Dating Explosive Volcanism Perforating the Precambrian Basement in Southern Norway

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Verschure, R. H., Maijer, C., Andriessen, P. A. M., Boelrijk, N. A. I. M., Hebeda, E. H., Priem, H. N. A. & Verdurmen, E. A. Th. 1983: Dating explosive volcanism perforating the Precambrian basement in southern Norway. *Norges geol. Unders. 380*, 35–49.

K-Ar and Rb-Sr dating have been performed on vaarious hypabyssal diatreme-facies volcanic rocks perforating the Sveconorwegian zone of the Precambrian basement in southern Norway. The dated rocks were taken from the Fen peralkaline–carbonatitic area, the Gardnos and Hjölmodalen explosion breccias, the marginal breccia of the Fjone calcite–syenite plug, damtjernites from Gulbrandstjern, Presteöya and Brånan, and the carbonatized damtjernitic explosion breccia with abundant xenoliths from Tveitan and Hönstjern in the Bamble region. The results reveal two episodes of explosive volcanic activity prior to the Permian magmatism, one about 600 Ma ago (latest Precambrian) and another probably about 350–300 Ma ago (Carboniferous). These episodes of volcanic activity possibly reflect precursor phases of the Caledonian orogeny and the Permian epeirogeny, respectively. A dolerite dike in the Fen area may be of Permian age.

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Introduction

Explosive outbursts of volcanic and related subvolcanic activity have penetrated the Precambrian continental crust at numerous points in southern Norway (Figs. 1 and 2). This part of the Baltic Shield is characterized by ages between 1200 and 800 Ma, which link the cratonization to the Sveconorwegian (Grenville) Episode of tectonism, metamorphism and magmatism. Evidence of the existence of an older continental crust is provided, for example, by the relict ages of about 1500 Ma reported from the Levang gneiss dome in the Bamble region (O'Nions & Baadsgaard 1971), the Telemark supracrustals (Priem et al. 1973) and the high-grade charnockitic country rocks of the anorthositic complex in Rogaland (Versteeve 1975, Priem & Verschure 1982).

The best known example of the explosive volcanic phenomena in southern Norway is the peralkaline–carbonatitic complex of the Fen area (e.g. Brögger 1921, Sæther 1957, Bergstöl 1960, 1979, Bergstöl & Svinndal 1960, Barth &

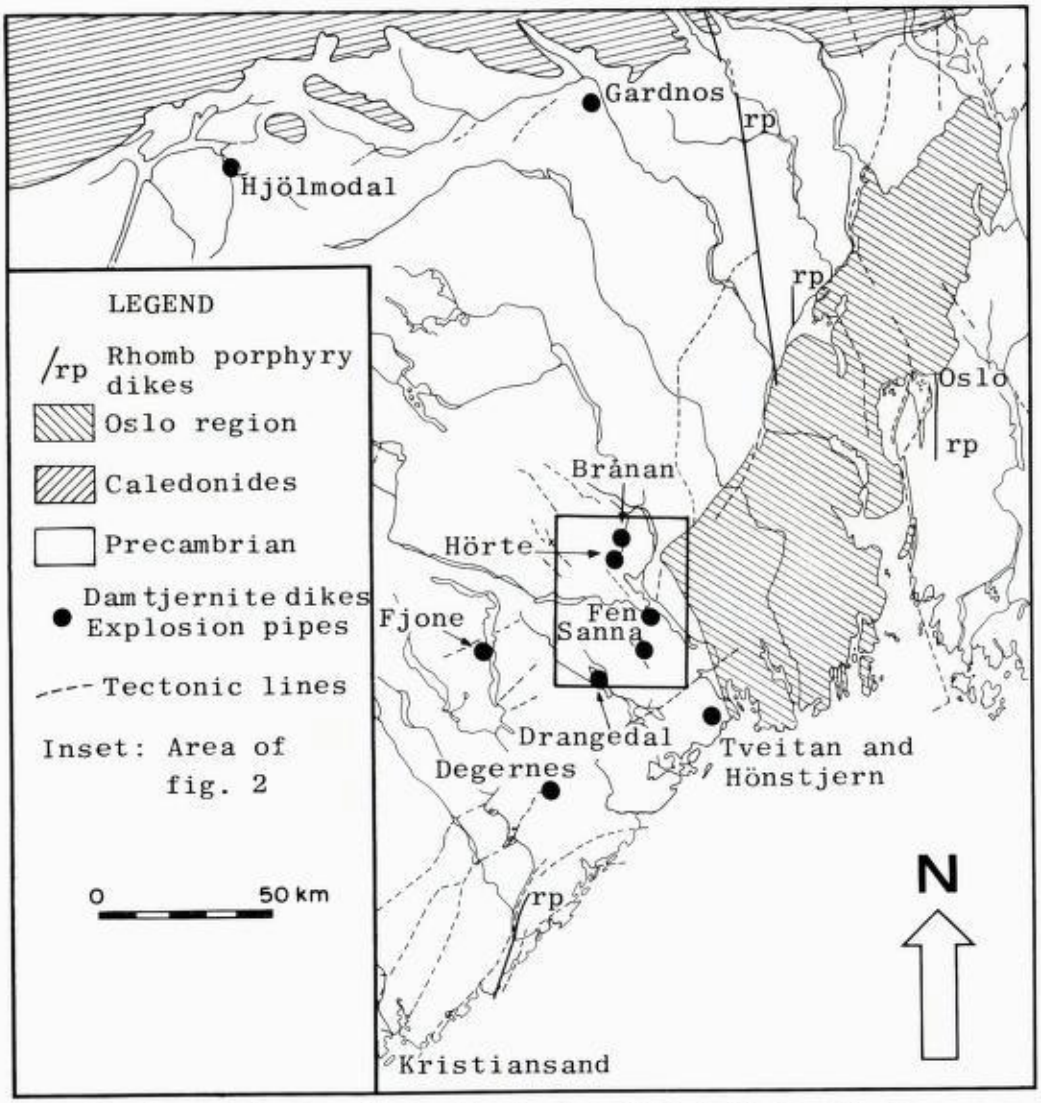

Fig. 1. Map showing the locations of the investigated rocks (modified after Ramberg & Barth 1966).

