Isotopic age determinations in South Norway: II. The problem of errorchron ages from Telemark rhyolites.

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Two sets of Telemark Supracrustal acid metavolcanics of the Rjukan Group were investigated by the Rb-Sr whole-rock method. Eleven samples within a sampling range of about 10 m were taken at Kvamsstøl at a distance of about 30 km from the Sveconorwegian reset Telemark Gneisses. This set defines a Sveconorwegian errorchron of 0.98 ± 0.05 Ga with an extremely high initial $^{87}Sr/^{86}Sr$ ratio of 0.8049 ± 0.0162 (MSWD = 9.3). The second set was taken from a 1 m thick layer along Vråvatn, 1.5 km from the Telemark Gneisses with a sample spacing of about 10 cm. This set defines a pre-Sveconorwegian (Gothian) errorchron of 1.29 ± 0.06 Ga with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7064 ± 0.0036 (MSWD = 13.3). A plot of the Kvamsstøl samples in a Hughes igneous spectrum diagram suggests K, and therefore probably also Rb metasomatism. The high initial $^{87}Sr/^{86}Sr$ ratio might thus provide evidence of Sveconorwegian resetting of volcanics that were metasomatized in pre-Sveconorwegian, Gothian times. It is not improbable that the apparent 1.29 ± 0.06 Ga age of the Vråvatn samples is a reasonable age approximation for the Rjukan Group acid volcanism. According to Beswick & Soucie's graphical procedure to quantify metasomatic alterations for one of the Kvamsstøl samples, enrichments of 60 % in SiO_2, 125 % in K_2O and depletions of 65 % in Na_2O, 97 % in CaO and 40 % in Fm (FeO + MgO +MnO) have been calculated. For one of the Vråvatn samples, enrichments of 60 % in SiO_2, and depletions of 60 % in CaO and 60 % in Fm were found.

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Introduction

The Southwestern Gneiss Region

The Southwestern Gneiss Region of southern Scandinavia, the area delimited by the Caledonian front and the Trans-Scandinavian Småland-Värmland Granitic Belt (Verschure 1985), is a polyorogenic Precambrian area comprising sequences of gneisses, migmatites and granites interlayered with amphibolites and minor metasediments. The gneisses are rather loosely designated as 'Telemark Gneisses'. Whole-rock Rb-Sr geochronology on km-spaced samples of Telemark Gneisses in central Telemark generally produces isochron ages of about 1.10 Ga (e.g. Priem et al. 1973, Kleppe & Råheim 1979, Kleppe 1980). These ages are attributed to metamorphic resetting during the Sveconorwegian orogenic period (1.20 - 0.85 Ga) of rocks deposited or emplaced during the Gothian orogenic period (1.70 - 1.20 Ga) (e.g. Lundegård 1971, Simonen 1971, Ploquin 1980, Verschure 1985). A number of Rb-Sr whole-rock isochrons in the Southwestern Gneiss Region revealed the presence of Gothian protoliths (e.g. O'Nions & Baadsgaard 1971, O'Nions & Heier 1972, Versteeve 1975, Berg 1977, Jacobsen & Heier, 1978, Wielens et al. 1981, Field & Råheim 1981, Field et al. 1985). The Gothian ages range from about 1.60 Ga in the north to about 1.20 Ga in the south. In central Telemark no Gothian rocks have been found so far.

The formation of Gothian protoliths of the Southwestern Gneiss Region includes deposition of volcano-sedimentary sequences on an unknown, presumably pre-Gothian, basement. Crustal addition during the Sveconorwegian period was mainly restricted to the emplacement of mafic igneous material. The grade of metamorphism increases in southern Scandinavia towards the south (Zeck & Wallin 1980). The final stage of the Sveconorwegian period is characterized by emplacement about 895 Ma to 960 Ma ago of huge quantities of anatectic Bohus-type granitic magma as disharmonious plutons, pegmatites and veins. The metamorphic history in southern Norway is still a matter of debate (e.g. Field & Råheim 1981, Weis & Demaiffe 1983).

The Telemark Supracrustal Suite

In central Telemark (e.g. Dons 1960, 1972) extensive areas of polymetamorphic volcano-sedimentary rock sequences of mainly low grade are found in the Norwegian part of the Southwestern Gneiss Region (Fig. 1). These rocks are referred to as the Telemark Supracrustal Suite. The age and structural relationships between the Telemark Supracrustals and Telemark Gneisses are still disputed. According to Dons (1960) the Telemark Supracrustals give the impression of «being young» and «swimming in a vast sea of granites and granitic gneisses». Regarding the Telemark Gneisses there are two main views: (1) The Telemark Gneisses represent reworked and mobilised products of protolithic Telemark Supracrustal material (e.g.,Werenskiold 1910, Barth & Reitan 1963, Mitchell 1967, Cramez 1969, Avilla Martins 1969, Venugopal 1970, Stout 1972, Priem et al. 1973, Kleppe 1980); and (2) the Telemark Gneisses represent the basement upon which the Telemark Supracrustals were deposited, whereafter both underwent reworking (e.g.,Törnebohm 1889, Sæther 1957, Dons 1960, 1972, Menuge 1982, Brewer & Atkin 1987, 1989). The type-area of the Telemark Supracrustal Suite in central Telemark is situated between two major tectonic zones, the Mandal-Ustaoset Line (Sigmond 1984, 1985) and the Kristiansand-Bang Shear Zone (e.g. Hageskov 1980). The suite is divided into three lithostratigraphic groups; from top to bottom:

III Bandak Group
II Seljord Group
I Rjukan Group

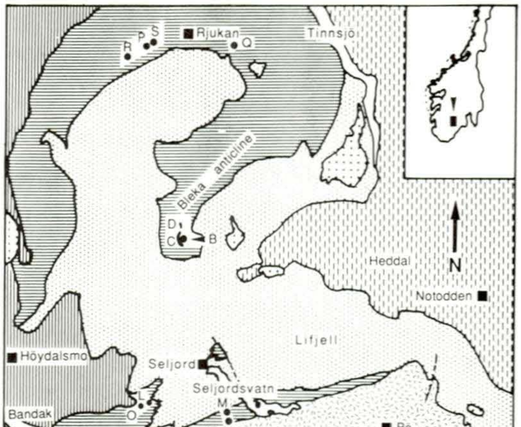

Fig. 1. Geological sketch-map of central Telemark after Dons (1960), Neumann & Dons (1961), Dons (1973), Priem et al. (1973) and Kleppe (1980). The sampling sites of the Tuddal Formation acid metavolcanics of this study are indicated by : B = Bleka anticline at Kvamsstøl and V = Vråvatn near Brauti. The sampled road sections of the Tuddal Formation acid metavolcanics of Priem et al. (1973) in the Bleka anticline are indicated by C and D. The sampling sites of the Tuddal Formation acid metavolcanics of Kleppe (1980) are indicated by L, M, N, O, P, Q, R and S.

