon, such a correlation fails. Sample Fen 44, the only fenitized gneiss in which no accessory zircon was found microscopically, contains 338 ppm Zr, which is higher than the average Zr content (278 ± 154 ppm) of fenitized gneisses. Also the presence of allanite cannot be correlated with a higher content of Ce or other REE. Allanite-bearing samples are among the highest in Ce and other REE contents (e.g., Fen 33) and among the lowest in Ce and other REE contents (e.g., Fen 47) (Table 10).

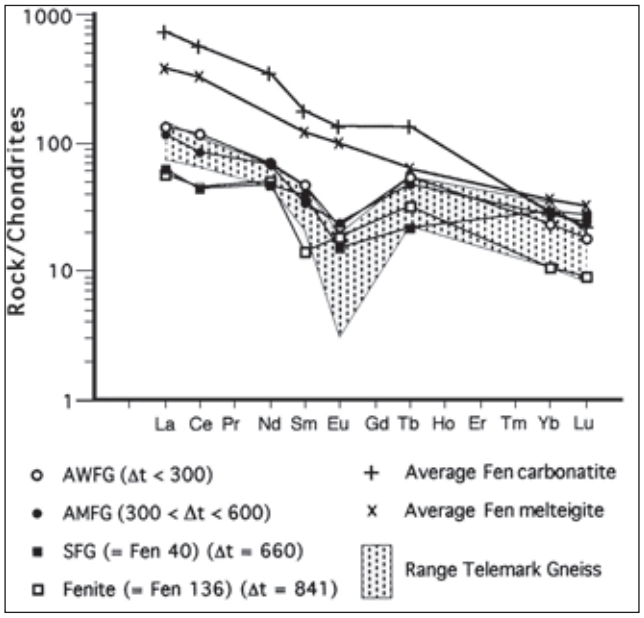


Fig. 16. Chondrite-normalized (Haskin et al. 1968) REE plot of the average of Weakly Fenitized Gneisses, AWFG, the average of Moderately Fenitized Gneisses, AMFG, the Strongly Fenitized Gneiss Fen 40 and the (pulaskitic) fenite Fen 136 and the range of Telemark gneisses (stippled). The plot shows a reduction in Eu anomaly with increasing fenitization. The average of Fen carbonatites and Fen melteigites/ijolites (Table 12) are added for comparison.

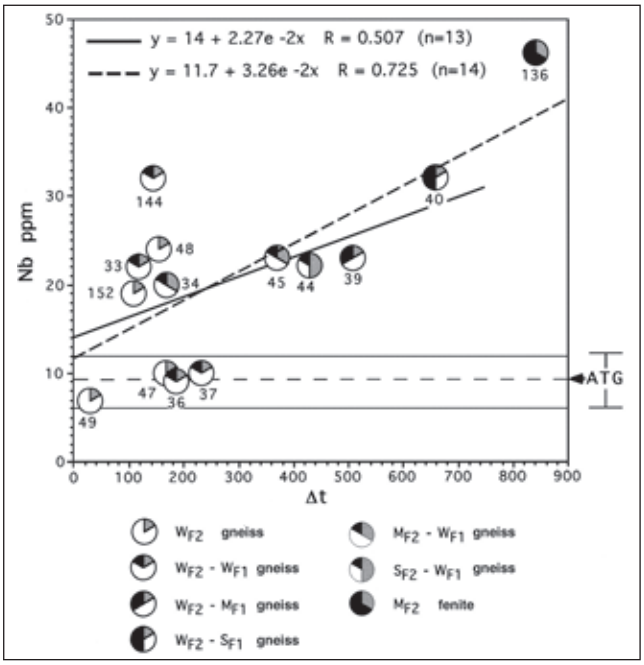


Fig. 17. Plot of Nb contents of fenitized gneisses and (pulaskitic) fenite Fen 136 versus Δt. Graphical indication of grade of fenitization and ATG values as in Fig. 13. For 13 samples, excluding the (pulaskitic) fenite Fen 136, the best-fit line is indicated by the drawn line. For 14 samples, including the (pulaskitic) fenite Fen 136 the best-fit line is indicated by the striped line. The clear positive trend of this best-fit line continues nearly linearly to the (pulaskitic) fenite Fen 136, suggesting late introduction of Nb.