Ramberg 1966, Ramberg & Barth 1966, Mitchell & Crocket 1970, Griffin 1973). Less well-known are the alkaline vents and dikes, explosion breccias, and ultramafic damtjernitic plugs and dikes at many other points (Figs. 1 and 2). All these (sub)volcanic phenomena are supposedly related to faults and basement fractures. Damtjernite is a porphyritic hypabyssal rock with kimberlitic and alnoitic affiniTIES (Brögger 1921). The rock varies widely in mineral composition, but mostly it consists of a groundmass of carbonate, biotite, pyroxene and magnetite in which are embedded phenocrysts of biotite, clinopyroxene and brown hornblende in varying proportions. In diatreme facies the rock contains varying amounts of xenoliths and xenocrysts of crustal and upper-mantle origin (Griffin & Taylor 1975).

A number of age data have been published for the peralkaline-carbonatitic complex of the Fen area: early 'chemical' U-Th-Pb ages of koppite (Sæther 1957), Pb-α ages of zircon (Neumann 1960) and K-Ar ages of biotites (Faul et al. 1959, Neumann 1960, Kulp & Neumann 1961, Broch 1964). On the basis of these ages, all between 600 and 560 Ma, an Eocambrian age was assigned to the Fen volcanism (Ramberg & Barth (1966).

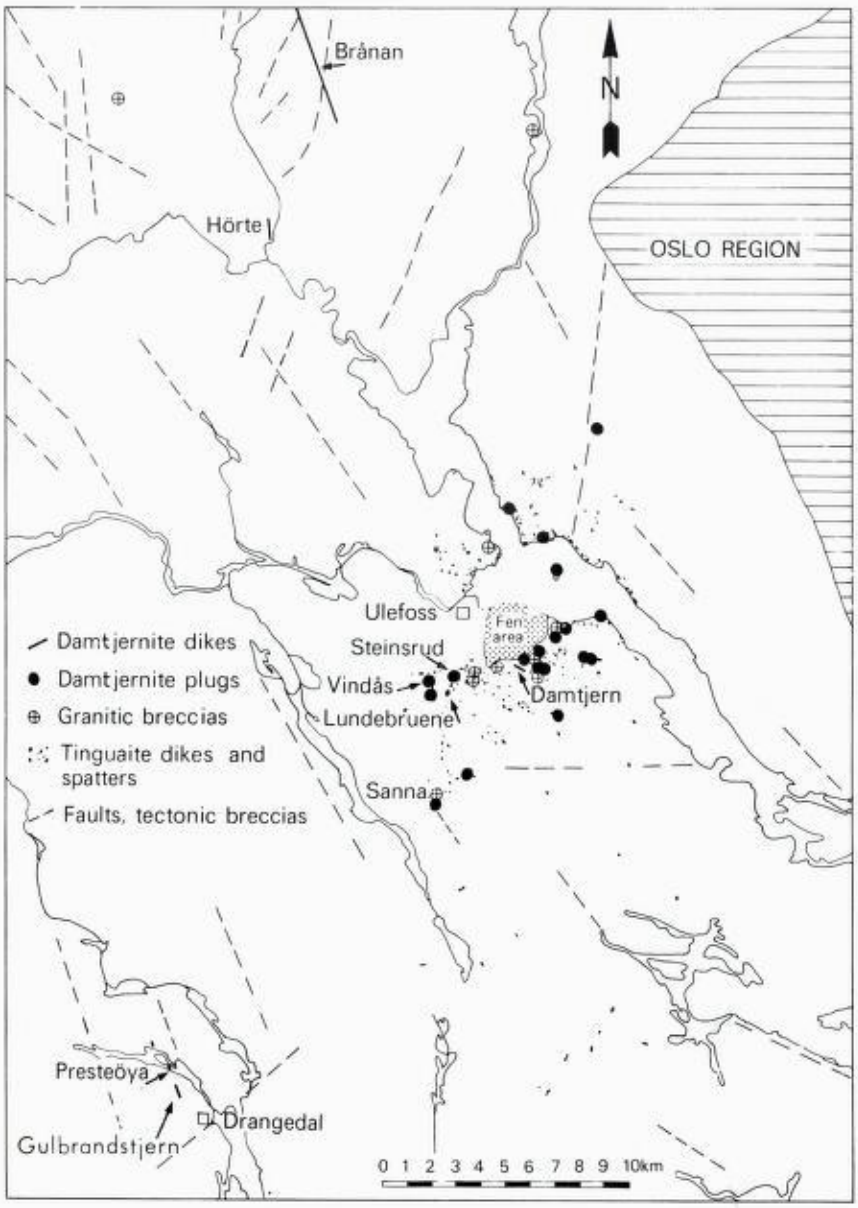

Fig. 2. Enlarged insert of Fig. 1 (modified after Ramberg & Barth 1966), showing the locations of the investigated rocks close to the Fen peralkaline–carbonatitic complex (indicated on the map as 'Fen area'). The locations of the samples from within the Fen complex are not shown.

The present study reports the results of K-Ar and Rb-Sr age measurements on separated minerals and whole-rocks from various types of explosive and related subvolcanic rocks in southern Norway (Figs. 1 and 2). A preliminary report of part of the data has been presented before (Verschure et al. 1977). The analytical data and calculated ages are listed in Tables 1, 2 and 3. More dating work is in progress.

