# Devonian ages from $^{40}Ar/^{39}Ar$ dating of plagioclase in dolerite dykes, eastern Varanger Peninsula, North Norway

PHILIP G. GUISE & DAVID ROBERTS*

Guise, P. G. & Roberts, D. 2002: Devonian ages from $^{40}Ar/^{39}Ar$ dating of plagioclase in dolerite dykes, eastern Varanger Peninsula, North Norway. *Norges geologiske undersøkelse 440*, 27-37.

Gas-release spectra derived from the analysis of plagioclase from three geographically distinct but geochemically comparable dolerite dykes from the eastern part of Varanger Peninsula, northern Norway, show similar features and favour an interpretation that the dykes were intruded in Late Devonian time at around 370 Ma. These particular dykes had previously yielded fairly similar, K-Ar whole-rock ages. As one of the dykes had earlier been traced into the Trollfjorden-Komagelva Fault Zone with the aid of a proton-magnetometer, this would indicate that all significant, displacive movement along this major fault zone had ceased by latest Devonian time. The dyke ages reported here fit into a known pattern of Mid Devonian to Early Carboniferous rifting and sporadic mafic magmatism reported from adjacent parts of Kola Peninsula and neighbouring areas along the northeastern margin of the Fennoscandian Shield.

*P.G.Guise, Department of Earth Sciences, University of Leeds, Leeds LS2 9JT, England, UK (Present address:- 56 Station Road, Tadcaster, North Yorkshire, Leeds LS24 9JR, England, UK).*
*D.Roberts, Norges geologiske undersøkelse, 7491 Trondheim, Norway.*
** - Corresponding author: E-mail -- david.roberts@ngu.no*

## Introduction

In the Caledonides of Scandinavia, many of the lithostratigraphical successions in diverse thrust sheets are intruded by mafic dykes. Occurring either in isolation or, in a few places, in swarms, dykes of this type generally relate to important phases of crustal extension and/or rift magmatism or, less commonly, to late-stage emplacements along joints or faults in compressional regimes. Subtle variations in chemical composition also allow for fair assessments to be made of the likely palaeotectonic settings of these hypabyssal rocks. In the few cases where isotopic ages are available, these serve as a bonus in helping us to define the local geological history with greater precision.

On Varanger Peninsula in Finnmark, in the extreme northeast of Norway (Fig. 1), the only sign of igneous activity is provided by dolerite dykes that cut Riphean to Vendian lithostratigraphic successions exposed on either side of the major, WNW-ESE trending, Trollfjorden-Komagelva Fault Zone (TKFZ). The geology of this peninsula is now well known through the systematic mapping and stratigraphic and sedimentological studies of Siedlecka & Siedlecki (1967) and Siedlecki (1980), summarised in Siedlecka & Roberts (1992). However, isotopic dating studies on the dykes of the peninsula have been few.

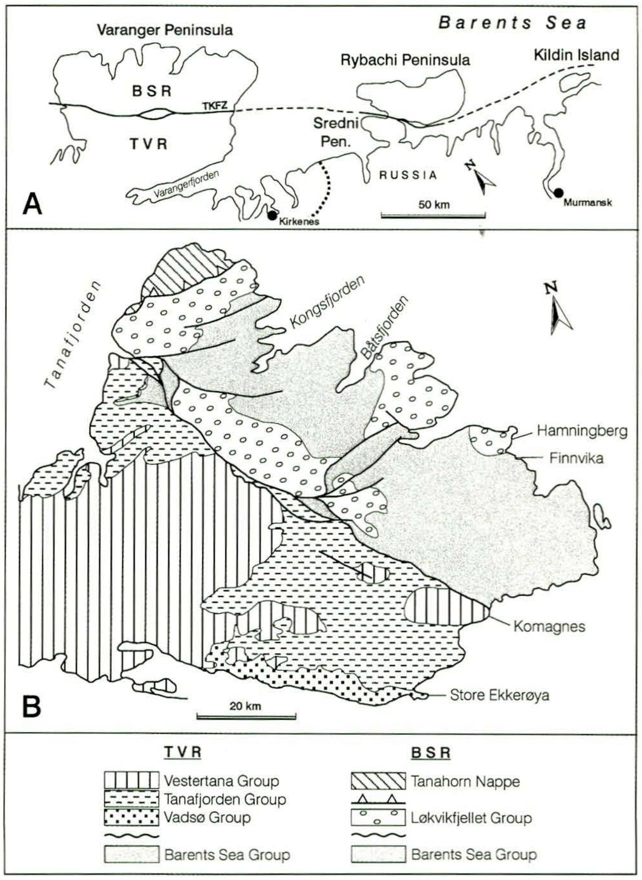


Fig. 1. (a) Outline map showing the location of the Rybachi and Sredni Peninsulas in relation to Varanger Peninsula. BSR – Barents Sea Region; TVR – Tanafjorden-Varangerfjorden Region; TKFZ – Trollfjorden-Komagelva Fault Zone. (b) Much simplified geological map of Varanger Peninsula, showing the locations of the studied dykes at Finnvika, Komagnes and Store Ekkerøya. Separate simplified legends are shown for the TVR and BSR. Major faults are indicated by continuous thick lines.

A K-Ar whole-rock investigation of dolerite/metadolerite dykes from different areas on the peninsula by Beckinsale et al. (1975) is the only detailed work published so far. Other investigations restricted to particular dykes are those of Roberts et al. (1995) and Roberts & Walker (1997). There have also been studies dealing with palaeomagnetic dating of certain dykes (Knutsen 1995, Torsvik et al. 1995).

In this contribution, we present the results of a $^{40}Ar/^{39}Ar$ investigation of plagioclase separated from two prominent dolerite dykes from the southeastern part of Varanger Peninsula, south of the TKFZ, one of which has earlier yielded disparate K-Ar and palaeomagnetic ages – Late Devonian and Vendian, respectively. The $^{40}Ar/^{39}Ar$ analytical data, in our view, help to resolve these differences. We also present plagioclase analytical data from another dyke, sampled from north of the TKFZ. All three dykes have given similar plateau ages.

## Geological setting

Our knowledge of the Neoproterozoic-Early Palaeozoic geological evolution of Varanger Peninsula derives from diverse, detailed investigations of lithostratigraphy, tectonic structure, low-grade metamorphism, micropalaeontology and remote sensing applications. Specific accounts or reviews include those of Siedlecka & Siedlecki (1967, 1971), Banks et al. (1971), Roberts (1972), Siedlecka (1975), Johnson et al. (1978), Pickering (1981), Taylor & Pickering (1981), Vidal (1981), Edwards (1984), Bevins et al. (1986), Rice et al. (1989), Karpuz et al. (1993), Rice (1994), Rice & Reiz (1994) and Laajoki (2002). In addition, the effects of Timanian deformation in the easternmost parts of Varanger Peninsula has been discussed by Roberts (1995, 1996).

The Trollfjorden-Komagelva Fault Zone provides a natural, structural divide, separating the peninsula into a northeastern *Barents Sea Region (BSR)* and a southwestern *Tanafjorden-Varangerfjorden Region (TVR)*. The established, formal lithostratigraphies for the two regions are presented in Fig. 2. Although details do not concern us here, the TVR has been termed a *pericratonic* sedimentation domain and the BSR a *basinal* domain (Siedlecka & Roberts 1995), with reference to the developing, northeastern passive margin of Baltica in Riphean-Vendian time (Olovyanishnikov et al. 2000, Roberts & Siedlecka 2002). Importantly, the critical stratigraphic relationship between the two domains, involving an unconformity where the Ekkerøya Formation lies directly upon a steeper dipping Båtsfjord Formation, has been described by Rice (1994) from one small area in western Varanger Peninsula. This unconformity has also been documented by Roberts & Karpuz (1995).