It is therefore clear that additional data are needed, especially from moderately and strongly fenitized gneisses ($\Delta t >$ 300) to produce sufficiently convincing trend lines of trace elements. Nevertheless, some remarks on trace element behaviour with fenitization can be made The contents of REE in fenitized gneisses, for example, are in general not much different from those of unfenitized gneisses (compare Tables 10 and 11), but even minor changes of REE with fenitization show some systematic variations. At higher grades of fenitization, the light and middle REE, Ce, Nd, Sm, Eu and Tb appear slightly lower, whereas the heavy REE, Yb and Lu appear slightly higher than in weakly fenitized gneisses (Fig 16). If these REE data are realistic, they reflect a slight decrease of light and middle REE and a minor increase of heavy REE with fenitization.

The best-fit line for Nb (Fig. 17) suggests a positive trend, which is what would be expected. The increase in Nb content of 9 ± 3 ppm in ATG to 17.0 ± 8.5 ppm in average fenitized gneisses, reflects the mixing of low Nb-bearing country rock gneisses with high Nb-bearing fluids derived from the intrusive Fen Complex, where carbonatite has been mined for its Nb content. On the contrary, Ta shows no significant

changes, with roughly equal amounts of Ta in ATG (0.74 ± 0.23 ppm, Table 11) and in average fenitized gneisses (0.76 ± 0.31 ppm, Table 10).

Discussion

The moderately and strongly fenitized Fen country rocks clearly show a severely changed to (nearly) completely new mineral assemblage coupled with considerable chemical modification, at least for a number of elements and element ratios. Weakly fenitized Fen country rocks show traces of the same new mineralogy and therefore can be expected to have a slightly modified chemical composition. However, small chemical changes are difficult to detect within the present small number of analysed rocks. Small chemical changes will be subordinate to the recorded scatter in composition of the original inhomogeneous gneisses (Table 10).

It can be noted here that, in relation to uncertainties regarding the meaning of homogeneity or inhomogeneity, a suite of rocks is taken in this study as being rather homogeneous if the standard deviation, s.d. – expressed as a percentage of the average content – is < 5%; and as rather inhomogeneous if 5% < s.d. < 10%, and as inhomogeneous if 10% < s.d. < 25% and as strongly inhomogeneous if s.d. > 25%. Thus, the Telemark gneisses (Table 11) are rather homogeneous for SiO_2 (s.d. = 3.3%) and Al_2O_3 (s.d. = 3.8%), rather inhomogeneous for K_2O (s.d. = 7.6%) and Na_2O (s.d. = 9.4%) and strongly inhomogeneous for all other major elements and all trace elements (s.d. being > 25%, for many elements even > 50%).

It follows, therefore, that none of the contents of either major or trace elements, as well as element combinations, can successfully be used as indicators of the grade of fenitization, especially in the case of weaker fenitization. Due to the inhomogeneity of the original country rock gneisses, any mass balance calculation based on an average country rock composition (Kresten 1988, 1994) is considered to be inadequate to quantify fenitization, especially if metasomatic changes are small in relation to the natural variation in unfenitized gneisses. Moreover, as noted earlier, most, if not all, of Kresten's 5 gneisses on which he based his original country rock composition are, in fact, weakly fenitized.

Another option to quantify the grade of fenitization would be to use the distance from the contact of the Fen Complex as an independent variable, because fenitization is a contact-metasomatic phenomenon related to the Fen intrusions. However, direct reliance on the distance from the intrusive contact has severe shortcomings. In the first place, the distance of some of the Fen samples from the true contact is not exactly known, especially the samples Fen 47, 48, 49 and 152 (Fig. 2) and to a lesser degree the samples from the Holla Hagen-Tveitlåven Section, where the unexposed contact of the Fen Complex has had to be inferred on the geological map. Secondly, different mineralogical and chemical intrusive rocks are found along the contacts of the now exposed Fen Complex, e.g., carbonatite and damkjernite at the beginning of the Håtveittjørn Section (apart from a few tens of metres of melteigite, Table 2), and melteigite at the beginning of the Mjølteig Section (Table 3). These different igneous rocks may well have caused differences in fenitization, both in intensity and in character; e.g., true fenites, such as Fen 136, regarded as igneous on account of their textures, are present in the Håtveittjørn Section (Fig. 4, Table 2) but are not seen in the Mjølteig A Section (Fig. 5, Table 3). Such an absence of the highest-grade fenitized rocks – with entirely new mineral parageneses and displaying microstructures of igneous appearance – near the melteigite contact has also been reported by Kresten & Morogan (1986). Moreover, the effects of Fen satellitic dykes and smaller plugs, exposed or concealed, are unknown and therefore could not be taken into account.