Experimental procedures and constants

The usual techniques were applied for the analysis of potassium, argon, rubidium and strontium (see, for example, Wielens et al. 1980). The analytical accuracy is believed to be within 1% for K, 2% for radiogenic Ar, 1% for XRF Rb/Sr, 1% for isotope dilution Rb and Sr, and 0.05% for $^{87}Sr/^{86}Sr$ (0.2% for the Fen 6 biotite, which represents an older analysis; Second Progress-Report 1967). The errors are the sum of the estimated contributions of the known sources of possible systematic error and the precision (2σ) of the total analytical procedures. The ages are based upon the IUGS recommended set of constants:

$\lambda_e(^{40}K) = 0.581 \times 10^{-10} a^{-1}$, $\lambda\beta(^{40}K) = 4.962 \times 10^{-10} a^{-1}$, abundance ^{40}K = 0.01167 atom percent total K and $\lambda(^{87}Rb) = 1.42 \times 10^{-11} a^{-1}$.

Results and discussion

FEN AREA

The investigated samples belong to different types of hypabyssal rocks. They come from six locations (Fig. 2):

1. The type-locality damtjernite forms a dike in diatreme facies near Damtjern, just outside the Fen complex. It is a dark porphyritic rock with phenocrysts of Ti-augite, brown hornblende and biotite (up to several cm in diameter), embedded in a fine-grained groundmass rich in carbonate and biotite. The damtjernite contains abundant xenoliths and xenocrysts of crustal rocks and upper-mantle spinel lherzolite. K-Ar analysis of biotite and hornblende yield ages of 564 ± 20 Ma and 597 ± 20 Ma, respectively.
2. Within the Fen complex, 0.5 km east of Söve, there is a dark, carbonatized damtjernite in diatreme facies. The rock contains abundant biotite flakes (up to 4 cm in diameter), which give a K-Ar age of 578 ± 20 Ma and a Rb-Sr model age between about 555 and 580 Ma, depending on the assumed initial $^{87}Sr/^{86}Sr$ ratio (0.705 or 0.702, respectively).
3. A less dark-coloured damtjernite in diatreme facies near Sanna (sannaite, Brögger 1921), 6 km SW of the Fen complex, consists of about 30% of alkali feldspar and a few sericitic aggregates (allegedly pseudomorphs after nepheline) in a groundmass rich in aegirine, carbonate, chlorite and

Fig. 3. Hybrid diatreme-facies damtjernite near Sanna (sannaite, Brögger 1921), with abundant fragments of country rock gneiss and phenocrysts of brown hornblende and biotite.

apatite (fig. 3). Phenocrysts of augite, large brown hornblende and some biotite are also present, as well as abundant fragments of country rock. Biotite and hornblende produce K-Ar ages of 580 ± 20 Ma and 598 ± 20 Ma, respectively.

4. The diatreme-facies damtjernite near Steinsrud, 1 km SW of the Fen complex, is likewise a less dark-coloured rock. Phenocrysts of clinopyroxene, large brown hornblende and biotite, along with phenocrysts or xenocrysts of feldspar (both sodic plagioclase and alkali feldspar) and aggregates of feldspar or feldspar-quartz are embedded in a groundmass of alkali feldspar, minor pyroxene, green amphibole, biotite, opaques, titanite and quartz. Biotite and hornblende give K-Ar ages of 523 ± 20 Ma and 597 ± 30 Ma, respectively.

5. The tinguaite dike near Lundebruene yields a K-Ar whole-rock age of 665 ± 20 Ma. According to Bergstöl (1960, 1979) tinguaite dikes and plugs occur only outside the actual Fen complex, but are especially frequent close to its borders (Fig. 2). He concludes that intrusion of the tinguaites is an early event in the evolution of the carbonatitic and peralkaline complex, a conclusion which is supported by the K-Ar date. The older age of the tinguaites is also confirmed by a xenolith of tinguaite observed in the type-locality damtjernite dike.

Table 1. K-Ar data and calculated ages.