Dolerite dykes are particularly common in certain parts of the Barents Sea Region, especially in northwestern and central areas. On the contrary, dykes are extremely rare in the TVR. Based on their K-Ar results, Beckinsale et al. (1975) distinguished two principal groups of dyke ages: (A) c. 360 Ma, and (B) c. 650 Ma (both ages recalculated after Dalrymple 1979); and a third group (C) of strongly cleaved dykes with questionable 'ages' of 945 to >1900 Ma. Dykes of age-groups B and C are restricted to the rocks of the BSR, whereas the far less common group A dykes occur on either side of the Trollfjorden-Komagelva Fault Zone. Later, unpublished work by Beckinsale (pers. comm. 1977) tended to favour an age closer to 550-560 Ma for the dykes of Group B. Palaeomagnetic studies by Knutsen (1995) also supported a Vendian age. An attempt to provide better age constraints for the dykes of Group A by application of the $^{40}Ar/^{39}Ar$ method to pyroxenes (Roberts et al. 1995) was not success-

1

| Age | Lithostratigraphic units and their thicknesses | | |
|---|---|---|---|
| | | Formation | Member |
| UPPER RIPHEAN | TANAFJORDEN GROUP 1448- 1665m | Grasdalen 280 m | Upper<br>Lower |
| | | Hangleĉærro 200 m | |
| | | Vagge 80 m | |
| | | Gamasfjellet 280-300 m | |
| | | Dakkovarre 273-350 m | Ferruginous sandstone 130 m<br>'k' member 62 m<br>'j' member 46 m<br>'i' member 35 m<br>Quartzitic sandstone 60-80 m |
| | | Stangenes 205-255 m | |
| | | Grønneset 130-200 m | |
| | VADSØ GROUP, 590 - 960 m | Ekkerøya 15-190 m | ★ V8 |
| | | Golneselva 50-135 m | |
| | | Paddeby 25-120 m | |
| | | Andersby 25-40 m | |
| | | Fugleberget 125 m | |
| | | Klubbnasen 50 m | |
| | | Veinesbotn 300 m | |

2

| Age | Lithostratigraphic units and their thicknesses | | |
|---|---|---|---|
| | | Formation | Member |
| CAMBRIAN - ORDOVICIAN | DIGERMULEN GROUP 1510 - 1555 m | Berlogaissa 300 m | |
| | | Kistedalen 710-735 m | Grey quartzite 200 m<br>Black shale 200 m<br>Black quartzite 10-35 m<br>Sandstone and shale 200 m<br>Quartzite and shale 100m |
| | | Duolbasgaissa 500-520 m | Massive bedded quartzite 300 m<br>Thin-bedded quartzite 200-220 m |
| | VESTERTANA GROUP 1317 - 1655 m | Breivika 600 m | |
| VENDIAN | | Stappogjedde 505-545 m ★ V1 | Manndrapselva 190 m<br>Innerelva 275 m<br>Lillevatnet 40-80 m |
| | | Mortensnes 10-60 m | |
| | | Nyborg 200-400 m | |
| | | Smalfjord 2-50 m | |

3

| Age | Lithostratigraphic units and their thicknesses | | |
|---|---|---|---|
| | | Formation | Member |
| RIPHEAN - VENDIAN | LØKVIKFJELLET GROUP 5710 - 5810 m | Skidnefjellet >800 m | |
| | | Stordalselva 1200 m | |
| | | Skjærgårdsneset 210 m | |
| | | Styret 1500-1600 m | |
| | | Sandfjorden 2000 m | |
| | BARENTS SEA GROUP 8900 - 10 000 m | Tyvjofjellet 1500 m | |
| | | Båtsfjord 1400-1600 m | Skovika 1100-1300 m<br>Annijokka 300 m |
| | | Båsnæringen 2500-3500 m | Hestman 600-1300 m<br>Godkeila 490-1450 m<br>Seglodden 100-350 m<br>Næringselva 500-1200 m |
| | | Kongsfjord >3500 m ★ V4 | Nålneset 2000 m / Risfjorden 1000-1500 m |

Fig. 2. Lithostratigraphic successions, Varanger Peninsula, showing the locations of the investigated samples of dolerite dykes, V1, V4 and V8. Columns 1 and 2 are from the Tanafjorden-Varangerfjorden Region, southwest of the TKFZ (Fig. 1), and column 3 from the Barents Sea Region, northeast of the fault zone.

ful, though the dataset did show a slight bias towards a possible Devono-Carboniferous age.

The Group C dykes, generally termed metadolerites, are particularly common in the Kongsfjord district (Fig. 1). They carry a penetrative cleavage which is also axial planar to abundant ENE-WSW-trending folds in the country rocks (Roberts 1972, Rice & Reiz 1994), and many of the dykes are boudinaged. One of these Kongsfjord dykes has been dated by the Sm-Nd method to around 550 Ma (data attributed to B.Sundvoll in Andersen & Sundvoll, 1995).

Group B dykes are most profuse in the Båtsfjord area (Fig.1). They are very weakly cleaved, a cleavage which is again parallel to the axial surfaces of open to tight folds in the host metasedimentary rocks. The dykes, cleavage and fold axes all trend approximately ENE-WSW. The Group A dolerites are comparatively fresh and either unmetamorphosed or very slightly altered. They generally trend between N-S and NE-SW.

Geochemically, the Group C metadolerites carry signatures quite close to those of abyssal tholeiites, though somewhat transitional to a continental margin regime (Roberts 1975). The Group A dolerites, on the other hand, have chemical features more akin to those of continental tholeiites developed in a plate-marginal rather than continental interior situation. Some unpublished geochemical data do exist for dykes of Group B (D.Roberts, in prep.), indicating that they are of transitional, oceanic/continental tholeiite character.

In addition to the above, it should be mentioned that just one dolerite dyke sampled from the eastern side of Båtsfjorden has provided indications of a considerably younger age. Based on preliminary Sm-Nd and Rb-Sr analytical data, this particular dyke may possibly have been emplaced during the Jurassic period (B.Sundvoll, written communication 1991).

A few dolerite dykes also occur on the nearby Rybachi and Sredni Peninsulas in NW Russia (Fig. 1a), cutting lithostratigraphical successions that are comparable to those on Varanger Peninsula (Polkanov 1935, Sinitsin 1967, Bekker et al. 1976, Lyubtsov et al. 2000); and similar dykes are also present on the adjacent mainland of the Kola Peninsula cutting Archaean and Palaeoproterozoic gneisses (Fieandt 1912, Hausen 1932, Fedotov & Amelin 1998). Some of these Kola dykes have yielded Vendian ages, whereas others are latest Devonian (Juve et al. 1995, Roberts & Onstott 1995, V. Negrutsa, pers. comm. 1991) to Early Carboniferous (Fedotov & Amelin 1998). In one case, on Rybachi, there is conflicting evidence from $^{40}Ar/^{39}Ar$ and palaeomagnetic dating of one particular swarm of mafic dykes, where either Vendian or Devonian ages have been suggested (cf. Torsvik et al. 1995, Roberts & Onstott 1995).

## The investigated dolerite dykes

The dykes investigated in this argon-dating study occur in the TVR near Komagnes (sample V1) and on the island of Store Ekkerøya (V8), and in the BSR close to the small bay Finnvika (V4) (Fig. 1). Their locations in the lithostratigraphical successions are shown in Fig. 2. Although Beckinsale et

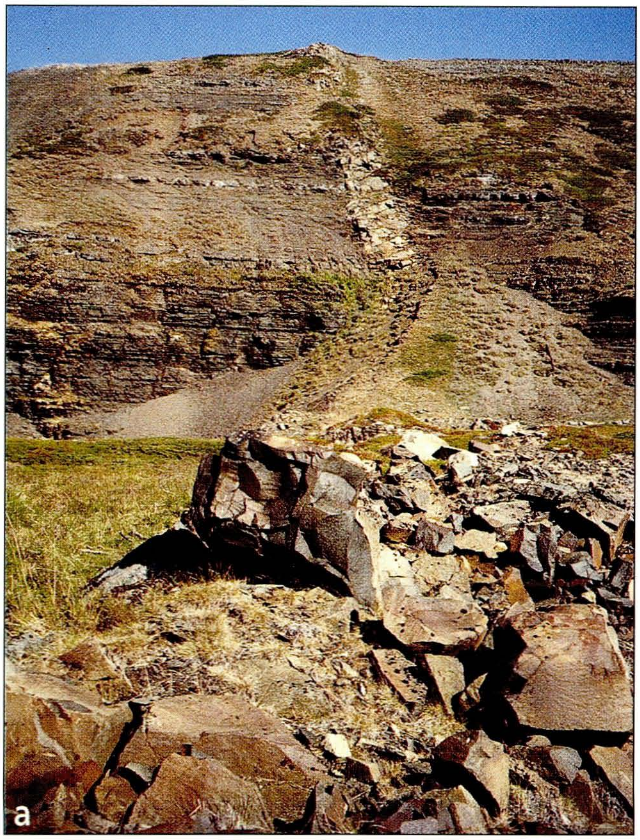

Fig. 3. (a) The dolerite dyke just west of Komagnes, cutting thin-bedded shales and mudstones of the Innerelva Member of the Stappogiedde Formation; photo looking almost due north. (b) Foreshore exposure of the dolerite dyke just northwest of Finnvika, cutting low-grade, turbiditic sedimentary rocks of the Kongsfjord Formation, Barents Sea Group.

al. (1975) did not give any precise sampling localities, it seems reasonably certain that all three dykes analysed for the present study belong to their Group A classification, i.e., with K-Ar whole-rock ages of around 360 Ma. With reference to the sample numbers V1, V4 and V8, these appear to correspond to samples R12, R51 and M10 of Beckinsale et al. (1975; cf. their fig.1 and table 1).