A third shortcoming, as stated earlier, is that the Fen country rocks have been fenitized both pervasively and through narrow channels; the latter are seen in the field as a network of tiny dark veinlets following cracks and fissures (Fig. 9). Although the density of veining roughly decreases with distance from the Fen Complex, the distribution of veins can also vary considerably within one and the same outcrop, suggesting that the intensity of fenitization may also vary and be different in samples collected from the same outcrop. This is obvious from the 5 samples (Fen 169, 170, 336, Ma 68 and 69) collected in the same outcrop at approximately 10 m from the contact with the Fen Complex along the Håtveittjørn Section (Table 2), which show rather variable – petrographically estimated – effects of fenitization. This also holds for the quite different samples, Fen 237 and 238, collected from the same outcrop at the Mjølteig A Section at 103 m from the intrusive contact.

On account of the arguments presented above, none of the country rock Telemark gneisses, either on average composition, or on the distance from the contacts of the Fen Complex, can be regarded as a suitable instrument for quantifying the grade of 'total fenitization'. Therefore, it is preferable to use the parameter Δt. The Δt values depend on the modification by fenitization of their Rb contents and especially of their Sr contents and Sr isotope ratios.

Major elements

The negative trend of the best-fit line of SiO_2 (Fig. 15 a) is the result of exchange of SiO_2 between the – on average much lower – values of SiO_2 in the Fen Complex (carbonatites, including mixed rocks: SiO_2 = 15.4 ± 13.1 wt.%, (n = 8); melteigites/ijolites: SiO_2 = 39.9 ± 2.1 wt.%, (n = 6); data from Kresten 1988) than in the Telemark gneiss (average SiO_2 = 75.81 ± 2.49 wt.%. (n = 11), Table 11). Equally, the positive trends of the best-fit lines of Fe_2O_3, MnO, MgO and CaO and possibly P_2O_5 (Figs. 15 d, e, f, g, and j) result from exchange between the higher, or much higher, contents of these elements in the Fen Complex (data from Kresten 1988) than in the average Telemark gneiss (Table 11).

The negative trend of the best-fit line of Al_2O_3 (Fig. 15 c) – although questionable – is not self evident. The average Al_2O_3 content of the Telemark gneiss, ATG (11.8 ± 0.7 wt.%), is equal to that of the average Al_2O_3 content of 6 melteigite

and ijolites (11.7 ± 4.9 wt.%), being lower in pyroxene melteigites (average Al_2O_3 = 7.43 ± 0.83 wt.%, (n = 3)) but higher in ijolites (average Al_2O_3 = 16.03 ± 1.95 wt.%; (n = 3); data from Kresten 1988). On the other hand, Al_2O_3 contents of carbonatites, including mixed rocks, are much lower (average Al_2O_3 = 0.88 ± 0.76 wt%, (n = 8); data from Kresten 1988). A negative trend of the best-fit line of Al_2O_3 could be expected on account of the low Al_2O_3 content of carbonatites if McKie's (1966) statement that "metasomatism must be related to carbonatite magma rather than to an alkaline silicate magma" is valid.