Each group has a thickness of more than 2000 m. Both on a regional and a local scale there are angular unconformities between the groups. The Rjukan Group and the Bandak Group resemble one another with regard to their lithology, i.e. metamorphic rhyolitic and basaltic lavas and tuffs, generally with well-preserved volcanic textures, and interlayering with quartz-rich sediments. The Rjukan Group is subdivided into two formations, the lower Tuddal Formation, mainly comprising acid metavolcanics, and the upper Vemork Formation comprising basic lavas and tuffs with minor metasediments. The Seljord Group is composed of conglomerates, mature quartzites with shallow-water sedimentary structures (Singh 1968, 1969), minor amounts of shale and calcareous sandstones. Both the Seljord

Group and the Rjukan Group contain many thick metagabbroic sills. Their chemistry suggests that they are comagmatic with basic lavas of the Bandak Group (Moine & Ploquin 1972), most of which plot in the alkali basalt field of a Kuno diagram, but their high K-content suggests metasomatic alteration. Metasomatic alteration of the Rjukan Group acid volcanics south of Rjukan has already been described by Wyckoff (1933). Brewer & Field (1985) and Brewer & Atkin (1989) reported elemental mobility to varying degrees in various basaltic rocks of the Telemark Supracrustal Suite owing to low-grade metamorphism. Even the more immobile elements Zr, Nb, Ti and Y were shown to have been mobilised in some cases.

Several isolated supracrustal areas, separated from the type-area by Telemark-type gneisses, have been distinguished in the Southwestern Gneiss Region (e.g. Kvale 1945, Naterstad et al. 1973, Berg 1977, Sigmond 1978, Prestvik & Vokes, 1982). In western Norway, such supracrustal rocks have been attributed by Sigmond (1978) to the Bandak Group. At Nyastøl bridge, the place where Naterstad et al. (1973) interpreted the contact between these supracrustal rocks and gneisses as depositional, we observed in a new road exposure a clear intrusive contact between gneissose megacryst granite and supracrustal material in the form of quartzites, conglomerates and acid volcanics. The gneissose megacryst granite contains rotated fragments of quartzite and porphyric acid volcanites showing veining by the granite.

In the type-area in central Telemark the boundary relations between the Telemark Supracrustal Suite and the Telemark Gneisses are obscured by intrusions and faults. Locally the contacts seem to be concordant and gradational (Avilla Martins 1969). Ploquin et al. (1972) and Ploquin (1980) concluded from major-element geochemistry that the acid volcanics of the Tuddal Formation grade southwards into Telemark Gneisses although the validity of long-range correlations with major elements as discriminators was questioned by e.g. Brewer & Field (1985) in the light of their mobility under metamorphic conditions. Kleppe (1980) described an intrusive contact relationship between Telemark Gneisses and Telemark Supracrustals. He found near the contact a rotated quartzite xenolith in Telemark Gneiss. From these observations it is clear that the Telemark Gneisses do not form the basement on which the Telemark Supracrustals were deposited. In these cases the alleged contact between Telemark Supracrustals and Telemark Gneisses involves quartzitic rocks that resist anatexis and probably effectively screen against granitization. Anyhow, Telemark(-type) supracrustal sedimentary and volcanic rocks form an important (e.g. Morton et al. 1970, Touret 1969, Ploquin 1980) and possibly the main Precambrian protolithic component of the south Norwegian crust.

Previous geochronological investigations

Notwithstanding that there is a considerable amount of geochronological data from the Telemark Supracrustal Suite (e.g. Priem et al. 1973, Jacobsen & Heier 1978, Kleppe & Råheim 1979, Kleppe 1980, O'Nions & Heier 1972, Menuge 1982, 1985), the depositional age of the Telemark Supracrustals is still disputed. Priem et al. (1973) analysed 34 samples of acid volcanics from both the Rjukan and the Bandak Groups collected throughout the type-area, and observed that Rb-Sr data points from both groups show a considerable scatter in an isochron diagram between boundary isochrons of 1.63 Ga old and 1.11 Ga. Priem et al. (1973) interpreted these results in terms of (1) a deposition of the Telemark Supracrustal acid volcanics contemporaneously with the about 1.63 Ga Trysil and Dala porphyries and granites of the Trans-Scandinavian Småland-Värmland Granitic Belt some 300 km to the northeast (e.g. Welin et al. 1966, Welin & Lundqvist 1970, Priem et al. 1970, Verschure 1985); and (2) high- to low-grade Sveconorwegian metamorphism about 1.11 Ga ago, causing on the one hand isotopic resetting to varying degrees of the Rb-Sr whole-rock systems in the Supracrustals, and on the other hand an apparently complete resetting of the Gothian Telemark Gneiss protoliths. Jacobsen & Heier (1978) calculated from the Rb-Sr data of the Rjukan acid volcanics published by Priem et al. (1973) T^{Sr}_{Ur} model ages in the range of 1.0 - 1.6 Ga.

Kleppe & Råheim (1979) and Kleppe (1980) obtained similar results to those of Priem et al. (1973). They published a considerable amount (214) of whole-rock Rb-Sr data of supracrustal acid volcanic material, Telemark Gneisses and Bohus-type granite plutons. For eight restricted sampling areas (Fig. 1) of Rjukan acid metavolcanics, 'errorchrons' (Fig. 2) were given with ages varying between 1.43 and 0.85 Ga and *initial* ^{87}Sr/^{86}Sr *ratios* between 0.7138 and 0.7936. The age of 1.43 Ga, however, has been calculated for a suite of rocks displaying an unrealistically low initial ^{87}Sr/^{86}Sr of 0.682. The data-points of all Rjukan acid volcanics scatter, like those of Priem et al. (1973), between boundary isochrons of 1.60 and 1.05 Ga. For the Bandak acid metavolcanics of three different sampling areas, errorchrons with ages 813 Ma, 905 Ma and 925 Ma with ^{87}Sr/^{86}Sr(i) 0.7094, 0.7144 and 0.7147 were given. Taking all Bandak data points together results in an errorchron of 1.02 Ga with initial ^{87}Sr/^{86}Sr of 0.7050±0.004. For the Telemark Gneisses and the Bohus-type granite plutons they found, like Priem et al. (1973), Rb-Sr isochron ages of about 1.10 Ga and 0.90 to 0.80 Ga, respectively.

Menuge (1982, 1985) published the results of a Sm-Nd investigation of Telemark Supracrustals. A Sm-Nd isochron plot of 9 acid and basic Rjukan volcanics gives an isochron age of about 1.20 Ga if two data-points are omitted. From Menuge's Sm-Nd data, of 6 out of 8 basic and acid metavolcanic lavas of the Bandak Supracrustal Group an isochron of about 1.60 Ga can be calculated, but Menuge considered this linear correlation not to have age significance (Verschure 1985, Menuge 1985).