Sample nr.	UTM-Coordinates	Rock type*	Material	K** (% Wt)	Radiogenic ^{40}Ar (ppm Wt)	Atmospheric ^{40}Ar (% total # ^{40}Ar)	Calculated age (Ma)***
Damtjern diatreme-facies damtjernite (type locality)							
Fen 260	$^{5}172$-$^{65}692$	breccia	biotite	6.54	0.300	10	564
Fen 260	$^{5}172$-$^{65}692$	breccia	hornblende	1.51	0.0740	4	597
Söve carbonatized diatreme-facies damtjernite							
Fen 6	$^{5}168$-$^{65}714$	breccia	biotite	8.07	0.381	10	578
Sanna hybridic diatreme-facies damtjernite							
Fen 225	$^{5}134$-$^{65}623$	breccia	biotite	6.84	0.324	10	580
Fen 225	$^{5}134$-$^{65}623$	breccia	hornblende	1.94	0.0935	2	598
Steinsrud hybridic diatreme-facies damtjernite							
Fen 281	$^{5}147$-$^{65}685$	breccia	biotite	6.63	0.279	19	523
Fen 281	$^{5}147$-$^{65}685$	breccia	hornblende	1.99	0.0977	2	597
Lundebruene tinguaite dike							
Fen 92	$^{5}145$-$^{65}678$	tinguaite	whole-rock	2.87	0.160	5	665
Fen carbonatized dolerite dike (Hydro quarry)							
Fen 1	$^{5}161$-$^{65}716$	dolerite	whole-rock	3.68	0.0694**	12	253
Gulbrandstjern hypabyssal-facies damtjernite							
Gul 1	$^{5}027$-$^{65}522$	damtjernite	biotite	6.27	0.310	4	601
Prestöya hypabyssal-facies damtjernite							
Pre 1	$^{5}024$-$^{65}534$	damtjernite	biotite	7.32	0.357	5	594
Brånan hypabyssal-facies damtjernite							
Brå 2	$^{5}077$-$^{65}951$	damtjernite	biotite	7.50	0.366	5	594
Hörte lamprophyre							
Hør 1	$^{5}073$-$^{65}873$	cpx-hbl lamprophyre	biotite	6.25	0.148	6	313
Fjone syenitic breccia							
Fjo 1	$^{4}694$-$^{65}591$	breccia	hornblende	0.846	0.0229	21	354
Gardnos explosion breccia							
Gar 9	$^{5}015$-$^{67}230$	breccia groundmass	whole-rock	3.71	0.103	25	362
Hjølmodalen explosion breccia							
Hjö 1A	$^{4}986$-$^{66}955$	breccia groundmass	whole-rock	2.93	0.152**	3	626
Hönstjern carbonatized damtjernite-like explosion breccia							
Htj 5	$^{5}354$-$^{65}418$	breccia	biotite	6.86	0.324	2	578
Tveitan carbonatized damtjernite-like explosion breccia							
Tve 1	$^{5}356$-$^{65}419$	breccia groundmass	whole-rock	371	0.0888**	5	316
Tve 4	$^{5}356$-$^{65}419$	breccia	chloritized biotite	3.44	0.0722**	26	280
Tve 9A	$^{5}356$-$^{65}419$	xenolith (gn-bio gneiss)	whole-rock	157	0.0626**	3	499
Tve 10A	$^{5}356$-$^{65}419$	xenolith (amphibolite)	whole-rock	2.26	0.0662**	5	380
Tve 11A	$^{5}356$-$^{65}419$	xenolith (bio amphibolite)	whole-rock	2.39	0.0823**	5	439
Tveitan country rock							
Tve 31	$^{5}351$-$^{65}422$	amphibolite	whole-rock	1.03	0.0582	17	675

* cpx, clinopyroxene; hbl, hornblende; gn, garnet; bio, biotite.
** Mean of duplicate or more analyses.
*** Error estimated at 3%, based upon estimated errors of 1% for K and 2% for Ar.

All three hornblende ages lie close to 600 Ma. The four biotite ages are lower, ranging from 580 to 523 Ma. This suggests that the hornblende ages approach the age of the volcanism, whereas the biotite K-Ar systems reflect varying degrees of resetting by post-volcanic processes.

There is also some evidence for a much younger magmatic event within the complex:

6. A strongly carbonatized dolerite from the Hydro quarry inside the Fen complex gives a K-Ar whole-rock date of about 255 Ma. If it is accepted as a true age, we are dealing either with a Permian dolerite, or with an older dolerite in which the K-Ar system has been completely reset in Permian time. Permian rejuvenation is conspicuously absent for biotites and hornblendes in the Fen area, however, so the K-Ar age is tentatively interpreted as reflecting the intrusion age of the dolerite. The dike may then be related to the Permian magmatism in the Oslo Graben. Sæther (1957) described several dolerites in the Fen area, all of them strongly altered, but he attributed the alteration to hydrothermal autometamorphism, being different from the alterations in other rocks of the Fen complex. On geological grounds both Sæther (1957) and Brögger (1921) regarded the dolerites in the Fen area as related to the Permian magmatism in the Oslo Graben, which is thus supported by the K-Ar date.

DAMTJERNITES OF THE SAME AGE OUTSIDE THE FEN AREA

Three damtjernites from outside the Fen area contain biotites which yield K-Ar ages concordant with the age of the Fen complex (Fig. 2):

1. A dark damtjernite dike near Gulbrandstjern (Kläy 1965), some 20 km SW of the Fen complex, consists of abundant phenocrysts of zoned pyroxene (Ti-augite, occasionally with aegirine-rich cores), biotite (strongly replaced by chlorite and apatite), opaques, zoned melanite and apatite in a groundmass of carbonate, chlorite, epidote, white mica, opaques, titanite, apatite and minor alkali feldspar. Biotite yields a K-Ar age of 601 ± 20 Ma.
2. Very similar in mineral composition, but containing less altered, zoned biotite, is the damtjernite dike on the nearby island Presetöya in Hoseivatn (Kläy 1965), which probably forms the continuation of the Gulbrandstjern dike. Biotite gives a K-Ar age of 594 ± 20 Ma.

Table 2. Rb-Sr biotite data and calculated model ages.

Sample nr.	UTM-Coordinates	Rock Type	Rb* (ppm Wt)	Sr* (ppm Wt)	$^{87}Sr/^{86}Sr$*	Calculated model age (Ma)**
Söve carbonatized diatreme-facies damtjernite						
Fen 6	$^{5}168-^{65}714$	breccia	413	161	0.7642	582 or 554
Tveitan carbonatized damtjernite-like explosion breccia						
Tve 4	$^{5}356-^{65}419$	breccia	511	387	0.71881	310 or 255

* Isotope dilution. Mean of duplicate analyses.
** Assuming an initial $^{87}Sr/^{86}Sr$ ratio of 0.702 or 0.705, respectively.

3. The damtjernite dike near Brånan (Werenskiold 1910), 20 km NNW of the Fen complex, is also similar in appearance. The rock, which has been described by Brögger (1921) and Griffin & Taylor (1975), consists of phenocrysts of zoned augite, zoned biotite and aggregates of carbonate in a groundmass of pyroxene, biotite, opaques, melanite, sericitic pseudomorphs after nepheline, apatite and carbonate. Biotite produces a K-Ar age of 594 ± 20 Ma.