The positive trends of Na_2O and K_2O (Figs. 15 h and i) cannot simply be deduced from the alkali content of the Fen intrusions. Na_2O is, on average, higher in Fen ijolite/melteigite than in the unfenitized gneisses, however, K_2O is lower, and both are considerably lower in Fen carbonatites (data from Kresten 1998). But Na and K metasomatism is a common, generally accepted feature of fenitization. Experimental investigations have indicated that immiscible nephelinitic and carbonatitic liquids coexist with a dense vapour phase, rich in alkalis, producing a good model for the association of nephelinite, carbonatite and fenitizing solutions (Best 1982). Another, or additional option is infiltration of Na_2O (and K_2O) set free after emplacement of alkali carbonatites, as occurred after the 1960 Oldoinyo Lengai eruption in Tanzania of natrocarbonatite lava and ash (with up to 32 wt.% Na_2O and 8 wt.% K_2O) (Dawson 1989). However, there is no evidence for an alkali-carbonatite ever being present at Fen other than alkali metasomatism in the country rocks (Andersen 1989).

The neither positive nor negative trend of TiO_2 (Fig. 15 b) is not unexpected. The average TiO_2 content of fenitized gneisses (0.29 ± 0.11 wt.%) is slightly lower than in carbonatites, including mixed rocks (0.4 ± 0.4 wt.%) – although individually strongly variable – and much lower than in melteigites/ijolites (2.68 ± 0.84 wt.%) (Kresten 1988).

The clear increase of LOI values (Fig. 15 k) with fenitization must be related to the Fenitization-2 phase, with its formation of carbonates and hydrated minerals.

Trace elements

The increase in the amounts of Sr with fenitization (Fig. 14) is best explained by exchange due to the much higher content of Sr in the Fen igneous rocks compared with the country rock gneisses (Table 9). The low contents of Rb in Fen carbonatites, lower than in Telemark gneisses (Table 9), could be an argument that a decrease of Rb (Fig. 13) is not unrealistic.

The minor changes in the amounts of REE with fenitization are in contrast to what would be expected. The abundances of light and middle REE are considerable higher in rocks of the Fen Complex than in the Telemark gneisses, while heavy REE are more or less similar. Light REE-enriched chondrite-normalized REE distribution patterns are, on average, 5 to 6 times steeper in carbonatites and more than 3 times steeper in melteigites/ijolites than in the average fenitized gneisses, AFG, and in average unfenitized gneisses, ATG (Fig. 16, Table 12). Normalization values based on Haskin et al. (1968) were chosen to make results comparable to those of Kresten (1994). Within the fenitized gneisses, the $(La/Yb)_N$ ratio decreases from the average weakly fenitized gneiss (AWFG) to the average moderately fenitized gneiss (AMFG) and to the strongly fenitized gneiss (SFG), Fen 40 (Table 12), stressing the observed minor decrease of LREE and a minor increase of HREE with fenitization. These facts indicate a lack of, or only minor exchange – i.e., restricted mobility – of these elements between the Fen Complex and the country rock gneisses during fenitization.

The restricted mobility of REE at Fen is the more remarkable when compared to that at Alnö in central Sweden, an alkaline carbonatitic complex of comparable size, age and depth of exposure and equally emplaced in high-grade Precambrian gneisses (Morogan 1989. At Alnö, REE show a clear increase with fenitization, especially light and middle REE). This difference in REE behaviour between Fen and Alnö was also noticed by Kresten (1994).

Europium may form an exception in REE behaviour during fenitization. Eu appears higher in (nearly) all fenitized gneisses compared to the unfenitized ones, resulting in a less pronounced negative Eu anomaly in fenitized gneisses. The Eu/Eu* ratio – i.e., the ratio between the measured concentration of Eu and the interpolated value between Sm and Tb – increases from average Telemark gneiss, ATG, to average fenitized gneisses, AFG (Fig. 16, Table 13). The increase of Eu in fenitized gneisses probably results from the greater mobility of divalent Eu.