Brewer & Field (1985) reported errorchron Rb-Sr ages varying between about 1.40 and 1.00 Ga for metarhyolites and metabasalts of the Rjukan Group as well as of the Bandak Group. They concluded that there had been a lack of homogenization on the scale of the outcrop due to regional and contact metamorphic conditions. From the Sm-Nd data of Menuge (1982, 1985) they made T_{DM} model age calculations (DePaolo 1981) for Telemark Gneisses that gave 1.43 to 1.40 Ga, Rjukan acid metavolcanics 1.46 to 1.40 Ga, Bandak acid metavolcanics 1.45 Ga and Bohus-type posttectonic granites between 1.40 and 1.39 Ga. This could mean that they were derived from 1.50 to 1.40 Ga old crust. T_{DM} model ages calculated for the Rjukan and Bandak metabasites range from about 1.60 to 1.20 Ga.

Clearly, the question about the depositional age of the three groups in the Telemark Supracrustal Suite is still unanswered. Some authors speculate that they were all deposited in Gothian time about 1.60 Ga ago (e.g. Priem et al. 1973); others that only the deposition of the Rjukan Group took place about 1.60 Ga ago, whereas the Seljord and Bandak Groups were deposited in a time-span from

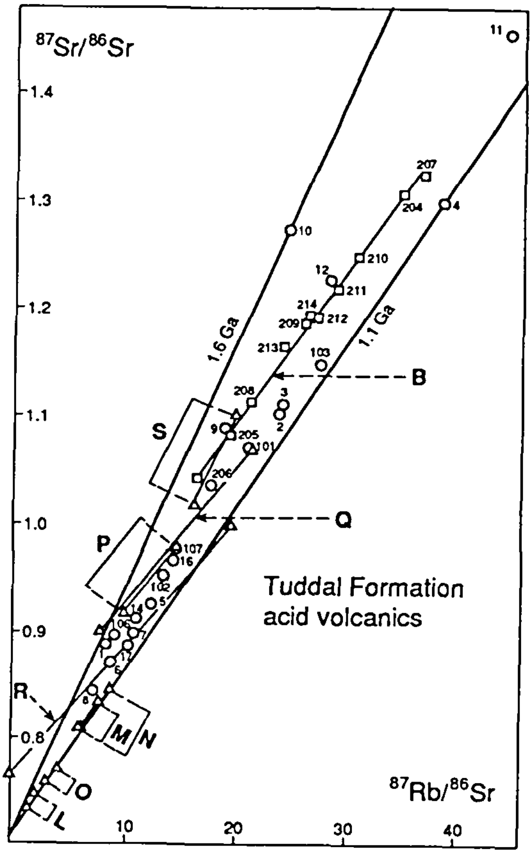

Fig. 2. Isochron cumulative data plot of Tuddal Formation acid metavolcanics from the type-area of the Telemark Supracrustal Suite. The Tuddal Formation acid metavolcanics from the Bleka anticline investigated in this study are indicated by squares. The errorchron through these points is labeled B. The samples from the same area, that were investigated by Priem et al. (1973) are indicated by circles. Isochron plots of the samples from the Tuddal Formation investigated by Kleppe (1980) are indicated by 'partial errorchrons' labeled L, M, N, O, P, Q, R and S. These partial errorchrons are drawn only between the extreme values of the measured data indicated by triangles. Boundary isochrons of 1.6 Ga and 1.1 Ga are also indicated. The apparent ages of the errorchrons are as follows: B = 0.98 Ga; L = 1.0 Ga; M = 1.0 Ga; N = 0.9 Ga; O = 0.9 Ga; P = 0.9 Ga; Q = 0.9 Ga; R= 0.9 Ga; S = 1.4 Ga.

about 1.40 to 1.10 Ga ago (Ploquin 1980, Kleppe 1980, Verschure 1985). Some authors (e.g. Verschure 1985) speculate that the Seljord and Bandak groups can be equated with the Dal and Jotnian supracrustal sediments with ages of about 1.20 to 1.10 Ga in southern and central Sweden and that the Rjukan Group, with ages of about 1.60 Ga, can be correlated with the Trysil acid volcanics of the Gothian Småland-Värmland Belt.

Structural and metamorphic development

All rocks in the Telemark Supracrustal type-area in central Telemark are folded (e.g. Dons 1960, Kleppe 1980). The Rjukan Group was folded along NNE-SSW axes during an early deformational phase (D_0), before the deposition of the Seljord Group. Both the Rjukan and the Seljord Group were subsequently folded along ENE-WSW axes during the most intensive deformational phase (D_1). In the type-area, the D_1 deformation increases in intensity towards the south. The main period of medium-grade metamorphism coincides with the D_1 deformational phase. The metamorphic grade seems to increase towards the Telemark Gneiss area, where a medium-grade paragenesis of kyanite-muscovite has been reported (Dahlgren 1984). After the D_1 deformational phase, rifting took place accompanied by basic and acid Bandak volcanism. A later deformational phase (D_2) produced NNW-SSE fold structures in all rocks of the Telemark Supracrustal Suite. Low-grade metamorphism connected with the D_2 deformation caused retrogradation of all earlier mineral parageneses. These features indicate a metamorphic and structural break between the Bandak Group and the lower Supracrustal Group. The Telemark Supracrustal Suite as well as the Telemark Gneiss were finally intruded by voluminous, post-tectonic, Bohus-type granitic plutons, pegmatites, aplites and veins about 960 Ma to 895 Ma ago.

Brewer & Field (1985) proposed a different tectonic history for the Telemark Supracrustal Suite. According to them, all groups exhibit only one single, prominent, regional penetrative cleavage. This cleavage is related to N-S trending folds containing a regional greenschistfacies mineralogy. Later folds occur only near post-tectonic granites and were related to the granite emplacement. Brewer & Atkin (1987,1989) distinguished three subsequent metamorphic events; burial, regional and thermal metamorphism.

Geotectonic implications regarding the Telemark Supracrustal Suite

There are two opposing geotectonic models with regard to the formation of the Telemark Supracrustals. The first model relates them to an Andean-type, westward-migrating, eastward-dipping, destructive plate margin. There is no agreement among the proponents of this model (e.g. Torske 1977, 1985, Berthelsen 1980, Brewer & Field 1985, Brewer & Atkin 1987) with regard to the orientation of this hypothetical margin. The second model relates the formation of the Telemark Supracrustal Suite to an anorogenic intraplate continental rift regime (Falkum & Petersen 1980, Menuge 1982, 1985, Falkum 1985).

Scope of the investigation

A whole-rock Rb-Sr investigation has been made at two sampling sites of acid metavolcanics from the Tuddal Formation of the Rjukan Group (Dons & Jorde 1987). The objectives were to investigate whether: (1) suites of samples of acid metavolcanics collected with a spacing of decimetres or a few metres, therefore minimizing differences in initial $^{87}Sr/^{86}Sr$, will give an isochron with a lower MSWD than the suites of samples collected over large areas (Priem et al. 1973, Kleppe 1980); (2) Sveconorwegian reworking of Tuddal acid metavolcanics can be demonstrated near the Telemark Gneiss region which apparently underwent complete whole-rock Rb-Sr resetting during Sveconorwegian gneissification and migmatitization of about 1.10 Ga ago; (3) the alleged Gothian age of about 1.60 Ga attributed to the Rjukan Group acid metavolcanics can be ascertained in the central part of the Supracrustal area, far from the Telemark Gneiss area, where a lesser degree of Sveconorwegian reworking took place.