# Field relationships

## Komagnes dyke

This c. 2.5 m-thick dyke is easy to detect in the old, raised cliff Giviaida, north of the main road, c. 1 km west of the promontory Komagnes (Fig. 3), on 1:50,000 map-sheet 2435 II Ekkerøy (4-NOR edition, grid-reference 038 910). The dyke trends c. N-S and dips at 75° east, and cuts through flat-lying, thin-bedded, blue-green shales and reddish-grey mudstones of the Innerelva Member of the Late Vendian, Stappogiedde Formation, the highest part of the Vestertana Group (Siedlecka & Roberts 1992) (Fig. 2). Another, similar, 40 cm-thick dolerite dyke is present in the same raised cliff c. 150 m west of the main dyke, but this is not considered further here.

Closer inspection reveals that the Komagnes dyke in the cliff-face really consists of two parallel dykes with a thin screen of hornfelsed sediment in between. Towards the foreshore, and in the intertidal zone, the dyke (or composite dyke) is nearer to vertical and even west-dipping, and splits into several thinner dykes with offshoots which locally curve into a bedding-parallel orientation. Adjacent to the dyke, or dykes, a near-vertical, widely spaced fracture cleavage is present in the hornfelsed shales. The Innerelva Member otherwise shows little effects of tectonic deformation. There is a good compactional fabric in the shales, however, and this burial diagenetic event has been dated (Rb-Sr on illite subfractions) to c. 560 Ma (Gorokhov et al. 2001).

In thin-sections of the dyke, a uniform mineralogy is dominated by plagioclase and clinopyroxene with ophitic to subophitic texture. The plagioclase is andesine to labradorite and locally shows oscillatory zoning, and the clinopyroxene shows the optical properties of pigeonite (Roberts 1975). Accessory minerals are (titano)magnetite, apatite, rare calcite and traces of interstitial or pyroxene-marginal chlorite. The feldspar shows only incipient stages of sericitisation.

## Finnvika dyke

This 9-9.5 m-thick dyke is located c.1 km northwest of Finnvika on the northern coast of Varanger Peninsula (Fig. 1); on 1:50,000 map-sheet 2436 II Syltefjord (4-NOR edition, grid-reference 108 235). The dyke trends between NE-SW and ENE-WSW and here dips at c. 75° southeast, cutting through thick-bedded, immature sandstones and intercalated, cleaved shaly units of the low-grade, turbiditic Kongsfjord Formation, the lowest stratigraphic unit of the Barents Sea Group (Figs. 2 & 3).

The dyke contacts are subparallel to bedding, but in the foreshore exposures the dyke locally transects bedding at a low angle in a left-stepping sense before resuming a bedding-parallel attitude. Cleavage in the pelites varies between vertical and east-southeast dip orientations. The dyke shows no evidence of deformation or metamorphism, other than small offsets along WNW-ESE faults, and clearly postdates the pervasive cleavage and some related, small-scale upright folds. In this same general area and same formation, Taylor & Pickering (1981) reported a Rb-Sr whole-rock isochron age of 520 ± 47 Ma on cleaved mudstones, interpreted to date the folding and associated axial-surface cleavage.

Petrographically, the Finnvika dyke is similar to the one from Komagnes, with plagioclase and clinopyroxene showing subophitic texture; and the feldspar looks to be quite fresh.

## Store Ekkerøya dyke

A near-vertical, N-S-trending dolerite dyke reaching up to 16 m in thickness cuts through gently NE-dipping strata of the Ekkerøya Formation, the highest unit of the Vadsø Group, in the southwestern part of the island of Store Ekkerøya (Figs. 1 & 2). The sampling locality is on 1:50,000 map-sheet 2435 II Ekkerøy (4-NOR edition) at grid reference 890 774. The dyke is particularly prominent in the cliffs at Flågan, a nature reserve and bird colony. The Ekkerøya Formation here consists of medium-bedded sandstone and subordinate conglomerate with intercalations of siltstone and mudstone (Siedlecka & Roberts 1992), and is devoid of cleavage or folds.

In thin-section, the central part of the Store Ekkerøya dyke is coarser grained than the other two dolerite dykes and varies in texture from ophitic to locally glomeroporphyritic, with the plagioclase laths occurring in scattered clusters up to 3.5-4 mm across. Both these feldspar clusters and the normal, individual laths show variable degrees of sericitisation. Nearer the dyke margins, grain size is comparable to that in the Komagnes and Finnvika dyke samples, and sericitisation is more advanced. The mineral paragenesis is otherwise the same as for the Komagnes and Finnvika dykes.

# $^{40}$Ar/$^{39}$Ar dating

## Analytical procedure

The plagioclase separates were prepared at the Geological Survey of Norway (NGU), Trondheim, and the samples irradiated at Risø Nuclear Reactor, Roskilde, Denmark. Full procedural details are presented in an Appendix. The fast neutron dose was monitored by Leeds biotite standard Tinto, 409.2 Ma (Rex et al. 1986) and hornblende Hb3gr, 1072 Ma (Turner et al. 1971). Flux variation over the package length was of the order of 3%. The interference correction factors used were; $(40/39)K = 0.048$, $(36/39)Ca = 0.38$ and $(37/39)Ca = 1492$.

Table 1. $^{40}Ar/^{39}Ar$ analytical data.

| Temp °C | $^{39}Ar_K$ { | $^{37}Ar_{Ca}$ Vol. x $10^{-9}$ cm³ | $^{38}Ar_{Cl}$ } | Ca/K | $^{*40}Ar/^{39}Ar_K$ | %Atm $^{40}Ar$ | Age { | Error Ma } | %$^{39}Ar_K$ |
|---|---|---|---|---|---|---|---|---|---|
| 660 | 0.20 | 3.1 | 0.008 | 32 | 52.47 | 58.6 | 442.7 | 16.6 | 4.5 |
| 755 | 0.53 | 11.7 | 0.009 | 44 | 43.87 | 40.7 | 377.1 | 3.3 | 12.2 |
| 830 | 0.68 | 16.6 | 0.008 | 49 | 43.82 | 23.4 | 376.7 | 4.8 | 15.6 |
| 885 | 0.55 | 12.5 | 0.008 | 45 | 43.72 | 14.4 | 376.0 | 3.7 | 12.7 |
| 930 | 0.39 | 7.7 | 0.006 | 39 | 44.00 | 35.9 | 378.2 | 5.2 | 9.0 |
| 980 | 0.32 | 4.3 | 0.005 | 27 | 44.33 | 39.5 | 380.7 | 10.4 | 7.2 |
| 1010 | 0.24 | 2.4 | 0.006 | 20 | 44.77 | 22.2 | 384.1 | 9.8 | 5.5 |
| 1060 | 0.32 | 4.0 | 0.006 | 25 | 44.86 | 17.5 | 384.8 | 6.1 | 7.3 |
| 1165 | 0.67 | 10.3 | 0.015 | 31 | 49.64 | 15.7 | 421.4 | 5.2 | 15.3 |
| 1300 | 0.46 | 8.8 | 0.012 | 38 | 52.45 | 46.1 | 442.5 | 5.3 | 10.5 |

V1 Plagioclase, run 2461 weight = 0.05322g, J value = 0.00530 ± 0.5 %
Total gas age 395 ± 3Ma ( weight %K = 0.22 , $^{*40}Ar$ = 37.7 x $10^{-7}$ cm3g$^{-1}$)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 630 | 1.5 | 1.8 | 0.04 | 2.3 | 42.61 | 37.3 | 367.4 | 2.8 | 5.8 |
| 760 | 4.7 | 15.0 | 0.07 | 6.3 | 42.81 | 9.6 | 368.9 | 0.4 | 17.9 |
| 830 | 2.9 | 8.6 | 0.04 | 6.0 | 43.22 | 9.3 | 372.1 | 1.0 | 10.9 |
| 865 | 1.7 | 3.5 | 0.03 | 4.1 | 42.94 | 14.0 | 369.9 | 2.0 | 6.4 |
| 905 | 1.5 | 2.1 | 0.03 | 2.7 | 42.58 | 12.2 | 367.1 | 1.4 | 5.8 |
| 955 | 1.8 | 1.5 | 0.03 | 1.6 | 42.79 | 17.3 | 368.8 | 1.7 | 7.0 |
| 1000 | 2.0 | 1.6 | 0.04 | 1.6 | 42.87 | 16.5 | 369.4 | 2.3 | 7.5 |
| 1050 | 3.5 | 3.3 | 0.06 | 1.9 | 42.43 | 8.9 | 365.9 | 0.8 | 13.2 |
| 1160 | 5.9 | 8.7 | 0.12 | 3.0 | 42.72 | 7.0 | 368.2 | 0.4 | 22.2 |
| 1300 | 0.9 | 5.5 | 0.03 | 12.2 | 46.17 | 32.7 | 394.9 | 2.8 | 3.4 |