Carbonatites and alkaline rocks constitute the world's largest source of Nb (e.g., Mariano 1989). Nb contents of carbonatites are characterized by their extreme variability. Woolley & Kempe (1989) reported Nb ranges of 1 to 15,000 ppm (average 1204 ppm, (n = 43)) for calciocarbonatites and of 10 to 16,780 ppm (average 1422 ppm, (n = 19)) for magnesiocarbonatites. Brøgger (1921) reported Nb_2O_5 + Ta_2O_5 contents of 0.78, 0.80 and 0.82% for 3 sövites (calciocarbonatites) and 0.07% for a rauhaugite (magnesiocarbonatite). Since the Nb : Ta ratio in Nb concentrate is around 100 : 1 (Bjørlykke & Svinndal 1960), Brøgger's data are translated as, respectively, 0.78, 0.80, 0.82 and 0.07% Nb_2O_5 by Barth & Ramberg (1966), corresponding to roughly 5500 ppm Nb in søvite and 500 ppm Nb in rauhaugite. The Fen carbonatite ore contained, on average, about 0.5% pyrochlore (Bjørlykke & Svinndal 1960, Chr. D. Thorkildsen, pers. comm. 1973) with 58 to 72% Nb_2O_5 which corresponds to roughly 2000 to 2500 ppm Nb in Fen carbonatite ore. Andersen & Qvale (1985) reported that the sövites and dolomite carbonatites generally contain 0.05 to 0.3% Nb_2O_5, but local enrichments up to 1% are common (especially along contacts with altered gneiss). The extreme variability of Nb contents in carbonatites seems to be due to a relatively late age of formation, being connected to zones of brecciation and veins. Bjørlykke & Svinndal (1960) came to the conclusion that "the formation of pyrochlore minerals is post-magmatic and may have taken place through metasomatic processes (caused by gasses and solutions, probably in many stages after the

Table 12. LREE (chondrite normalized, Haskin et al. 1968) enrichments of the average Telemark gneiss (ATG), the average Fen gneiss (AFG), carbonatites and melteigites.

Rock type	$(La/Yb)_N$	n	Source data
ATG	5.25 ± 2.32	11	This study
AFG	5.85 ± 2.87	14	
AWFG (Δt < 300)	6.79 ± 3.11	9	
AMFG (300 < Δt < 600)	4.30 ± 0.73	3	This study
SFG (= Fen 40) (Δt = 660)	2.24	1	
Fenite (= Fen 136) (Δt = 841)	5.45	1	
Carbonatites (sövite. rauhaugite)	28.9 ± 10.1	30	Mitchell & Brunfelt 1975, Andersen 1987 & Kresten 1994
Melteigites (ijolite, melteigite)	22.6 ± 21.6	13	Mitchell & Brunfelt 1975; Kresten 1994

formation of the alkaline rocks)". Also, according to Mariano (1989), "niobium is usually concentrated in intermediate pulses of carbonatite activity. In contrast, early carbonatites and very late pulses enriched in REE's are relatively impoverished in Nb". However, at least some earlier, magmatic pyrochlore occurs in cumulate-like apatite-phlogopite-pyrochlore bodies (Andersen 1986).

The roughly equal Ta values in averaged fenitized and averaged unfenitized gneisses are, in fact, unexpected. As with Nb, Ta values of Fen carbonatites (average Ta = 26.3 ± 51.4 ppm, (n = 9)) and melteigites/ijolites (average Ta = 9.1 ± 5.0 ppm, (n = 6); Kresten 1994) are also considerably higher than in fenitized and unfenitized gneisses. Precisely why the behaviours of geochemically similar Nb and Ta are different is not yet understood.

Extensions of the best-fit lines to lower values of Δt

The extensions of the best-fit lines to unfenitized rocks with values of Δt = 0 provide a tool to evaluate the Telemark gneiss as a reference rock type for unfenitized gneisses. Compared to the average Telemark gneiss ATG, the average protolith of the Fen country rock gneisses (see Figs. 13, 14, 15, and 17) most probably: (i) fit well for CaO and Na_2O; (ii) was slightly higher for Fe_2O_3, MgO, P_2O_5, Nb and A/CNK; (iii) was slightly lower for MnO, K_2O and Rb; (iv) was clearly higher for TiO_2, Al_2O_3, Sr and A/NK; (v) was clearly lower for SiO_2.

Thus, it seems that the Fen country rock protolith was, on average, slightly more 'granodioritic', with less quartz and K-feldspar and more ferro-magnesian minerals, especially Al_2O_3-bearing hornblende, than the more 'granitic' Telemark gneiss.