Two suites of samples were collected. One suite of 11 samples was taken from a blasted outcrop of about 10 m with a sample spacing

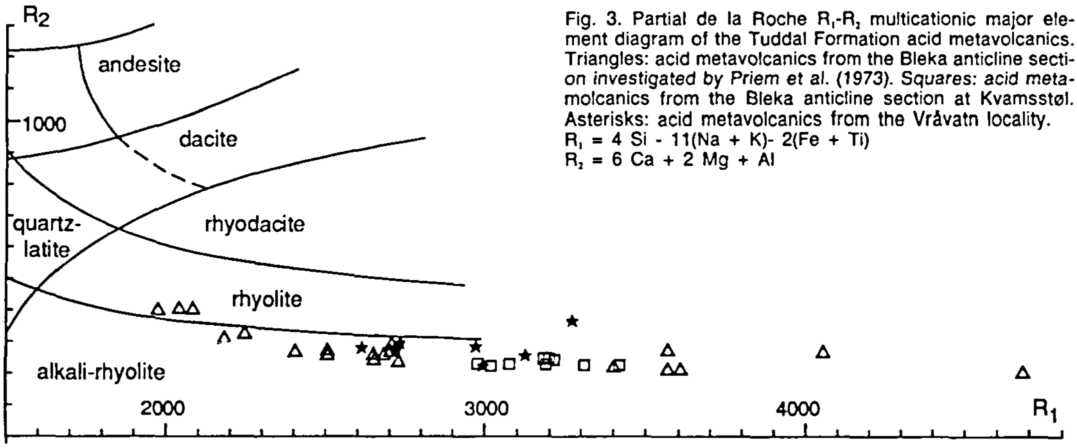

Fig. 3. Partial de la Roche R_1-R_2 multicationic major element diagram of the Tuddal Formation acid metavolcanics. Triangles: acid metavolcanics from the Bleka anticline section investigated by Priem et al. (1973). Squares: acid metamolcanics from the Bleka anticline section at Kvamsstøl. Asterisks: acid metavolcanics from the Vråvatn locality.
R_1 = 4 Si - 11(Na + K)- 2(Fe + Ti)
R_2 = 6 Ca + 2 Mg + Al

of about 1 m. The outcrop occurs near Kvamsstøl (indicated by 'B' on Fig. 1) in the centre of the type area. It forms part of the 4.5 km long road section in the southern part of the Bleka anticline along the Hjartdøla river that was investigated by Priem et al. (1973). Another suite of 10 samples was taken from a blasted road exposure along the northern shore of Vråvatn (indicated by 'V' on Fig. 1), about 1.5 km from the nearest outcrop of Telemark Gneisses. The samples were taken with a sample spacing of about 10 cm from a 1 m thick layer, possibly a single flow, with gneissose appearance.

Petrography

Samples 82 Tel 203-1 to 203-11 from Vråvatn are fine-grained quartzo-feldspathic gneisses with an average grain-size of 0.1-0.2 mm and granoblastic texture, mainly composed of quartz, albite and microcline. A clear foliation is due to the parallel orientation of (partly chloritized) biotite and coarser grained lenses or ribbons of quartz ('platy quartz'), up to 2 mm in size. In the outcrop the rock shows tight to isoclinal folding. Minor phases include colourless mica and euhedral magnetite. Accessories are zircon and allanite and some late interstitial carbonate.

Samples 83 Tel 204 to 214 from the Bleka anticline at Kvamsstøl are metarhyolites with a porphyritic texture. Euhedral phenocrysts (0.5-1 mm in size) of quartz, magnetite and alkali feldspar, often with a core of chessboard albite rimmed by K feldspar, are embedded in a very fine-grained matrix (average grain-size 0.01-0.05 mm) of euhedral magnetite, quartz and feldspars, crowded with flakes of sericitic white mica. Accessories include apatite, and secondary calcite. In places, the rocks show conspicuous nodules, up to about 10 cm across, consisting of concentric shells of alternating quartz and feldspars with sericitic white mica, locally enclosing phenocrysts of quartz and alkalifeldspars They are interpreted as metamorphosed lithophysae (Wyckoff 1933)

Chemistry

Major element compositions are given (Tables 1, 2 and 3) of samples investigated from: (1) Vråvatn, (2) Kvamsstøl and (3) the c. 4.5 km long Bleka anticline section along the Hjartdøla valley studied by Priem et al. (1973). Chemically they are (alkali)rhyolites, some of them very rich in SiO_2. Fig. 3 shows the plot of the major element compositions of the samples in the multicationic R_1-R_2 diagram of de la Roche et al. (e.g. 1980). The data-points of both the Bleka anticline and the Vråvatn samples lie in the field of granitoid rocks of the Postorogenic - Anorogenic Alkaline Suite distinguished in the R_1-R_2 diagram by Batchelor & Bowden (1985), supporting the geotectonic model of Falkum & Petersen (1980). The combined Bleka anticline samples exhibit a linear trend in the alkali-rhyolite - rhyolite field towards extreme SiO_2 contents outside the field occupied by normal rhyolitic rocks. The very

Table 1. Whole-rock major element an alyses (in wt.%) of the Tuddal Formation acid metavolcanics of the Vråvatn locality along road nr. 38 near the junction with the road to Brauti. The R_1-R_2 multicationic values (de la Roche et al. 1980) are also given: $R_1 = 4\,Si - 11(Na + K) - (Fe + Ti)$; $R_2 = 6\,Ca + 2\,Mg + Al$.

	Tel 203-1	Tel 203-2	Tel 203-3	Tel 203-4	Tel 203-5	Tel 203-7	Tel 203-8	Tel 203-10	Tel 203-11
SiO_2	77.16	77.04	76.63	76.99	76.72	79.07	77.79	76.96	77.65
TiO_2	.10	.96	.09	.10	.09	.79	.10	.09	.10
Al_2O_3	11.71	11.67	11.84	11.64	11.68	10.53	11.42	11.56	11.61
Fe_2O_3	1.23	1.32	1.34	1.26	1.24	1.21	1.23	1.40	1.31
MgO	.30	.27	–	.01	.21	.14	.01	.30	.27
CaO	.74	.43	.36	.47	.42	.35	.49	.35	1.10
MnO	.02	.02	.01	.01	.01	.01	.01	.01	.01
Na_2	4.43	4.17	3.88	4.38	4.02	3.59	3.84	3.90	3.54
K_2O	2.45	3.80	4.16	3.50	4.00	3.57	3.50	4.67	2.60
P_2O_5	.01	–	.01	.01	.01	.01	–	.01	.01
Total	98.15	98.80	98.32	98.37	98.40	99.27	98.39	99.25	98.20
R_1	2959	2725	2716	2718	2712	3106	2966	2610	3269
R_2	309	288	271	288	285	250	281	279	359

Table 2. Whole-rock major element analyses (wt. %) of the Tuddal Formation acid metavolcanics at Kvamsstøl. The R_1-R_2 multicationic values (de la Roche et al. 1980) are also given.