V4 Plagioclase, run 2462 weight = 0.06140g, J value = 0.00530 ± 0.5 %
Total gas age 369 ± 2Ma ( weight %K = 1.2 , $^{*40}Ar$ = 185 x $10^{-7}$ cm3g$^{-1}$)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 555 | 1.4 | 0.5 | 0.14 | 0.8 | 35.22 | 80.0 | 308.7 | 4.2 | 2.1 |
| 680 | 3.6 | 3.7 | 0.17 | 2.0 | 42.66 | 29.2 | 367.8 | 0.8 | 5.5 |
| 750 | 5.4 | 10.3 | 0.10 | 3.8 | 44.78 | 9.0 | 384.2 | 0.7 | 8.2 |
| 825 | 5.7 | 7.1 | 0.13 | 2.5 | 43.98 | 14.2 | 378.0 | 0.6 | 8.7 |
| 870 | 5.7 | 3.2 | 0.11 | 1.1 | 43.69 | 9.2 | 375.7 | 0.5 | 8.7 |
| 920 | 8.7 | 3.4 | 0.17 | 0.8 | 43.44 | 8.0 | 373.8 | 0.3 | 13.3 |
| 975 | 9.8 | 2.5 | 0.22 | 0.5 | 43.54 | 10.1 | 374.6 | 0.2 | 15.0 |
| 1025 | 10.5 | 3.3 | 0.28 | 0.6 | 43.60 | 12.7 | 375.1 | 0.2 | 16.0 |
| 1120 | 10.0 | 7.3 | 0.66 | 1.5 | 51.96 | 20.9 | 438.8 | 0.4 | 15.3 |
| 1300 | 4.7 | 9.1 | 0.43 | 3.9 | 59.08 | 22.0 | 491.4 | 0.6 | 7.2 |

V8 Plagioclase, run 2460 weight = 0.08236g, J value = 0.00530 ± 0.5 %
Total gas age 393 ± 2Ma ( weight %K = 2.1 , $^{*40}Ar$ = 366 x $10^{-7}$ cm3g$^{-1}$)

Errors are 1σ. $^{*40}Ar$ ∫ volume of Radiogenic $^{40}Ar$, gas volumes corrected to STP.

Isotopic analyses were performed with a modified MS10 mass spectrometer; measured atmospheric $^{40}Ar/^{36}Ar$ was 287.8 ± 0.2 and sensitivity 1.1 x $10^{-7}$ cm³V$^{-1}$. The J-value uncertainty is included in the errors for the total gas ages but the individual step ages have analytical errors only. All errors are quoted at the 1-sigma level. The analytical data are presented in Table 1. Age spectra and age correlation plots were produced using 'Isoplot/Ex' (Ludwig 2000).

## Results and interpretation

***V1 plagioclase:*** The age spectrum shows some disturbance with older ages at both low- and high-temperature, gas release steps. A plateau of 377.6 ± 1.8 Ma is defined by 70% of the gas released (Fig. 4). The isotope correlation plot gives a good linear trend for the plateau steps and yields the same age. The intercept $^{40}Ar/^{36}Ar$ of 296 is close to the accepted atmospheric argon value of 295.5. The last two steps of the experiment lie on the excess argon side of the linear array, evidence for the contribution of older ages of these steps.

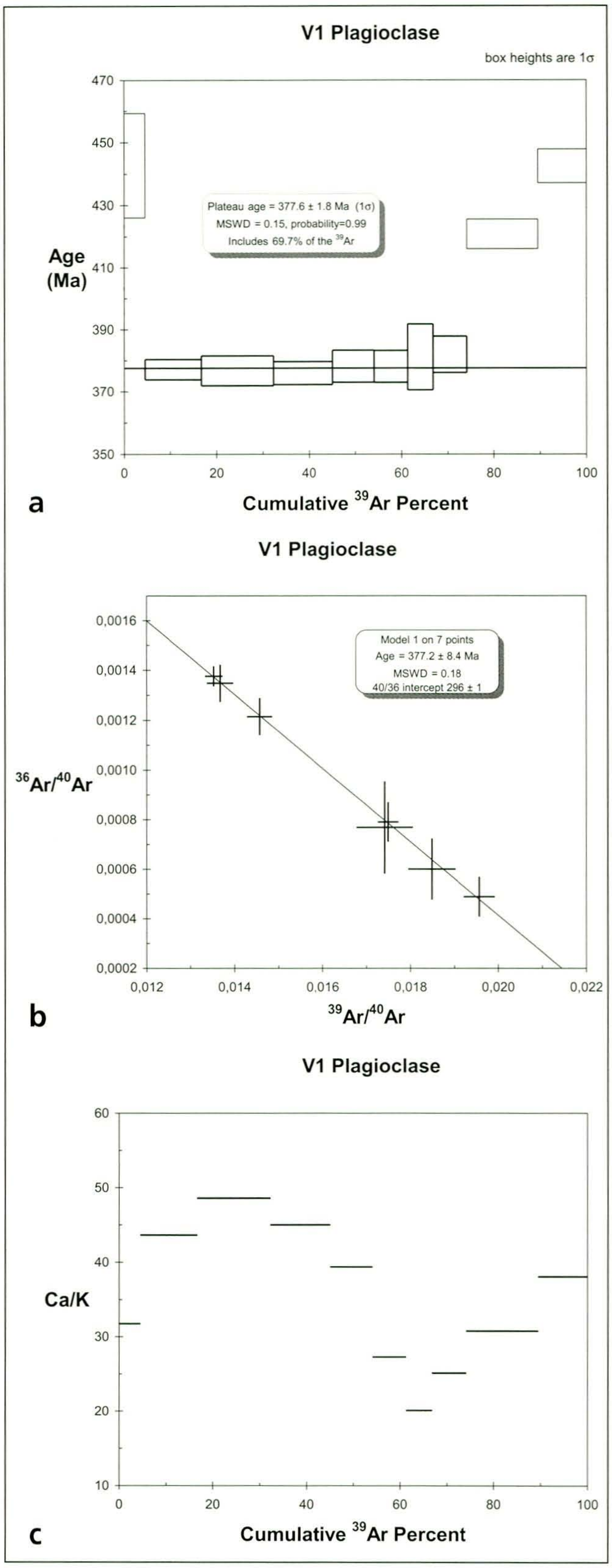


Fig. 4. Plagioclase sample V1: (a) $^{40}Ar/^{39}Ar$ age spectrum; (b) isotope correlation plot; (c) Ca/K plot.

Variations in the Ca/K ratio show no correlation with the age spectrum. This indicates that all the slight compositional variations present in the plagioclases are therefore giving the same age. It should be noted that the K content of this particular plagioclase is much lower than that of the other two samples, resulting in the larger errors on ages for individual steps and higher Ca/K values. This may suggest the hidden presence of subtle differences in the mineralogy of this particular separate, compared with that of V4 and V8.

We interpret the 378 ± 2 Ma plateau age (Fig. 4) as closely corresponding to the actual crystallisation age of this dyke.

***V4 plagioclase:*** The age spectrum of V4 shows a well-defined plateau at 369 Ma consisting of more than 95% of the gas released (Fig. 5). This age is further confirmed by the isotope correlation plot which has a good linear trend with the $^{40}Ar/^{36}Ar$ intercept at 297, again close to the atmospheric argon value. In this sample, there is no indication of excess argon being present. This spectrum conforms to that expected of a sample that underwent rapid cooling and has since remained thermally undisturbed. The variation in the Ca/K ratios of the steps is not reflected in the age spectrum.

The 369 ± 0.23 Ma plateau looks to provide as good an age as one is likely to get from this technique, and this is supported by the inverse isochron plot. Accordingly, we interpret this to represent the crystallisation age of the Finvika dyke.

***V8 plagioclase:*** This sample shows a disturbed spectrum with evidence of argon loss in the low-temperature steps and the presence of excess argon in the high-temperature steps (Fig. 6). The disturbance is such that there is no plateau as defined by the criteria of Isoplot/Ex (Ludwig 2000). However, a fit was forced through the steps shown in Fig. 6 to give an age of 375 ± 1 Ma (95% confidence) with just over 50% 0f the gas released. The isotope correlation plot again gives a linear trend, but confirms the presence of excess argon in the two highest temperature steps. A line fitted through the first eight steps of the experiment gives an age of 377 Ma and an $^{40}Ar/^{36}Ar$ intercept of 278 with large uncertainty. This value is lower than the accepted atmospheric argon value, which would be expected when there has been loss of radiogenic $^{40}Ar$. Variation in the Ca/K ratio is approximately mirrored in the age spectrum, indicating that slightly differing compositional variations could also be contributing to the disturbance of the age spectrum.