The biotites from the three damtjernite dikes thus give similar ages close to 600 Ma, confirming the age of about 600 Ma assigned to the damtjernitic volcanism in the Fen area.

OTHER VOLCANIC ROCKS AND EXPLOSION BRECCIAS OUTSIDE THE FEN AREA

A lamprophyric dike, a syenitic plug and four explosion breccias have been investigated (Fig. 1):

1. The fine-grained, inhomogeneous, melanocratic to mesocratic, calcite-bearing lamprophyric dike near Hörte (Werenskiold 1910) contains abundant augite and brown hornblende, and varying contents of biotite and alkali feldspar. Locally, euhedral sericitic aggregates are observed (allegedly pseudomorphs after nepheline). Biotite produces a K-Ar age of 313 ± 10 Ma.

2. The syenitic plug near Fjone, along Nisservatn (Dons 1965) resembles the less dark-coloured parts of the lamprophyric dike near Hörte. Hornblende collected near the marginal breccia of this reddish, medium-grained, calcite- and quartz-bearing syenite plug gives a K-Ar age of 354 ± 10 Ma.

It may also be relevant to note that Touret (1970) has reported a K-Ar age of about 310 Ma for a biotite from the plug of hornblende periodotite at Degernes, along the great breccia zone which runs northeast from Kristiansand towards the Oslo Graben. All this evidence, although admittedly still rather scarce, points to a phase of subvolcanic alkaline magmatism in southern Norway about 250–300 Ma ago (Carboniferous).

Two of the investigated explosion breccias do not contain a magmatic component:

3. The Gardnos breccia (Broch 1945) forms an oval-shaped diatreme measuring about 4 by 5 km. It is filled with breccia of unsheared, angular country rock and mineral splinters, ranging in size from fragments of about 10 cm in diameter to dust-like particles, and an extremely fine-grained chloritic graphitic groundmass. According to Broch, fragments of folded phyllites of supposedly Cambrian age are present, implying that the diatreme has formed subsequent to Caledonian folding movements. The sample investigated in this study is the fine-grained groundmass filling the spaces

Table 3. Rb-Sr whole-rock data.

Sample nr.	UTM-Coordinates	Rock type*	Rb** (ppm Wt)	Sr** (ppm Wt)	Rb/Sr** (Wt/Wt)	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$
Xenoliths of the Tveitan carbonatized damtjernite-like explosion breccia							
Tve 6	5356-6519	albitite	90.4	440	0.2055	0.71199	0.56
Tve 7	5356-6519	gn gneiss	137	110	1.247	0.77819	3.6
Tve 8	5356-6519	bio gneiss	133	235	0.566	0.73179	1.6
Tve 9	5356-6519	gn-bio gneiss	136	507	0.2673	0.71236	0.77
Tve 10	5356-6519	amphibolite	178	357	0.497	0.71466	1.4
Tve 11	5356-6519	bio amphibolite	188	258	0.728	0.72575	2.1
Tve 12	5356-6519	bio gneiss	99.2	365	0.2718	0.71903	0.78
Tve 13	5356-6519	bio gneiss	115	413	0.2766	0.71898	0.80
Tve 14	5356-6519	bio-hbl granite	76.7	86.7	0.884	0.74057	2.6
Tve 15	5356-6519	sheared gneiss	103.5	153	0.679	0.74853	2.0
Tve 16	5356-6519	bio-hbl gneiss	193	103	1.883	0.81751	5.5
Tve 18	5356-6519	hbl-bio gneiss	101	93.2	1.083	0.74824	3.1
Tve 19	5356-6519	gn gneiss	82.8	247	0.336	0.72219	0.97
Tveitan country rocks							
Tve 28	5351-6522	gn-bio gneiss	90.9	238	0.3831	0.72247	1.1
Tve 29	5351-6522	pegmatitic hbl-bio gneiss	93.9	197	0.4749	0.72751	1.7
Tve 30	5351-6522	pegmatitic hbl-bio gneiss	95.7	186	0.5159	0.72915	1.5
Tve 31	5351-6522	amphibolite	69.9	258	0.2711	0.71222	0.78
Tve 32	5351-6522	bio gneiss	80.3	249	0.3231	0.72191	0.94
Tve 33	5351-6522	bio gneiss	112	372	0.3003	0.72121	0.87
Tve 34	5351-6522	gn-hbl-bio gneiss	78.3	287	0.2737	0.71836	0.79

* gn, garnet; bio, biotite; hbl, hornblende.
** X-ray fluorescence spectrometry. Mean of duplicate analyses.

between larger fragments of presumably Sveconorwegian gneisses. A K-Ar whole-rock analysis of the groundmass yields a date of 362 ± 10 Ma. This age may be interpreted as reflecting a complete resetting of the K-Ar system, or nearly so, during the fragmentation due to the explosive brecciation. The K-Ar date may then be taken as setting a maximum to the age of the explosive activity, which supports Broch's conclusion that the Gardnos breccia is post-Caledonian.

4. The Hjölmodalen breccia (Svinndal & Barkey 1967) closely resembles the Gardnos breccia. The rock shows less alteration, however, and the size of the diatreme is much smaller, some 130 x 150 m. A K-Ar analysis of the groundmass gives a date of 626 ± 20 Ma. If the explosive volcanism leading to the Hjölmodalen breccia was contemporaneous with that of the Gardnos breccia, this date may be interpreted as reflecting a much less advanced resetting of the K-Ar system of the gneiss mateial than in the case of the Gardnos breccia.

The age of the Gardnos and Hjölmodalen breccias is thus not yet firmly established. On the basis of the K-Ar age of the Gardnos breccia, however, this phase of explosive activity may tentatively be correlated with the alleged phase of subvolcanic alkaline magmatism about 350–300 Ma ago.