It should be noted that the samples of the reference Telemark gneiss were collected in 1969 and 1970 for whole-rock Rb-Sr dating purposes (Priem et al. 1973), meaning that the most leucocratic granitic gneisses could have been preferentially selected during the actual sampling.

Extensions of the best-fit lines to higher values of Δt

The extensions of the best-fit lines from the strongly fenitized gneiss, Fen 40, to higher values of Δt demonstrate the deviating character of the fenite sample Fen 136. The extension of the trend lines to higher values of Δt (Figs. 13, 14, 15 and 17) demonstrate that fenite Fen 136: (i) fits well for SiO_2, K_2O, Sr and Nb; (ii) is slightly lower for TiO_2 and Rb; (iii) is clearly higher for Al_2O_3 , Na_2O, A/NK and A/CNK; (iv) is clearly lower for Fe_2O_3, MnO, MgO, CaO and P_2O_5.

Enrichment of incompatible elements (e.g., Na_2O and Al_2O_3) and depletion of compatible elements support the concept that true fenites, in the sense of Brøgger, such as Fen 136, represent (largely) molten rocks, as supposed earlier from textural evidence.

Making a distinction between 2 phases of fenitization, the question arises if Fenitization-1, or Fenitization-2, or both, is responsible for the observed metasomatic changes of the various chemical elements. For most elements, this question cannot be answered with certainty from the present data, but a few exceptions exist. The gradual increase of LOI with fenitization can be attributed with certainty to Fenitization-2, which involves hydration and carbonation processes at lower temperature, in contrast to dehydration processes at higher temperature in the case of Fenitization-1. Also, the clear increase of Nb with fenitization is probably related to Fenitization-2, as Nb minerals were formed relatively late in carbonatite formation, both at Fen (Bjørlykke & Svinndal 1960) and elsewhere (Mariano 1989).

The syenitic composition of the fenite sample Fen 136, which has an igneous appearance, suggests that melting took place from rocks already reduced in or even free from quartz; implying that the reduction of SiO_2 took place early, i.e., during Fenitization–1. Also, the lower values of Fe_2O_3, MnO, MgO, CaO and P_2O_5 in fenite Fen 136 suggest that an increase of these elements took place before melting of fenite Fen 136, i.e., during Fenitization-1.

In the case of the fenitization at the Alnö alkaline carbonatitic complex in central Sweden, Morogan & Woolley (1988) also came to the conclusion that "the fluids with which the 'fenites' equilibrated were apparently different in composition for different parts of the aureole and varied with time, implying more than one magmatic source".

Table 13. Eu anomalies of the average Telemark gneiss (ATG), the average Fen gneiss (AFG), average weakly fenitized Fen gneiss (AWFG), average moderately fenitized Fen gneiss (AMFG), strongly fenitized Fen gneiss (SFG) and (pulaskitic) fenite.

Rock type	Eu/Eu* Average	n	Range	Remarks
ATG	0.31 ± 0.14	11	0.11 – 0.51	
AFG	0.50 ± 0.19	14	0.19 – 0.91	
AWFG	0.41 ± 0.14	9	0.19 – 0.63	
AMFG	0.63 ± 0.04	3	0.58 – 0.66	
SFG (= Fen 40)	0.46	1		to low Tb value?
Fenite (= Fen 136)	0.91	1		unusual low Sm value