We interpret the weighted mean age of c. 375 Ma as a likely approximation to the intrusive age of this dyke.

Of the three samples, the age of V4 at 369 Ma can be accorded the highest confidence. The other two samples, V1 and V8, both show varying degrees of disturbance in their spectra. It is noteworthy that the V4 sample was collected from the very centre of the 9 m-thick Finnvika dyke. Sample V1, on the other hand, was taken c. 80 cm in from the margin of the 2.5 m-thick Komagnes dyke; and V8 approximately 1 metre in from the margin of the 16 m-thick Store Ekkerøya dyke. It is therefore possible that the disturbances recorded in V1 and V8 may relate to acquisition of radiogenic argon from the country rocks during magma ascent; or from fluids

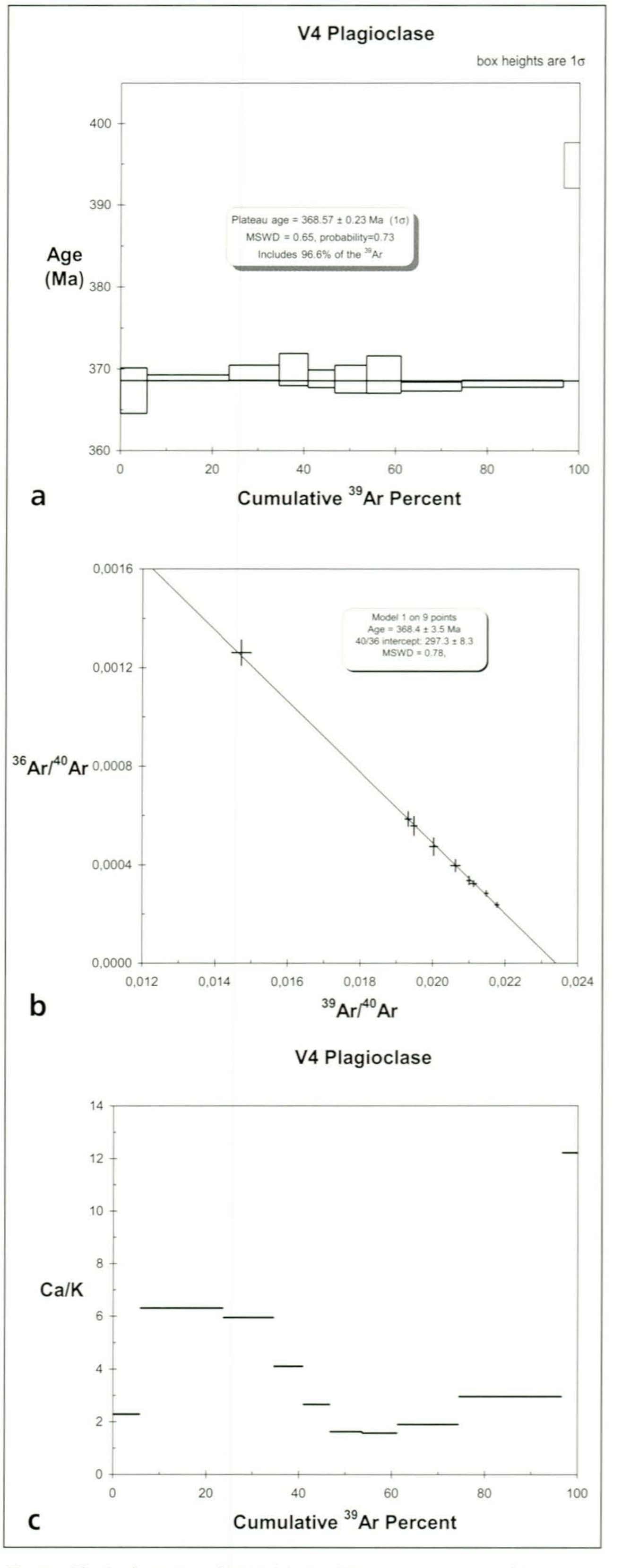


Fig. 5. Plagioclase sample V4: (a) $^{40}Ar/^{39}Ar$ age spectrum; (b) isotope correlation plot; Ca/K plot.

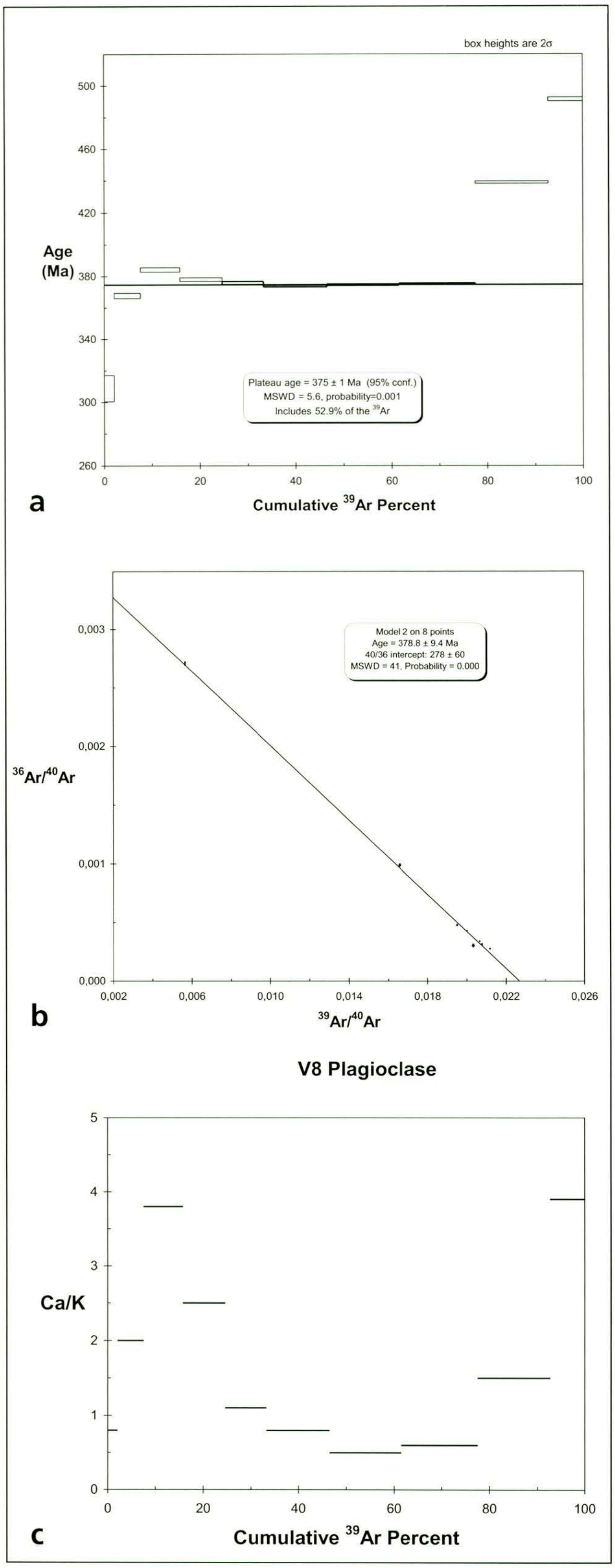


Fig. 6. Plagioclase sample V8: (a) $^{40}Ar/^{39}Ar$ age spectrum; (b) isotope correlation plot; (c) Ca/K plot.

circulating along or close to the dyke margins. Whatever the case, the three, fairly similar ages do tend to confirm the occurrence of a significant event – and mostly likely one of dyke intrusion – at around 370 Ma.

## Discussion

Based on all published dating, both isotopic and palaeomagnetic, of mafic dykes cutting Neoproterozoic rocks from the Varanger-North Kola segment of the northern margin of the Fennoscandian Shield, there appear to be two principal ages of dolerite dyke intrusion, namely Vendian and Devonian. The dykes investigated by us belong to Group A of Beckinsale et al. (1975), i.e., those which provided Late Devonian, K-Ar whole-rock ages. One of these dolerite dykes, the V1 dyke from Komagnes, has also been analysed palaeomagnetically, and in this case provided a Vendian age with no indication of any Devonian magnetic resetting (Torsvik et al. 1995). The palaeomagnetic data from the Komagnes dyke are almost identical to those derived from a dolerite dyke from the Sredni Peninsula that, in this case, has provided a Vendian age by both K-Ar and $^{40}Ar/^{39}Ar$ analytical methods.