	Tel 204	Tel 205	Tel 206	Tel 207	Tel 208	Tel 209	Tel 210	Tel 211	Tel 212	Tel 213	Tel 214
SiO_2	77.54	80.00	79.54	78.14	78.75	78.26	78.62	78.81	78.77	79.78	78.56
TiO_2	.09	.08	.08	.09	.08	.08	.08	.082	.08	.09	.09
Al_2O_3	11.63	10.12	10.60	10.90	10.45	10.85	10.99	10.48	10.31	11.23	11.74
Fe_2O_3	1.11	1.11	.61	1.18	.93	.97	1.04	1.11	1.12	1.23	1.30
MgO	.27	.22	.12	.20	.17	.21	.14	.20	.21	.15	.18
CaO	.05	.13	.10	.09	.08	.13	.05	.11	.07	.18	.11
MnO	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01
Na_2O	1.02	2.28	3.86	1.23	1.66	1.90	1.82	1.78	1.97	1.60	1.32
K_2O	6.73	4.59	3.99	6.49	5.65	5.71	6.35	5.99	6.43	5.47	6.11
P_2O_5	.01	–	–	–	–	–	0.1	–	0.1	–	–
Total	98.46	98.54	98.91	98.33	97.78	98.10	99.11	98.57	98.98	99.74	99.42
R_1	3197	3414	2976	3217	3309	3176	3076	3186	3013	3433	3299
R_2	247	224	225	234	222	237	227	227	220	247	251

Table 4. Rb-Sr whole-rock data of the Tuddal Formation acid volcanics.

Sample Nr.	Rb [ppm Wt]	Sr [ppm Wt]	Rb/Sr [Wt/Wt]	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$
[Vråvatn section road 38 near junction with road to Brautli. UTM ‘588.0-“80.0]					
82 Tel 203-1	70.4	77.1	0.91	0.75302	2.65
82 Tel 203-2	101	63.2	1.60	0.79380	4.67
82 Tel 203-3	122	49.7	2.45	0.83716	7.18
82 Tel 203-4	103	69.5	1.48	0.78853	4.31
82 Tel 203-5	118	61.3	1.92	0.80784	5.61
82 Tel 203-7	105	55.2	1.90	0.80887	5.54
82 Tel 203-8	106	78.5	1.34	0.78158	3.92
82 Tel 203-9	107	73.4	1.45	0.78670	4.24
82 Tel 203-10	105	50.1	2.10	0.82022	6.15
82 Tel 203-11	64.3	146	0.45	0.73006	1.27
mean Rb [ppm] = 100.1 11 18.6 mean Sr [ppm] = 72.4 28.0					
[Bleka-anticline section road Hjartdal-Bjordal at the small suspension bridge over the Hjartdøla river near Kvamsstøl. UTM ‘762.5-“094.0]					
83 Tel 204	284	24.5	11.6	1.3045	35.6
83 Tel 205	186	28.1	6.61	1.0805	19.8
83 Tel 206	158	28.0	5.66	1.0409	16.9
83 Tel 207	279	22.9	12.2	1.3210	37.4
83 Tel 208	223	30.7	7.27	1.1116	21.9
83 Tel 209	230	26.2	8.78	1.1848	26.6
83 Tel 210	258	25.0	10.4	1.2460	31.5
83 Tel 211	249	25.8	9.68	1.2182	29.4
83 Tel 212	248	27.0	9.21	1.1905	27.9
83 Tel 213	231	28.3	8.17	1.1631	24.7
83 Tel 214	262	29.2	8.98	1.1906	27.2
mean Rb [ppm] = 237 ± 38 mean Sr [ppm] = 26.9 ± 2.3					

Table 3. Whole-rock major element analyses (wt.%) of the Tuddal Formation acid metavolcanics of the Bleka anticline investigated by Priem et al. (1973). The R_1-R_2 multicationic values (de la Roche et al. 1980) are also given.

	Tel 1	Tel 2	Tel 3	Tel 4	Tel 5	Tel 6	Tel 7	Tel 8	Tel 9	Tel 10	Tel 11	Tel 12	Tel 14	Tel 16	Tel 17	Tel101	Tel102	Tel103	Tel104	Tel106	Tel107
SiO_2	76.7	77.5	79.4	76.8	76.0	70.4	70.7	70.8	80.8	84.5	80.4	79.5	73.7	75.0	71.8	76.4	77.5	75.6	76.9	76.3	75.9
TiO_2	.08	.20	.15	.22	.21	.51	.51	.51	.08	.05	.17	.06	.23	.25	.27	.11	.10	.10	.08	.09	.10
Al_2O_3	12.3	11.2	10.0	12.4	11.6	14.1	14.2	14.0	9.47	7.29	11.6	10.5	13.2	12.7	14.1	12.2	11.7	12.6	11.9	12.4	12.7
Fe_2O_3	1.52	2.50	2.29	3.23	2.87	3.34	3.17	3.06	1.09	1.16	1.28	1.29	1.40	1.65	3.31	1.29	1.33	1.67	1.46	1.47	1.64
MgO	.11	.14	–	.19	.12	.56	.50	.32	.10	.16	.41	–	.26	.48	.41	.14	–	.20	.05	–	.08
CaO	.19	.16	.11	.18	.21	.85	.90	.99	.13	.42	.18	.08	.39	.22	.11	.17	.06	.23	.13	.14	.11
MnO	–	–	.02	–	–	–	–	–	.01	.02	–	.01	–	–	–	–	–	–	–	–	–
Na_2O	5.34	1.44	1.62	.36	3.57	3.92	3.60	3.39	2.00	.00	.53	1.53	2.48	2.13	3.38	2.62	3.58	2.21	3.75	4.92	4.29
K_2O	2.88	5.94	4.61	5.69	4.45	5.29	5.39	5.92	4.45	3.90	4.60	5.61	7.44	6.61	5.65	6.08	4.81	6.47	4.74	3.80	4.27
P_2O_5	.03	.01	–	–	–	.10	.10	.09	–	.01	.01	–	.02	.02	.01	–	.01	.03	–	.01	.01
Total	99.15	99.09	98.20	99.07	99.03	99.07	99.07	99.08	98.13	97.51	99.18	98.58	99.12	99.06	99.04	99.05	99.09	99.11	99.01	99.13	99.10
R_1	2501	3200	3571	3563	2683	1974	2082	2039	3603	4684	4051	3404	2244	2645	2178	2696	2726	2700	2640	2402	2500
R_2	265	244	207	262	258	392	399	399	204	197	266	214	313	257	309	263	236	285	247	261	265

high SiO_2 values, up to about 85 wt % for some of the combined samples from the Bleka anticline, might indicate that silica was introduced into some rocks. Silicification is a common feature of low- to medium-grade acid volcanics.