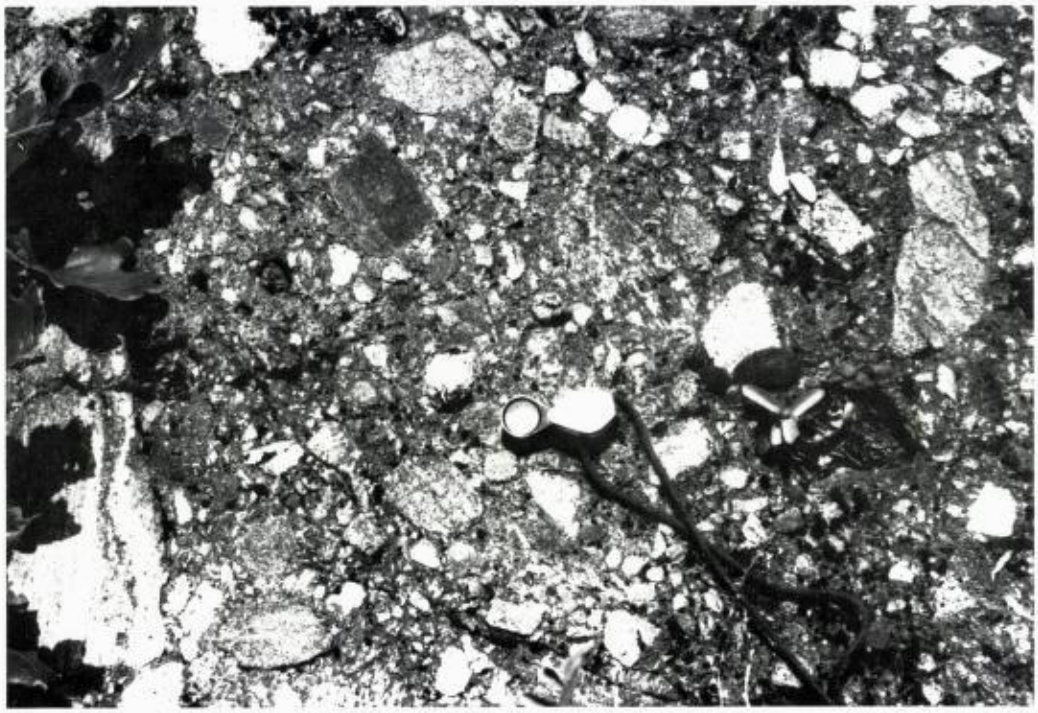

Fig. 4. Carbonatized damtjernite-like explosion breccia near Tveitan, Bamble region, with numerous fragments of country rock.

Two explosion breccias produce ambiguous and conflicting age data:

5. In the Bamble region two carbonatized damtjernite-like explosion breccias have been studied, the Hönstjern breccia and the Tveiten breccia (Fig. 4). They are situated less than 0.5 km apart, in an area dominated by anatectic paragneisses with intercalated amphibolites and metagabbros (Morton et al. 1970). The breccias lie about 10 km W of the nearest exposure of Permian intruisives of the Oslo Graben. The breccias are very similar; they consist of a wide variety of xenoliths and xenocrysts in a very fine-grained groundmass consisting mainly of carbonate, green biotite, opaques and apatite (Fig. 4). Among the xenoliths three groups can be distinguished: (1) small, rounded fragments (up to 0.5 cm in diameter) of ultramafic, occasionally porphyritic rocks with phenocrysts of biotite or brown hornblende; (2) larger, angular fragments (up to 10 cm in diameter) of crustal gneisses, amphibolites, granites and metagabbros; and (3) occasional fragments of a similar damtjernitic breccia. Many of the xenoliths and xenocrysts are strongly altered, but the abundant apatite phenocrysts and the cores of biotite phenocrysts and perthite xenocrysts do not show any alteration. Numerous veinlets of carbonate transect both the xenoliths and the groundmass.

Biotite phenocrysts from the Hönstjern breccia yield a K-Ar age of 578± 20 Ma, concordant with the age of the Fen complex. The partly chloritized biotite booklets from the Tveitan breccia give much younger ages, however: a K-Ar age of 280 ± 10 Ma and a Rb-Sr model age between about 310 Ma and 255 Ma, depending on the assumed initial $^{87}Sr/^{86}Sr$ ratio (0.702 and 0.705, respectively). The early Permian age of the Tveitan biotite is supported by four K-Ar whole-rock dates obtained from the same breccia: an age of 316 ± 10 Ma for the groundmass and ages between 500 and 380 Ma for three crustal xenoliths. The latter three ages could very well be interpreted as reflecting varying degrees of resetting of the K-Ar systems of Sveconorwegian crustal fragments during transport by the exploding magma in Permian time.

A suite of 14 gneiss and amphibolite xenoliths from the Tveitan breccia has been investigated (for petrographic details see Table 4). The Rb-Sr datapoints scatter widely (Fig. 5), but all lie between boundary lines corresponding to ages of 1.4 Ga and 0.2 Ga. Five gneisses and one granite define a crude linear correlation along a 0.9 Ga line; these may be interpreted as signalling derivation from (possibly slightly reset) Sveconorwegian source rocks. The