Notwithstanding this evident conflict of results between the palaeomagnetic and isotopic dating of the Komagnes dyke, the plagioclase age spectra reported here from these three, widely separated dykes are mutually comparable and, together, favour an interpretation that the dykes were emplaced and crystallised at around 370 Ma. This interpretation thus supports the earlier K-Ar dating study of Beckinsale et al. (1975), where these very same dykes yielded concordant maximum ages of around 363 ± 10 Ma (recalculated following Dalrymple 1979). On current Phanerozoic time-scales, the Devonian-Carboniferous boundary is placed at either 362 (Tucker et al. 1998) or 355 Ma (Remane et al. 2000), and the Varanger dykes analysed in this investigation would thus fall in the Famennian stage of Late Devonian time.

In a wider perspective of the Fennoscandian Shield and East European Craton, the eastern and northern margins of Baltica were characterised by a major episode of rifting in Mid Devonian to Early Carboniferous time (Ziegler 1988, Johansen et al. 1993, Nikishin et al. 1996). Rift basin formation along a mainly NW-SE trend occurred beneath the Pechora Basin and eastern Barents Sea (Fig. 7), mimicking the structural trend in the pre-Palaeozoic basement. In the Kola Peninsula region and western parts of the Barents Sea, a more NE-SW rifting trend is evident (Nikishin et al. 1996, Gudlaugsson et al. 1998, Wilson et al. 1999), and a general doming of the Kola-White Sea area occurred in Late Devonian time (Fig. 7). In the Timan-Pechora rift system, Late Devonian basaltic volcanism was widespread, and the Kontozero graben on Kola Peninsula is well known for its alkaline and kimberlitic magmatism during the period 380 to 360 Ma (Kramm et al. 1993). In western parts of Kola, Pb-Zn vein mineralisations of Late Devonian age are commonly associated with N-S to NE-SW trending dolerite dykes (Juve et al. 1995).

An allied topic is the fact that U-Pb zircon data from

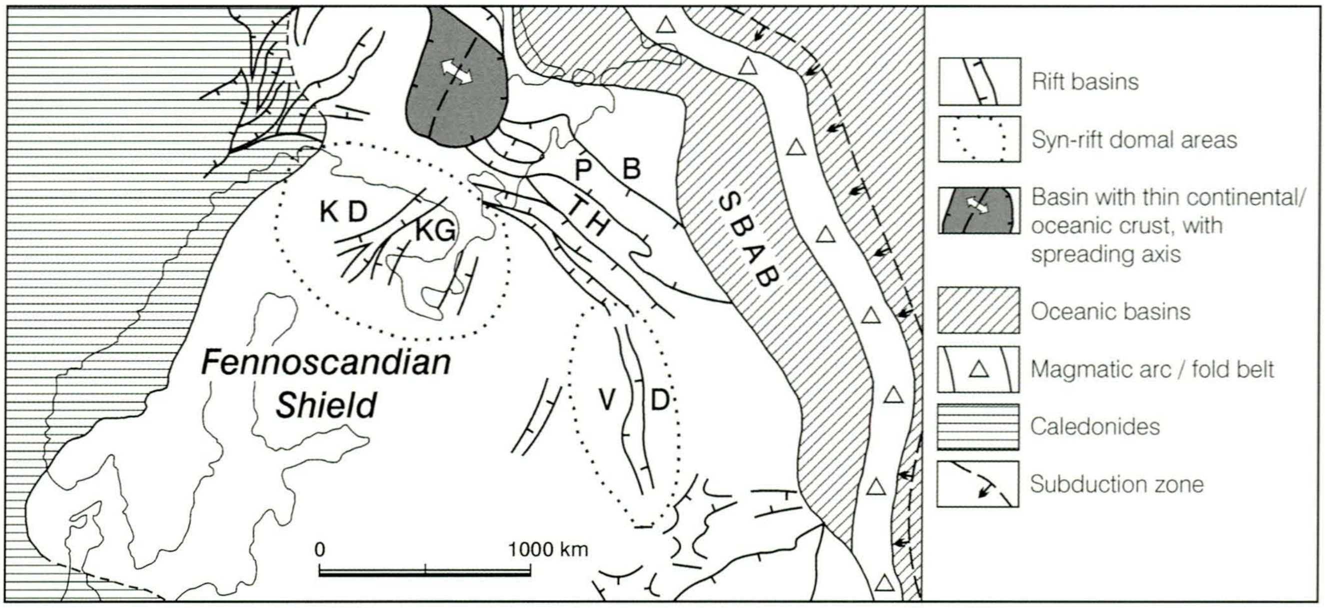


Fig.7 Simplified sketch-map of Baltica showing the main Late Devonian-Early Carboniferous rifts basins and other features. Modified from Nikishin et al. (1996). KD – Kola Dome; KG – Kontozero graben; PB – Pechora Basin; SBAB – Sakmarian back-arc basin; TH – Timan High; VD – Vyatka Dome.

Palaeoproterozoic and Archaean rocks from this northern Fennoscandian domain commonly show Devonian to Early Carboniferous lower intercepts on concordia (e.g., Levchenko et al. 1995, Larson & Tullborg 1998). A similar, Devonian, lower intercept date has been reported from a dolerite dyke with an interpreted Vendian age (U-Pb, zircon) from near Hamningberg in the Barents Sea Region (Roberts & Walker 1997). This recurrent feature has been interpreted by Larson & Tullborg (1998) to relate to the thermal effects of a Devonian foreland basin, with a sediment cover ⩾3 km thick (now removed), arising from rapid erosion of the Caledonian mountain chain. Although support for this notion of a Devonian sedimentary blanket comes from ongoing fission-track studies (G. Murrell, pers. comm. 2002), Nikishin et al. (1996) have stated that the Fennoscandian Shield, except for its rift basins, "may have remained emergent throughout the Devonian". Whether or not a thick, Devonian, foreland basin sedimentary cover existed in this shield area, there is now sufficient evidence from this northern Fennoscandian region that there are mafic dykes of both Devonian and Vendian age, and that the latter may or may not show Devonian overprints.

Returning to Varanger Peninsula, and the Komagnes dyke in particular, Herrevold (1993) and Karpuz et al. (1993) have reported that the dyke could be traced inland with the help of a handborne proton-magnetometer beneath a thin Quaternary cover into the trasé of the Trollfjorden-Komagelva Fault Zone, without change of strike, until its magnetic signature eventually faded and disappeared. No strike-slip offset of the magnetic anomaly could be detected. Accepting that the dyke is almost certainly of Devonian age, then this would indicate that all major strike-slip movements along the fault zone had ceased by Late Devonian time. A similar suggestion was also made by Beckinsale et al. (1975), at that time based on the general, though sporadic occurrence of their Group A dykes on either side of the TKFZ.

## Conclusions

Age spectra derived from the analysis of plagioclase separates from three, geochemically similar dolerite dykes from the eastern part of the Varanger Peninsula, northern Norway, show comparable features and lead to an interpretation that the dykes were intruded in Late Devonian time, at c. 370 Ma. These particular dykes had previously yielded quite similar, K-Ar whole-rock ages. An inferred Vendian age for one of the dykes, at Komagnes, based on palaeomagnetic data, should now be dismissed. This particular dyke has been traced beneath thin superficial deposits, by magnetometer, directly into the Trollfjorden-Komagelva Fault Zone, without any visible strike-slip offset of the magnetic anomaly, thus indicating that all major displacive movement along this fault zone had ceased by latest Devonian time.

*Acknowledgements*

We are grateful to Elizabeth Eide and Anna Siedlecka for their pertinent and most useful comments on an early version of the manuscript. Constructive comments and valuable suggestions by the reviewers, Martin Timmerman and Stephen Lippard, were helpful in improving the final manuscript. Irene Lundquist assisted in drafting three of the figures.

## References


Alexander, E.C.Jr., Mickelson, G. M. & Lanphere, M.A. 1978: MMHb-1: A new $^{40}Ar$-$^{39}Ar$ dating standard. *United States Geological Survey Open File Report 78-701*, 6-8.

Andersen, T. & Sundvoll, B. 1995: Neodymium isotope systematics of the mantle beneath the Baltic shield: evidence for depleted mantle evolution since the Archaean. *Lithos 35*, 235-243.

Banks, N.L., Edwards, M.B., Geddes, W.P., Hobday, D.K. & Reading, H.G. 1971: Late Precambrian and Cambro-Ordovician sedimentation in East Finnmark. *Norges geologiske undersøkelse 296*, 197-236.

Beckinsale, R.D., Reading, H.G. & Rex, D.C. 1975: Potassium-argon ages for basic dykes from East Finnmark: stratigraphic and structural implications. *Scottish Journal of Geology 12*, 51-65.

Bevins, R.E., Robinson, D., Gayer, R.A. & Allman, S. 1986: Low-grade metamorphism and its relationship to thrust tectonics in the Caledonides of Finnmark, North Norway. *Norges geologiske undersøkelse Bulletin 404*, 33-44.

Dalrymple, G.B. 1979: Critical tables for conversion of K-Ar ages from old to new constants. *Geology 7*, 558-560.