The Kvamsstøl samples are significantly higher in Rb and lower in Sr than the Vråvatn samples (Table 4). The major element compositions of these two sets of samples do not differ significantly, except for K_2O: the Kvamsstøl samples are higher in K_2O. It is also considered possible that the high K_2O and Rb contents were caused by metasomatic processes that operated in the region of the Bleka anticline, although a high Rb content in itself does not seem to be an unusual feature for acid volcanics (e.g. Hildreth 1981, Bacon et al. 1981). Because samples of acid volcanics high in Rb and K_2O often plot well inside the igneous spectrum (Hughes 1973), they may thus, on these grounds alone, not be regarded as metasomatized rocks. In Fig. 4 all but one of the Kvamsstøl samples plot to the right of the igneous spectrum, suggesting that the investigated rocks are metasomatic and enriched in K_2O and therefore probably also in Rb. The amounts of metasomatically added Rb are probably similar for all the samples, as indicated by the relatively low standard deviation of the mean, 237±38 ppm. The Vråvatn rocks, however, plot inside the igneous spectrum; thus, metasomatic introduction of K and Rb is not indicated.

The Vråvatn samples have practically identical Al_2O_3 contents and their content of MgO is very low. R_2 is thus an expression of the CaO content, mainly in the form of secondary calcite. It is probable that also Sr has been introduced into these rocks. The amounts of Sr must have differed substantially in view of the high standard deviation of the mean, 72.4 ± 28 ppm.

The Vråvatn samples highest in CaO and Sr (82 Tel 203-11) and the Kvamsstøl sample highest in K_2O and Rb (83 Tel 204) have been selected to quantify their possible metasomatic modification using the graphical method of Beswick & Soucie (1978). Values obtained in this way depend on a number of assumptions. The principal assumption is that the tightly-defined trends obtained by compiling 543 chemical analyses of unaltered post-Mesozoic rocks of rhyolitic to basaltic composition in logarithmic molecular proportion ratio diagrams (LMPR plots) are typical for unaltered volcanics in general. Furthermore, Beswick & Soucie (1978) have assumed that during metasomatism Al_2O_3 remains constant.

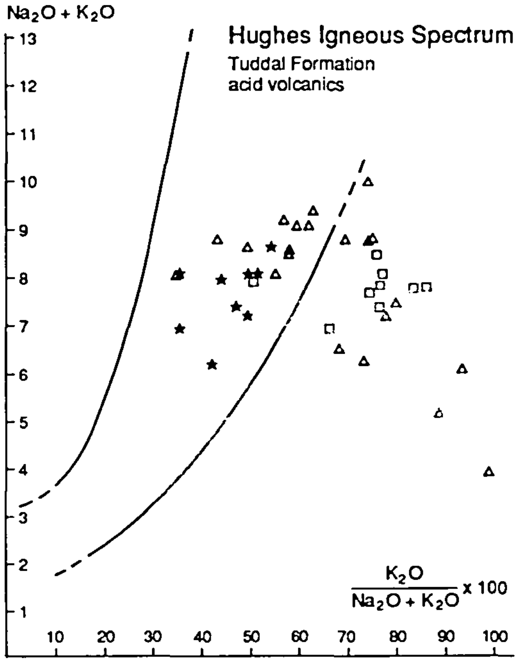

Fig. 4. The acid metavolcanics of the Tuddal Formation plotted in a Hughes igneous spectrum diagram. Triangles: acid metavolcanics from the Bleka anticline section investigated by Priem et al. (1973). Squares: acid metavolcanics from the Bleka anticline section at Kvamsstøl. Asterisks: acid metavolcanics from the Vråvatn locality.

According to Beswick & Soucie's graphical method, the initial precursor of the Vrvatn rock 82 Tel 203-11 has been enriched in SiO_2 by 60 %, depleted in CaO by 60 % and in Fm (FeO + MgO + MnO) by 60 %, while Na_2O and K_2O remained constant. The total mass should have increased by 35 - 40 %, largely due to silicification. Such mass changes are not excessive if they occur shortly after deposition.

If the method is applied to the Kvamsstøl sample 83 Tel 204 the initial precursor of this rock has been enriched in SiO_2 by 60 %, in K_2O by 125 %, and depleted in Na_2O by 65 %, in CaO by 97 % and in Fm (FeO + MgO + MnO) by 40 %. The total mass should have increased by 35 - 40 %, largely due to silicification.

Results

The Rb-Sr analytical data are listed in Table 4 and isochron plots are shown in Figs. 5 and 6. The following geochronological data were obtained:

1) The 11 samples from the Bleka anticline at Kvamsstøl define a Sveconorwegian errorchron (MSWD = 9.3) with an age of 0.98±0.05 Ga and ^{87}Sr/^{86}Sr(i) of 0.8049±0.0162, at 95% confidence level (Fig. 5).

2) The 10 samples from Vråvatn, define a Gothian errorchron (MSWD = 13.3) with an age of 1.29±0.06 Ga and ^{87}Sr/^{86}Sr(i) of 0.7064±0.0036, at 95 % confidence level (Fig. 6).

Discussion

Clearly, the results of the present study do not provide unambiguous answers to the questions put forward in the objectives.

(1) Both suites of samples, from Vråvatn and Kvamsstøl, are fairly well aligned in an isochron plot. However, notwithstanding the closer-spaced sampling of the former suite the alignment of the data is poorer than that of the latter. Evidently, a tight-spaced sampling strategy, although minimizing possible differences in 87Sr/86Sr(i), does not in all cases ensure a better alignment of the datapoints. The extremely high ^{87}Sr/^{86}Sr(i) of 0.8049±0.0162 for the Kvamsstøl samples might signal metasomatic introduction of radiogenic ^{87}Sr into Gothian acid volcanics about 0.98 Ga ago. However, for the Kvamsstøl rocks the rather good alignment of the data-points in the isochron diagram makes introduction of radiogenic ^{87}Sr in Sveconorwegian time highly improbable. The alignment of the Kvamsstøl data could have been achieved only if each sample gained exactly the right amount of ^{87}Sr to produce such an alignment and this seems very unlikely. Metasomatic introduction of varying amounts of Rb in Gothian times during or shortly after deposition of the acid volcanics, followed by a nearly complete isotopic equilibration of the whole-rock systems in Sveconorwegian times about 0.98 Ga ago, could therefore be a more plausible explanation for the high initial ^{87}Sr/^{86}Sr ratio. A possible sequence of events in the isotopic history of the Kvamsstøl rocks is sketched in Fig. 7.