Table 4. Petrography of 14 crustal xenoliths from the carbonatized damtjernite-like explosion breccia near Tveitan, Bamble region[1]

		texture								primary minerals								secondary minerals				
		hypidiomorphic	fine-grained	medium-grained	leucocratic	mesocratic	melanocratic	foliated	banded	quartz	K-feldspar perthite	plagioclase	anorthite %	garnet	hornblende	hbl colour	biotite (primary)	biotite (secondary)	chlorite	carbonate	sericitization (plagioclase)	albitization (plagioclase)
Tve 6	Albitite	*		*	*			*				xx	0						x	x		**
Tve 7	Gn gneiss		*		*			*		xx	xx	xx	20	x					x		*	*
Tve 8	Bio gneiss		*			*		*		xx	xx	xx	20					x	x	x	*	*
Tve 9	Gn-bio gneiss		*	*		*		*		xx		xx	30	x					x	x	*	
Tve 10	Amphibolite		*				*	*		x		xx	40		xx	gb		x			*	
Tve 11	Bio amphibolite			*			*	*				xx	35		xx	pg	xx	x	x		*	*
Tve 12	Bio gneiss		*		*	*		*	*	xx		xx	30		x	g	xx	x	x	x	*	*
Tve 13	Bio gneiss		*	*	*			*		xx		xx	30				x		x		*	*
Tve 14	Bio-hbl granite	*	*	*	*					xx	xx	xx	20		x	dg	x					
Tve 15	Sheared gneiss		*		*			*		xx	xx	xx	0				x		x	x	*	**
Tve 16	Bio-hbl gneiss		*		*			*		xx	xx	xx	20		x	dg	x			x	*	
Tve 18	Hbl-bio gneiss			*	*	*		*		xx	xx	xx	20		xx	dg	x		x	x		
Tve 19	Gn gneiss		*		*			*		xx		xx	20	x							*	*
Tve 21	Gn-bio gneiss		*	*		*		*		xx	xx	xx	20	x			x		x		*	*

[1] *, Applicable; xx, major component; x, minor component; g, green; b, brown; p, pale; d, dark; gn, garnet; bio, biotite; hbl, hornblende.

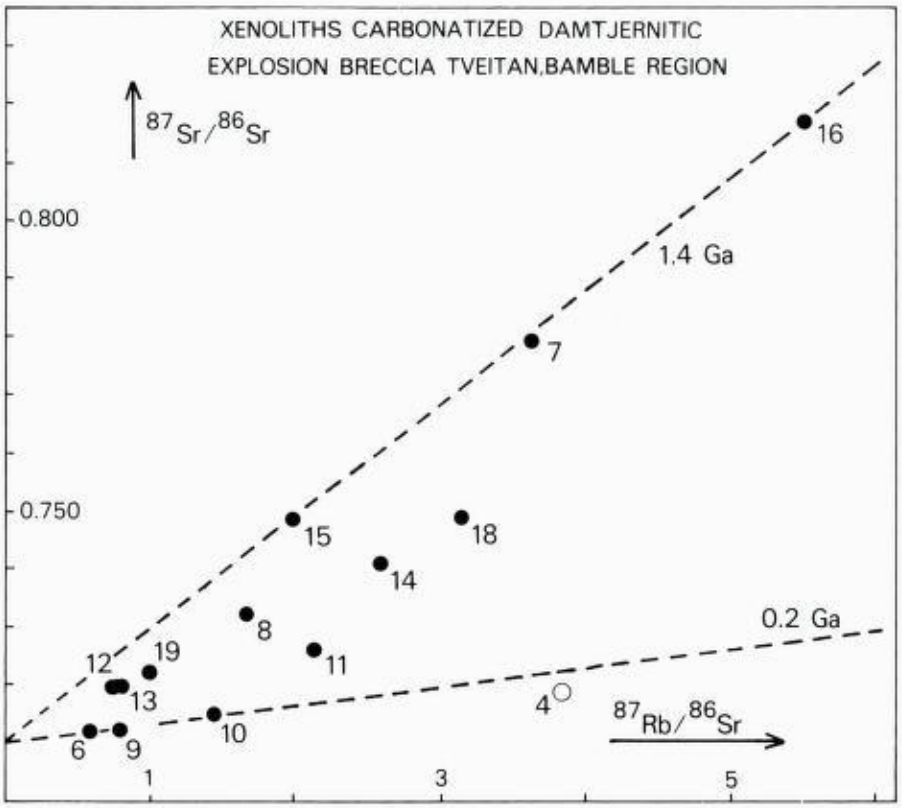

Fig. 5. Plot of the Rb–Sr whole-rock data of xenoliths (closed circles) and of the biotite (open circle) from the carbonatized damtjernite-like explosion breccia near Tveitan, Bamble region.

three points defining the upper boundary line of 1.4 Ga. (Tve 7, 15 and 16) may testify to the presence of older, pre-Sveconorwegian elements among the source rocks. On the other hand, the three points defining, or close to the lower boundary line of 0.2 Ga could very well reflect complete resetting, or nearly so, of the Rb-Sr systems of fragments of Sveconorwegian or older rocks during transport by the exploding magma in Permian time.

There thus appears to be a difference between the age of the Hönstjern breccia and that of the Tveitan breccia; about 580 Ma for the former and about 280 Ma for the latter. The simplest explanation is that the age difference is real, the Hönstjern breccia having been formed in the latest Precambrian, in relation to the damtjernite volcanism elsewhere, and the Tveitan breccia having formed in the Permian and associated with the magmatism in the nearby Oslo Graben. The similarity between both breccias is then difficult to understand, however. Another explanation could be that both breccias were formed about 280 Ma ago, but that the Hönstjern breccia contains biotite derived from an older rock, carried upwards by the exploding magma.