Dalrymple, G.B. & Lanphere M.A. 1971: $^{40}Ar/^{39}Ar$ technique of K-Ar dating: a comparison with the conventional technique. *Earth & Platentary Science Letters 12*, 300-315.

Edwards, M.B. 1984: Sedimentology of the Upper Proterozoic glacial record, Vestertana Group, Finnmark, North Norway. *Norges geologiske undersøkelse 394*, 76 pp.

Engels, J.C. & Ingamells, C.O. 1971: Information Sheets 1 and 2, LP-6 Biotite 40-60 mesh. *United States Geological Survey*, Menlo Park, Calif. U.S.A.

Fedotov, Z.A. & Amelin, Y.U. 1998: Post-Svecofennian dolerite dykes in the Kola Peninsula: dual nature of cratonic magmatism. *Vestnik Trudy Murmanskogo Gosudarstvennogo Tekhnicheskogo Universiteta 1 (3)*, 33-41 (in Russian).

Fieandt, A. von 1912: Fiskarhalföns och ön Kildins geologi. *Fennia 32*, 1-99.

Gorokhov, I.M., Siedlecka, A., Roberts, D., Melnikov, N.N. & Turchenko, T.L. 2001: Rb-Sr dating of diagenetic illite in Neoproterozoic shales, Varanger Peninsula, northern Norway. *Geological Magazine 138*, 541-562.

Gudlaugsson, S.T., Faleide, J.I., Johansen, S.E. & Breivik, A.J. 1998: Late Palaeozoic structural development of the southwestern Barents Sea. *Marine and Petroleum Geology 15*, 73-102.

Hausen, H. 1932: Die Bleiglanz-Zinkblende-Lagerstätten an der Küste von Petsamo (N.Finland). *Fennia 57*,

Herrevold, T. 1993: *Strukturgeologisk analyse av den austlegste delen av Trollfjorden-Lomagelvaforkastinga, Varanger.* Cand. Scient. thesis, University of Bergen (unpublished).

Johansen, S.E., Ostisty, B.K., Birkland, O., Fedorovsky, Y.F., Martrosjan, V.N., Christensen, O.B., Cheredeev, S.I., Ignatenko, E.A. & Margulis, L.S. 1993: Hydrocarbon potentioal in the Barents Sea region: play distribution and potential. In: Vorren, T.O. et alia (eds.) *Arctic geology and petroleum potential. Vol. 2.* NPF Special Publication, Elsevier, Amsterdam, 273-320.

Johnson, H.D., Levell, B.K. & Siedlecki, S. 1978: Late Precambrian sedimentary rocks in East Finnmark, north Norway, and their relationship to the Trollfjord-Komagelv Fault. *Journal of the Geological Society, London 135*, 517-533.

Juve, G., Størseth, L.R., Vetrin, V.R. & Nilsson, L.P. 1995: Mineral deposits of the international 1:250,000 map-sheet Kirkenes. (extended abstract) *Norges geologiske undersøkelse Special Publication 7*, 375-378.

Karpuz, M.R., Roberts, D., Olesen, O., Gabrielsen, R.H. & Herrevold, T. 1993: Application of multiple data sets to structural studies on Varanger Peninsula, northern Norway. *International Journal of Remote Sensing 14*, 979-1003.

Knutsen, J.O. 1995: *Kompleks flerkomponent magnetisering i senprekambriske doleritt/metadoleritt ganger på Varangerhalvøyen.* Cand. Scient. hovedoppgaven, University of Bergen, 85 pp.

Kramm, U., Kogaro, L.N. & Kononova, V.A. 1993: Middle and Late Devonian as a short period of magmatic activities in the Palaeozoic alkaline Kola province (Russia and Finland): Rb-Sr data. *In: Magmatism of rifts and fold belts.* Nauka, Moscow, 148-168.

Laajoki, K. 2002: New evidence of glacial abrasion of the Late Proterozoic unconformity around Varangerfjorden, northern Norway. Special Publication, *International Association of Sedimentologists 33*, 405-436.

Larson, S.Å. & Tullborg, E-L. 1998: Why Baltic Shield zircons yield late Paleozoic, lower-intercept ages on U-Pb concordia. *Geology 26*, 919-922.

Levchenkov, O.A., Levsky, L.K., Nordgulen, Ø., Dobrzhinetskaya, L.F., Vetrin, V.R., Cobbing, J., Nilsson, L.P. & Sturt, B.A. 1995: U-Pb zircon ages from Sørvaranger, Norway, and the western part of the Kola Peninsula, Russia. *Norges geologiske undersøkelse Special Publication 7*, 29-47.

Ludwig, K.R. 2000: Users manual for Isoplot/Ex version 2.3. A Geochronological Tool kit for Microsoft Excel. *Berkeley Geochronology Center, Special Publication No. 1a.*

Lyubtsov, V.V., Predovsky, A.A., Negrutsa, V.Z., Siedlecka, A. & Roberts, D. 1999: Neoproterozoic sedimentary rock successions of the Barents and White Sea coasts of the Kola Peninsula, Northwest Russia. *Norges geologiske undersøkelse Report 99.138*, 84 pp.

Nikishin, A.M., Ziegler, P.A., Stephenson, R.A., Cloetingh, S.S.P.L., Furne, A.V., Fokin, P.A., Ershov, A.V., Bolotov, S.N., Korotaev, M.V., Alekseev, A.S., Gorbachev, V.I., Shipilov, E.V., Lankreijer, A., Bembinova, E.Y. & Shalimov, I.V. 1996: Late Precambrian to Triassic history of the East European Craton: dynamics of sedimentary basin evolution. *Tectonophysics 268*, 23-63.

Olovyanishnikov, V.G., Siedlecka, A. & Roberts, D. 2000: Tectonics and sedimentation of the Meso- to Neoproterozoic Timan-Varanger Belt along the northeastern margin of Baltica. *Polarforschung 68*, 269-276.

Pickering, K.T. 1981: The Kongsfjord Formation – a Late Precambrian submarine fan in North-east Finnmark. *Norges geologiske undersøkelse 367*, 77-104.

Polkanov, A.A. 1935: Principles for stratigraphy of the Precambrian, and stratigraphic subdivisions of crystalline formations of the Kola Peninsula. In: Proceedings, 1st *All-Union Geological Research Conference, Moscow*, 94-117.

Remane, J. (ed.) 2000: International stratigraphic chart. *International Union of Geological Sciences, Trondheim, Norway.*

Rex, D.C. & Guise, P.G. 1986: Age of the Tinto felsite, Lanarkshire : a possible $^{39}Ar$-$^{40}Ar$ monitor. *Bulletin of Liaison and Information. I.G.C.P. Project 196, No 6.*

Rex, D.C., Guise, P.G. & Wartho, J-A. 1993: Disturbed $^{40}Ar$-$^{39}Ar$ spectra from hornblendes: thermal loss or contamination? *Chemical Geology 103*, 271-281.

Rice, A.H.N. 1994: Stratigraphic overlap of the Late Proterozoic Vadsø and Barents Sea Groups and correlation across the Trollfjorden-Komagelva Fault, Finnmark, N.Norway. Norsk Geologisk Tidsskrift 74, 48-57.

Rice, A.H.N. & Reiz, W. 1994: The structural relations and regional tectonic implications of metadolerite dykes in the Kongsfjord Formation, North Varanger region, Finnmark, N.Norway. *Norsk Geologisk Tidsskrift 74*, 152-165.

Rice, A.H.N., Gayer, R.A., Robinson, D. & Bevins, R.E. 1989: Strike-slip restoration of the Barents Sea Caledonides terrane, Finnmark, North Norway. *Tectonics 8*, 247-264.

Roberts, D. 1972: Tectonic deformation in the Barents Sea Region of Varanger Peninsula, Finnmark. *Norges geologiske undersøkelse 282*, 1-39.

Roberts, D. 1975: Geochemistry of dolerite and metadolerite dykes from Varanger Peninsula, Finnmark, North Norway. *Norges geologiske undersøkelse 322*, 55-72.

Roberts, D. 1995: Principal features of the structural geology of the Rybachi and Sredni Peninsulas, Northwest Russia, and some comparisons with Varanger Peninsula, North Norway. *Norges geologiske undersøkelse Special Publication 7*, 247-258.

Roberts, D. 1996: Caledonian and Baikalian tectonic structures on Varanger Peninsula, Finnmark, Norway, and coastal areas of Kola

Peninsula, NW Russia. *Norges geologiske undersøkelse Bulletin 431*, 59-65.

Roberts, D. & Karpuz, M.R. 1995: Anvendelse av et ERS-1 SAR satellittbilde til strukturstudier på Varangerhalvøya, og sammenligning med Landsat-TM; en foreløpig rapport. *Norges geologiske undersøkelse Report 95.163*, 14 pp.