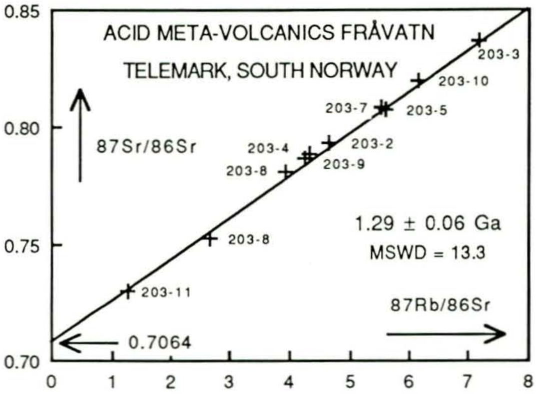

Fig. 5. Isochron plot of the Tuddal Formation acid metavolcanics from the Bleka anticline at Kvamsstøl.

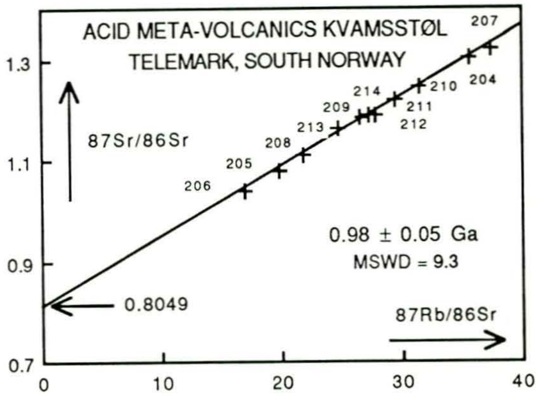

Fig. 6. Isochron plot of the Tuddal Formation acid metavolcanics from the Vråvatn locality.

The considerable spread of the data-points of the Bleka acid metavolcanics in the cumulative isochron diagram (Fig. 2), may partly be caused by introduction of varying amounts of Rb after deposition. The 1.60 Ga upper boundary line of Priem et al. (1973) might be related to the assumption that some samples had a too low ^{87}Sr/^{86}Sr(i). The 87Sr/86Sr(i) values of all Bleka anticline acid metavolcanics of the Rjukan Group have a wide range in the order of 0.702 to 0.805.

Metasomatic introduction of K_2O in the combined samples from the Bleka anticline at Kvamsstøl and in those of Priem et al. (1973) is indicated by the location (Fig. 4) of some of the samples (squares and triangles) to the right side of the igneous spectrum. The cluster of the Bleka samples at Kvamsstøl investi-

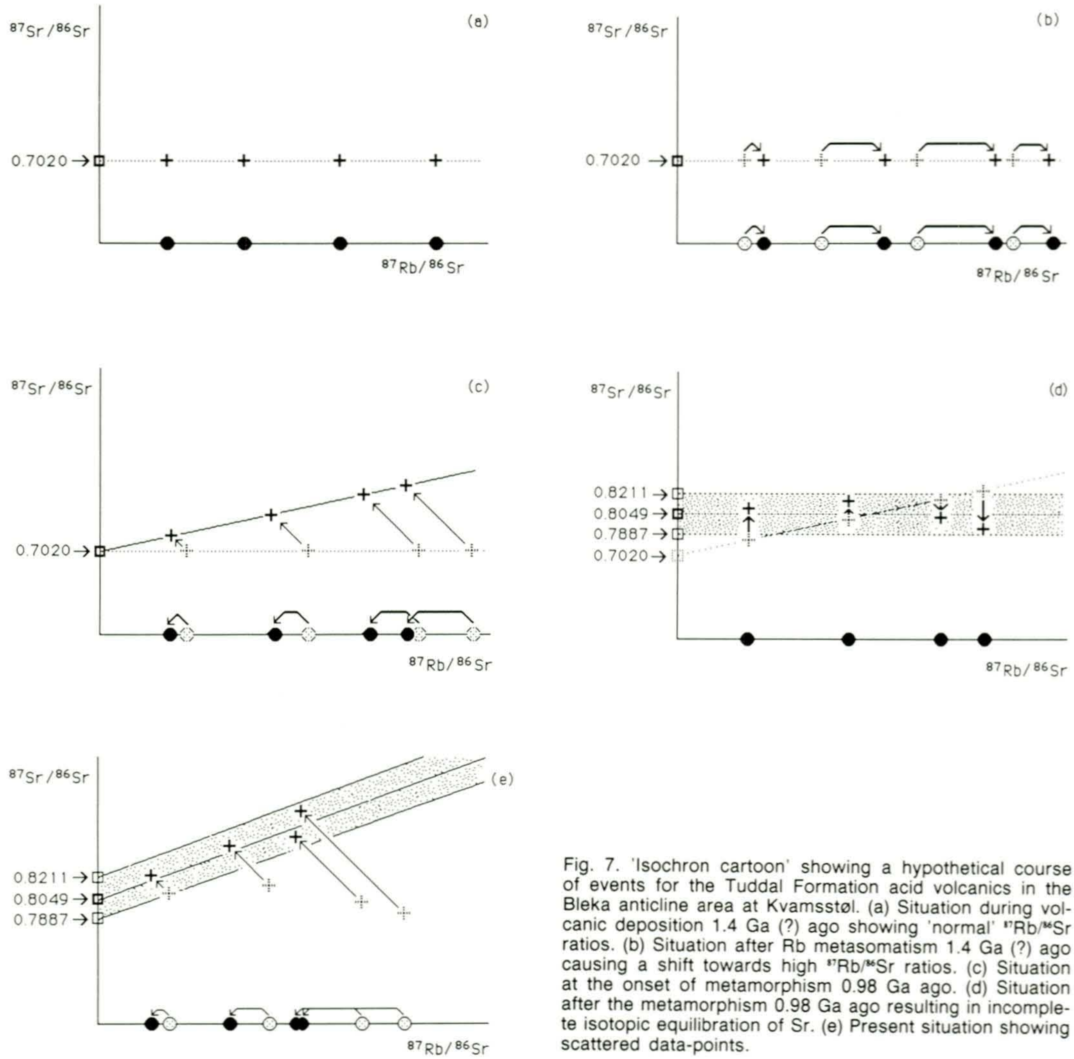

Fig. 7. 'Isochron cartoon' showing a hypothetical course of events for the Tuddal Formation acid volcanics in the Bleka anticline area at Kvamsstøl. (a) Situation during volcanic deposition 1.4 Ga (?) ago showing 'normal' ^{87}Rb/^{86}Sr ratios. (b) Situation after Rb metasomatism 1.4 Ga (?) ago causing a shift towards high ^{87}Rb/^{86}Sr ratios. (c) Situation at the onset of metamorphism 0.98 Ga ago. (d) Situation after the metamorphism 0.98 Ga ago resulting in incomplete isotopic equilibration of Sr. (e) Present situation showing scattered data-points.

gated in this study (squares) is indicative of the replacement of sodium by potassium. For the samples investigated by Priem et al. (1973) (triangles) there is a slight downward trend, indicating a net loss of sodium over potassium. It is striking that the 1.60 Ga upper boundary line is mainly based on sample 69 Tel 10 that shows the most extreme K-metasomatism in Fig. 4. Therefore, sample 69 Tel 10 probably has a much higher ^{87}Sr/^{86}Sr(i) and consequently a much lower age than was calculated by Priem et al. (1973). As a consequence, the 1.60 Ga value for the depositional age of the acid Rjukan volcanics is probably not valid.