Conclusions

1. Fenitization at Fen is a pluri-metasomatic process of at least two phases related to the intrusion of the Fen Complex, as shown by field evidence and petrography.
2. Fenitization at Fen is clearly coupled to brecciation that developed during at least two phases. These brecciations created the pathways for the metasomatizing fluids.
3. Two main phases of metasomatic alteration are distinguished at Fen: a first phase, Fenitization-1, involving dehydration reactions and (partial) melting at higher temperatures; and a second phase, Fenitization-2, involving hydration and carbonation reactions at lower temperatures.
4. The fenitization aureole at Fen is much wider than was stated by Brøgger (1921). The first fenitization modified the country rock gneisses from less than 1% at a distance of roughly 700 m from the Fen Complex to (nearly) 100% adjacent to the Complex. The second phase of fenitization modified rocks from less than 1% at a distance of at least 1500 m from the Fen Complex, up to 10% close to the Complex.
5. The Fen country rock comprises 'Telemark gneisses' (Neumann 1960), which are migmatitic gneisses of granitic composition with a considerable inhomogeneity for most elements. Therefore, mass balance calculations based on the composition of one Fen country rock sample are unsuitable to quantify fenitization.
6. The Telemark gneisses of the Kviteseid area 14 to 45 km west of the Fen area (Priem et al. 1973) are free from fenitization, and are taken as a useful approximation for non-fenitized Fen country rock. The differences in time, Δt, between the whole-rock Rb-Sr isochron age of the Kviteseid Telemark gneisses and the calculated whole-rock Rb-Sr ages of fenitized Fen rocks, using the initial $^{87}Sr/^{86}Sr$ ratio of the Kviteseid Telemark gneiss, are taken as parameters for the grade of fenitization.
7. For many elements the chemical changes caused by fenitization can be explained by the differences of their contents in the Kviteseid Telemark gneisses and in the Fen Complex. Compare, for example, the negative trends in a Δt diagram for SiO_2 and the positive trends for Fe_2O_3, MnO, MgO, CaO and possibly P_2O_5. An equal explanation may hold for increasing amounts of Sr and Nb and the decreasing amounts of Rb in a Δt diagram. Although fenitization is regarded as a classic example of alkali metasomatism, the positive trends of Na_2O and K_2O cannot be explained by the present alkali contents of the rocks of the Fen Complex and those of the Telemark gneisses. The contents of TiO_2 and REE in fenitized and non-fenitized gneisses suggest a lack of, or limited, mobility during fenitization, the contents of these elements in the Telemark gneisses being considerably lower than in the intrusive rocks of the Fen Complex. The behaviour of partly divalent Eu seems slightly different from other light and middle REE, which may explain the reduction of the negative Eu anomaly of country rocks with fenitization.
8. The character of fenitization, both in mineralogical changes and in chemical trends, is similar along the contacts of carbonatite on the one hand and of melteigite and related rocks on the other hand, but the intensity of fenitization may be different. True fenites, pulaskitic fenites, in the sense of Brøgger (1921), i.e., rocks with a magmatic texture that are regarded as ultrametasomatized, molten country rocks, occur close to the contacts with carbonatites, but were not found along the contacts with melteigites.
9. The isotopic Rb-Sr Δt parameter can be used to quantify other metasomatic processes.
10. The whole-rock Rb-Sr Δt method can be applied also when Rb-Sr ages of the country rocks are not available, by assuming a probable age for these country rocks and by choosing a reasonable initial $^{87}Sr/^{86}Sr$ value for the Rb-Sr age calculations of the analysed metasomatized rocks .

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Appendix

In this article, the spelling of damkjernite is used following the original usage by Brøgger in 1921. Some authors (e.g., Sæther 1957) renamed damkjernite to damtjernite because they erroneously assumed that Brøgger (1921, p. 276) misspelled the name of the small lake in the Fen area which gave its name to the rock. However, both Brøgger and Goldschmidt used for their initial geological mapping of the Fen area in 1918 the topographical map 'Amtskart Telemark Bratsberg 1:200,000', first issued in 1856-57 and revised in 1904. On these maps, as was common in those days, the spelling 'kjern' (small lake) instead of 'tjern' is used (Ulf Hansen, Statens Kartverk, pers. comm. 2004). The controversy

probably originated because Brøgger (1921) indicated the geology of the Fen area on a specially drafted 1 : 15,000 topographical map that had changed spellings of certain map names. Apparently, this was no motive for Brøgger to change the spelling of the rock-name damkjernite.

On the latest version of the 1 : 50,000 topographical map the name of this small lake is now spelled as Damtjørn.

The experimental procedures and constants are those mentioned in Maijer & Verschure 1998: Petrology and isotope geology of the Hunnedalen monzonoritic dyke swarm, SW Norway: a possible late expression of Egersund Anorthosite magmatism. Norges geologiske undersøkelse Bulletin 434, 83-107.

All the Fen samples are presently stored in the Mineralogisk-geologisk museum in Oslo.