Roberts, D. & Onstott, T.C. 1995: $^{40}Ar/^{39}Ar$ laser microprobe analyses and geochemistry of dolerite dykes from the Rybachi and Sredni Peninsulas, NW Kola, Russia. *Norges geologiske undersøkelse Special Publication 7*, 307-314.

Roberts, D. & Walker, N. 1997. U-Pb zircon age of a dolerite dyke from near Hamningberg, Varanger Peninsula, North Norway, and its regional significance. *Norges geologiske undersøkelse Bulletin 432*, 95-102.

Roberts, D. & Siedlecka, A. 2002: Timanian orogenic deformation along the northeastern margin of Baltica, Northwest Russia and Northeast Norway, and Avalonian-Cadomian connections. *Tectonophysics 352*, 169-184.

Roberts, D., Rex, D.C. & Guise, P.G. 1995. $^{40}Ar$-$^{39}Ar$ analyses of pyroxenes from dolerite dykes from southeastern Varanger Peninsula, Finnmark. *Norges geologiske undersøkelse Report 95.158*, 14 pp.

Roddick, J.C. 1983: High-precision intercalibration of $^{40}Ar$-$^{39}Ar$ standards. *Geochimica Cosmochimica Acta 47*, 887-898.

Siedlecka, A. 1975: Late Precambrian stratigraphy and structure of the northeastern margin of the Fennoscandian Shield (East Finnmark-Timan region). *Norges geologiske undersøkelse 316*, 313-348.

Siedlecka, A. & Siedlecki, S. 1967: Some new aspects of the geology of Varanger Peninsula (Northern Norway). *Norges geologiske undersøkelse 247*, 288-306.

Siedlecka, A. & Siedlecki, S. 1971: Late Precambrian sedimentary rocks of the Tanafjord-Varangerfjord Region of Varanger Peninsula, northern Norway. *Norges geologiske undersøkelse 269*, 246-294.

Siedlecka, A. & Roberts, D. 1992: The bedrock geology of Varanger Peninsula, Finnmark, North Norway: an excursion guide. *Norges geologiske undersøkelse Special Publication 5*, 45 pp.

Siedlecka, A. & Roberts, D. 1995: Neoproterozoic sedimentation and subsequent tectonic deformation in the northern coastal areas of Norway and Russia. (extended abstract). *Norges geologiske undersøkelse Special Publication 7*, 331-332.

Siedlecki, S. 1980: Geologisk kart over Norge, berggrunnskart Vadsø – M 1:250 000. *Norges geologiske undersøkelse.*

Sinitsin, A.V. 1967: Geological position of the Ust'ponoi structure and the Ponoi-Kachkovka-Snezhitsa metamorphic complex (Kola Peninsula). *Sovetskaya geologia 9*, 124-130 (in Russian),

Staudacher, Th., Jessberger, E.K., Döflinger, D. & Kiko, J. 1978: A refined ultrahigh-vacuum furnace for rare gas analysis. *Journal of Physics, Section E: Sci. Instr. 11*, 781-784.

Steiger, R.H. & Jäger, E. 1977: Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronlogy. *Earth & Planetary Science Letters 36*: 359-362.

Taylor, P.N. & Pickering, K.T. 1981: Rb-Sr isotopic age determination on the Late Precambrian Kongsfjord Formation, and the timing of compressional deformation in the Barents Sea Group, East Finnmark. *Norges geologiske undersøkelse 367*, 105-110.

Torsvik, T.H., Roberts, D. & Siedlecka, A. 1995: Palaeomagnetic data from sedimentary rocks and dolerite dykes, Kildin Island, Rybachi, Sredni and Varanger Peninsulas, NW Russia and NE Norway: a review. *Norges geologiske undersøkelse Special Publication 7*, 315-326.

Tucker, R.D., Bradley, D.C., Ver Straeten, C.A., Harris, A.G., Ebert, J.R. & McCutcheon, S.R. 1998: New U-Pb zircon ages and the duration and division of Devonian time. *Earth & Planetary Science Letters 158*, 175-186.

Turner, G., Huneke, J.C., Podosek, F.A. & Wasserburg, G.J. 1971: $^{40}Ar$-$^{39}Ar$ ages and cosmic ray exposure ages of Apollo 14 samples. *Earth & Planetary Science Letters 12*, 19-35.

Vidal, G. 1981: Micropalaeontology and biostratigraphy of the Upper Proterozoic and Lower Cambrian sequence in East Finnmark, northern Norway. *Norges geologiske undersøkelse 362*, 53 pp.

Wilson, M., Wijbrans, J., Fokin, P.A., Nikishin, A.M., Gorbachev, V.I. & Nazarevich, B.P. 1999: $^{40}Ar/^{39}Ar$ dating, geochemistry and tectonic setting of Early Carboniferous dolerite sills in the Pechora basin, foreland of the Polar Urals. *Tectonophysics 313*, 107-118.

Ziegler, P.A. 1988: Evolution of the Arctic-North Atlantic and the western Tethys. *American Association of Petroleum Geologists Memoir 43*, 198 pp.

# APPENDIX

Plagioclases were separated at NGU, Trondheim, using standard procedures. Samples for $^{40}Ar/^{39}Ar$ analysis were individually weighed, wrapped in high-purity aluminium foil and loaded into a Spectrosil phial. Irradiation for 10 hours was carried out at the Riso facility, Roskilde, Denmark. A fast neutron dose of approximately 9 x $10^{17}$ neutron/cm$^2$ was given and monitored by Leeds biotite standard Tinto, 409.2 Ma (Rex et al. 1986) and hornblende HB3gr (Turner et al. 1971). The Tinto standard has been cross calibrated against HB3gr, LP-6 (Engels et al. 1971), Fy12a (Roddick 1983) and MMHb-1 (Alexander et al. 1978), ages used for each of these standards as given in Roddick (1983). Flux variation over the package length was of the order of 3%.

Argon was extracted from each sample in a double-vacuum, resistance-heated furnace, developed in Leeds after the ideas of Prof. G. Turner (personal communication) and Staudacher et al. (1978). Samples were loaded into the arms of a glass storage tree above the furnace and the entire system baked overnight at 125°C under vacuum. Following further degassing of the getters and furnace (to 1350°C), a sample was dropped into the crucible and step heating commenced. The temperature of the furnace was monitored with a Minolta/Land™ Cyclops 52 infra-red optical pyrometer and is estimated to be accurate to ± 25°C with reproducibility of ± 5°C. The furnace was allowed to cool for 10 minutes after each 30-minute heating step and the evolved gas purified over two successive getters (mixtures of Ti-Zr metal shavings and Ti sponge), heated to 800°C and then allowed to cool. The gas was then transferred to a small volume inlet section by absorption on charcoal at liquid nitrogen temperature prior to admission to the mass spectrometer. Argon isotope analyses were performed using a modified MS 10 mass spectrometer with 4.2kGauss magnet and voltage peak jumping under computer control. Ion beams were detected by a VG pre-amplifier with 4 x $10^{10}$ ohm resistor, digitised with a KeithleyTM 2000 voltmeter and stored on computer disc for subsequent processing.

Measured mass spectrometer peak intensities were corrected for the following: Amplifier response and non-linearity; linear extrapolation to gas inlet time; spectrometer mass discrimination; and radioactive decay of $^{39}Ar$ and $^{37}Ar$. Interfering isotopes from neutron reactions on K and Ca corrections used were: (36/39)Ca 0.38, (37/39)Ca 1492 and (40/39)K 0.048. Atmospheric argon extraction blanks dominated mainly by the contribution from the Al sample packet ranged from 5 x $10^{-9}$ cm$^3$, $^{40}Ar$ STP up to 660°C when the Al melts through 3 x $10^{-10}$ at 900°C and 2 x $10^{-9}$ at 1350°C.

The mass spectrometer discrimination and sensitivity were monitored by analysing atmospheric argon from a pipette system. The measured atmospheric $^{40}Ar/^{36}Ar$ (typically 287.8 ± 0.2 for these analyses) and the sensitivity (typically 1.1 x $10^{-7}$ $Vcm^{-3}$ STP) change with filament life. The $^{40}Ar/^{39}Ar$ ratio, age, and errors for each gas fraction were calculated using formulae similar to those given by Dalrymple & Lanphere (1971). Errors in these ratios were evaluated by numerical differentiation of the equation used to determine the isotope ratios and quadratically propagating the errors in the measured ratios. J-value uncertainty is included in the errors quoted on the total gas ages but the individual step ages have analytical errors only. All errors are quoted at the 1-sigma level unless otherwise stated; and ages calculated using the constants recommended by Steiger & Jäger (1977). Age spectra and isotope correlation plots were produced using 'Isoplot/Ex' (Ludwig 2000).