For comparison, Rb-Sr whole-rock analyses have also been carried out on a suite of six gneisses and one amphibolite from country rock, collected at an

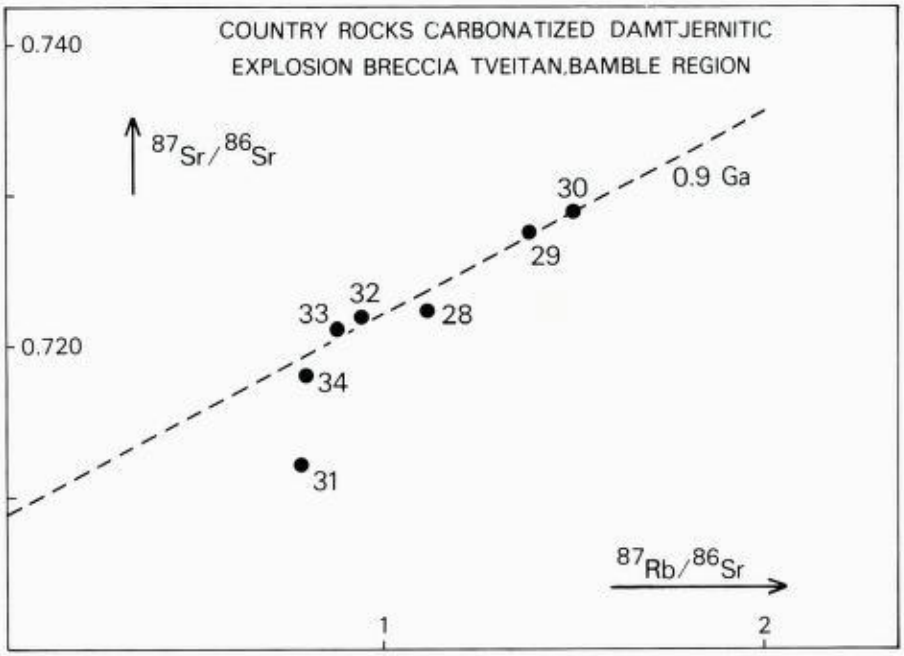

Fig. 6. Plot of the Rb-Sr whole-rock data of country rock gneisses and amphibolite (31) 0.5 km NW of the carbonatized damtjernite-like explosion breccia near Tveitan, Bamble region.

outcrop 0.5 km NW of Tveitan (Table 4). The Rb-Sr data-points (Fig. 6) display a crude linear correlation along a line corresponding to an age of 0.9 Ga, roughly concordant with the six intermediate crustal xenoliths from the Tveitan breccia. The scatter of data-points may be related to the retrogradation and minor carbonate veining in these rocks (Table 5). The amphibolite Tve 31 falls below this line, which may be due to a lower initial $^{87}Sr/^{86}Sr$ ratio; its low K-Ar age may be attributed to a partial resetting.

Conclusions

Two episodes of (sub)volcanic activity, both of explosive nature and associated with alkaline magmatism, are apparent in southern Norway before the Permian magmatism in the Oslo Graben. The first episode is dated at about 600 Ma, but the age of the second episode is still uncertain; it probably lies at about 350–300 Ma. The older episode may be related to a precursor phase of the Caledonian orogeny, as has already been proposed by Brögger (1921) for the Fen complex. Similarly, the younger episode may be related to a precursor phase of the epeirogenic movements which ultimately led to the formation of the Oslo Graben system. The intrusion of the doleritic dikes in the Fen area could be related to the Permian magmatism in the Oslo Graben. Doig (1970) has reported the existence of an extensive 580–570 Ma old alkaline magmatic province on both sides of the Nort Atlantic region. It is of interest to note that Doig also reports some Late Paleozoic ages for alkaline rocks in the western part of this province.

Table 5. Petrography of country rock gneisses and an amphibolite 0.5 km NW of the carbonatized damtjernite-like explosion breccia near Tveitan, Bamble region[1]

	texture									primary minerals							secondary minerals				
	equigranular	inequigranular	fine-grained	medium-grained	leucocratic	mesocratic	melanocratic	foliated	banded	quartz	K-feldspar perthite	plagioclase	anorthite	garnet	biotite	hornblende	chlorite	chlorite + carbonate (pseudomorph hbl?)	carbonate	veinlets (carb + chl + adularia)	sericite
Tve 28: Gn-bio gneiss		*		*		*		*		xx	xx	xx	25	x	xx		x	x	x		x
Tve 29: (Pegm.) hbl-bio gneiss		*	*	*		*		*		xx	xx	xx	25	x	x	x	x	x	x		x
Tve 30: (Pegm.) hbl-bio gneiss		*	*	*		*		*		xx	xx	xx	25		x	x	x				
Tve 31: Amphibolite	*		*				*					xx	70			xx	x	x			xx
Tve 32: Bio gneiss		*	*	*		*		*	*	xx		xx	30		x		xx			x	x
Tve 33: Bio gneiss		*	*	*	*			*		xx		xx	30		x		xx		x		x
Tve 34: Gn-hbl-bio gneiss		*	*	*		*		*		xx	xx	xx	25	x	x	x	xx	x	x	x	x

[1] *, Applicable; xx, major component; x, minor component; carb, carbonate; chl, chlorite; bio, biotite, gn, garnet; hbl, hornblende; pegm, pegmatitic.

Acknowledgements. – The authors thank Sverre Svinndal and Henri Barkey, Norges Geologiske Undersøkelse, Trondheim, for advice and help in sampling. Assistance in the field by Jostein Völlestad, Drangedal, and Sigmund Tveten, Tveitan, is gratefully acknowledged. This work forms part of the research programme of the 'Stichting voor Isotopen-Geologisch Onderzoek', supported by the Netherlands Organization for the Advancement of Pure Research (Z.W.O.).

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Note added in proof: Throughout this paper the editors prefer the modern spelling damtjernite instead of the original spelling damkjernite used by the majority of the authors on the Fen area (e.g. Barth & Ramberg 1960, Bergstöl 1979, Brögger 1921, Griffin & Taylor 1975).