A Rb-Sr model age-calculation of the Kvamsstøl samples, assuming (1) Rb introduction during or shortly after the deposition of the volcanics and (2) an initial ^{87}Sr/^{86}Sr ratio of 0.705, would result in an age within the 1.12 - 1.39 Ga bracket. Priem et al.'s (1973) assumed age of about 1.60 Ga for the Rjukan Group is not substantiated. It is evident that the depositional age of the Telemark Supracrustal Suite remains enigmatic. The depositional age of the Rjukan Group may or may not be of the order of 1.30 Ga, depending on the weight assigned to the model-age calculation of the Kvamsstøl samples and the best-fit age

Table 5. UTM coordinates of the investigated samples.

Sample no.	*UTM coordinates*
Mapsheet 1614 III Hjartdal	
Tel 1	7675 1255
Tel 2	7695 1255
Tel 3	7685 1085
Tel 4	7685 1080
Tel 5	7685 1040
Tel 6	7680 0940
Tel 7	7710 0965
Tel 8	7710 0960
Tel 9	7725 0940
Tel 10	7735 0935
Tel 11	7745 0925
Tel 12	7755 0920
Tel 14	7830 0900
Tel 16	8740 0895
Tel 17	7850 0885
Tel 101	7675 1255
Tel 102	7675 1255
Tel 103	7680 1260
Tel 104	7670 1270
Tel 106	7670 1265
Tel 107	7670 1265
Tel 204 to Tel 214	7625 0940
Mapsheet 1513 I Bandak	
Tel 203-1 to Tel 203-11	5880 8010

of about 1.30 Ga obtained for the Vråvatn samples.

(2) Sveconorwegian isotopic reworking of the Vråvatn samples, situated close to the Telemark gneisses, which themselves apparently underwent complete isotopic reworking about 1.11 Ga ago, seems improbable in view of the Gothian errorchron age of 1.29±0.06 Ga. This age relationship is presently one of the major problems regarding the metamorphic history of southern Norway.

(3) Although the Kvamsstøl samples reflect an addition of K_2O and stem from a low-grade metamorphic area, they yield a lower apparent age than those from Vråvatn with a higher degree of metamorphism. A possible inheritance of radiogenic ^{87}Sr from older crustal material appears to be improbable in view of the 'normal' 87Sr/86Sr(i) ratio of the Vråvatn samples from the same (Tuddal) Formation.

The results of the present study are in accordance with many earlier observations (e.g. Cormier 1969, Fairbairn & Hurley 1970, Råheim & Compston 1977, Priem et al. 1978, Black et al. 1979, Page 1978, Field & Råheim 1979, 1980, Brattli et al. 1983, Cliff et al. 1985) that Rb-Sr dating of acid volcanic rocks often produces false isochrons, or isochrons that approach the time of metamorphism. It seems plausible that pre-metamorphic metasomatic introduction of alkalies may play an important role. Consequently, in Rb-Sr studies rocks should be checked petrographically and chemically for possible alkali metasomatism. Premetamorphic metasomatic introduction of Rb might also explain the puzzling stooped isochron plots (e.g. Cormier 1969, Fairbairn & Hurley 1970). Such plots may, for the lower ^{87}Rb/^{86}Sr ratios, provide an approximation for the age of the magmatism/metasomatism, and for the higher ^{87}Rb/^{86}Sr ratios an approximation of the age of the metamorphism (Bell & Blenkinsop 1978). The variation in the ^{87}Sr/^{86}Sr(i) ratios may also be gleaned from them.

Isotopic dating of metamorphosed rocks is dependent on the isotopic equilibration distance, which in itself depends on various parameters, e.g., porosity and permeability, deformation, metamorphic grade, rock-type, and the time-temperature path. Hofmann (1979) speculated about the inverse relation between metamorphic temperatures and the range of isotopic equilibration due to moving fluids. If the sampling range is in the order millimetre-metre, the dating of minerals and thin rock slabs normally reflects the latest phase of metamorphism. This type of isochron could be called an 'internal isochron'. Hofmann (1979) considered that the 'slab method' was most promising in dating migmatites, where the presence of a partial melt has equilibrated the rock over distances of up to one metre. Locally, in such 'micro-range' sampling studies, relict mineral components may have remained undisturbed and therefore disclose an age older than the latest metamorphism (e.g. Hebeda et al. 1980). Apparently, radiogenic ^{87}Sr is redistributed only between newly-formed minerals (Verschure et al. 1980). In the case of a 'meso-range' sampling, metre-hectometre ('normal isochron') whole-rock dating often reflects an earlier state of isotopic equilibrium, i.e. an earlier metamorphic, or even an 'initial' igneous or sedimentary petrogenetic event. Between samples in the 'macro-range', hectometre-megametre, isotopic equilibration is nonexistent. However, the best fit of the mean values of separate isochrons from an area of tens of kilometres ('areal isochron') seems to indicate an earlier petrogenetic event (Köhler & Müller-Sohnius 1980, 1985). Therefore, it is possible that such macro-range 'areal sampling' in the case of the acid volcanics of the Telemark Supracrustal Suite might disclose traces of an earlier, possibly magmatic, petrogenetic event. The errorchron that can be drawn through the mean ^{87}Sr/^{86}Sr and ^{87}Rb/^{86}Sr values of the combined errorchrons obtained for the Tuddal rocks (Fig. 2) yields an age of about 1.3 Ga. This errorchron could very well represent a Gothian areal isochron revealing the age of the Rjukan Group acid volcanism.

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Appendix

Experimental procedures and constants

Major elements, Rb and Sr contents and Rb/Sr ratios were measured by X-ray-fluorescence spectrometry on pressed-powder pellets (major elements on beads) using a Philips PW 1450/AHP automatic spectrometer. Mass-absorption corrections for both sample and external standard are based upon the Compton scattering of the Mo-Ka primary beam (Verdurmen 1977). The isotopic composition of Sr was measured directly on unspiked Sr for the whole-rocks. The Rb and Sr isotope analyses of the Vråvatn samples were carried out on a computer-controlled Varian-Mat CH5 mass-spectrometer, the samples from the Bleka anticline were measured on a Finnigan-Mat 261 mass-spectrometer with multiple cage collector and digital output. Analytical uncertainties are estimated to be within 0.5% for XRF Rb/Sr, 0.05 % for ^{87}Sr/^{86}Sr with the Varian-Mat CH5, and 0.03 % for ^{87}Sr/^{86}Sr with the Finnigan-Mat 261. *These estimated overall limits of relative error are the sum* of the known sources of possible systematic error and the precision of the total analytical procedures. Best-fit lines through the Rb-Sr data-points were calculated by means of a least-squares regression analysis according to York (1966, 1967). Errors in the isochron ages and initial ^{87}Sr/^{86}Sr ratios are given at the 95 % confidence level. The age *calculations are based upon the constant* ^{87}*Rb* = 1.42 x $10^{-11}a^{-1}$.

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