On the age and tectonic significance of Permo-Triassic dikes in the Bergen–Sunnhordland region, southwestern Norway

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New $^{40}Ar/^{39}Ar$ step heating data for amphiboles from three N–S to NNW–SSE-trending alkaline dikes in western Norway yield remarkably consistent plateau ages at about 221 Ma. Together with most previously published amphibole and whole-rock K/Ar ages from Sunnhordland, which cluster around 220 Ma, the new data provide convincing evidence for a Late Triassic main pulse of dike intrusion. We conclude that most (but not all) of the K-Ar data are reliable and that Permian K-Ar and fission-track ages from four dikes in the region suggest an earlier pulse of intrusion at around 250–260 Ma. However, it is argued that the previously published Jurassic whole-rock age of one of the dikes is caused by hydrothermal alteration of the groundmass. A ~220 Ma $^{40}Ar/^{39}Ar$ plateau (and isochron) age of unaltered hornblende is believed to reflect more closely the age of intrusion, in agreement with other ages of late dikes in the region. The Permian (250–260 Ma) and Triassic (220–230 Ma) pulses of dike injection are correlated with Permian and Triassic phases of extension in the North Sea basin to the west. The strong influence of Permo-Triassic stretching at the eastern side of the Viking Graben and only mild rejuvenation of Permo-Triassic structures in the late Jurassic help to explain the apparent absence of Jurassic magmatism in southwestern Norway.

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Introduction

Coast-parallel basaltic dikes are an unusual and important element in the post-Caledonian tectonic record of the eastern margin of the North Sea rift system. They have been used as indications for early (Permo-Triassic) extension related to North Sea rifting (e.g. Færseth et al. 1995), and syn-intrusion extension directions have been inferred from their geometries (Fossen 1998; Valle 1998). The value of such data relies strongly on knowledge of their ages, or more specifically on the reliability of previously published K-Ar ages. In the present contribution we re-evaluate the existing data in the light of new $^{40}Ar/^{39}Ar$ results from some of these dikes.

General setting and previous work

The dikes

Close to 100 post-Caledonian dikes in the Sunnhordland–Sotra region (Reusch 1888; Kvale 1937; Skordal 1948; Færseth et al. 1976; Løvlie & Mitchell 1982) occur along N–S to NNW–SSE trending lineaments that transect all ductile and many brittle tectonic structures in the region, including Caledonian thrusts and Devonian extensional shear zones and faults. In particular, they cut mylonites related to the extensional Hardangerfjord Shear Zone (Fig. 1), which is a gently (25–30°) NW-dipping Devonian ductile shear zone in the basement connected to semi-brittle faults (e.g. the Lærdal–Gjende fault system) in overlying Caledonian units (Fossen 1992). They also postdate abundant ~NE–SW-trending normal faults with cohesive fault rocks and striated slip surfaces. The kinematics of the latter fault population are consistent with ~NW–SE extension, whereas the extension direction had changed to ~E–W at the time of dike injection (Fossen 1998; Valle 1998).

The dikes are with few exceptions less than one meter wide, and may form en-echelon-arranged subvertical segments, which are linked by fractures that may or may not be filled with dike material. Individual dikes can be traced for up to a few hundred meters along strike, although typically less than a few tens of meters.

Most dikes appear fresh but some alteration of the fine-grained matrix has occurred. The nature of the alteration is difficult to assess petrographically because of the extremely fine grain size, but it is clear that some proportion of the high temperature matrix mineralogy has not survived. Furthermore, in some cases amphiboles and pyroxenes are fractured, particularly in dike D1 (see Fig. 1 for location), which has been brecciated and calcite-cemented during reactivation of the N–S-trending fracture zone along which it intruded. The petrology of the alkaline dikes indicates derivation from a mantle source and emplacement at high crustal levels along the N–S to NNW–SSE-trending subvertical fractures (Færseth 1978).

Previous dating

Several of the dikes were dated in the 1970s by the K-Ar

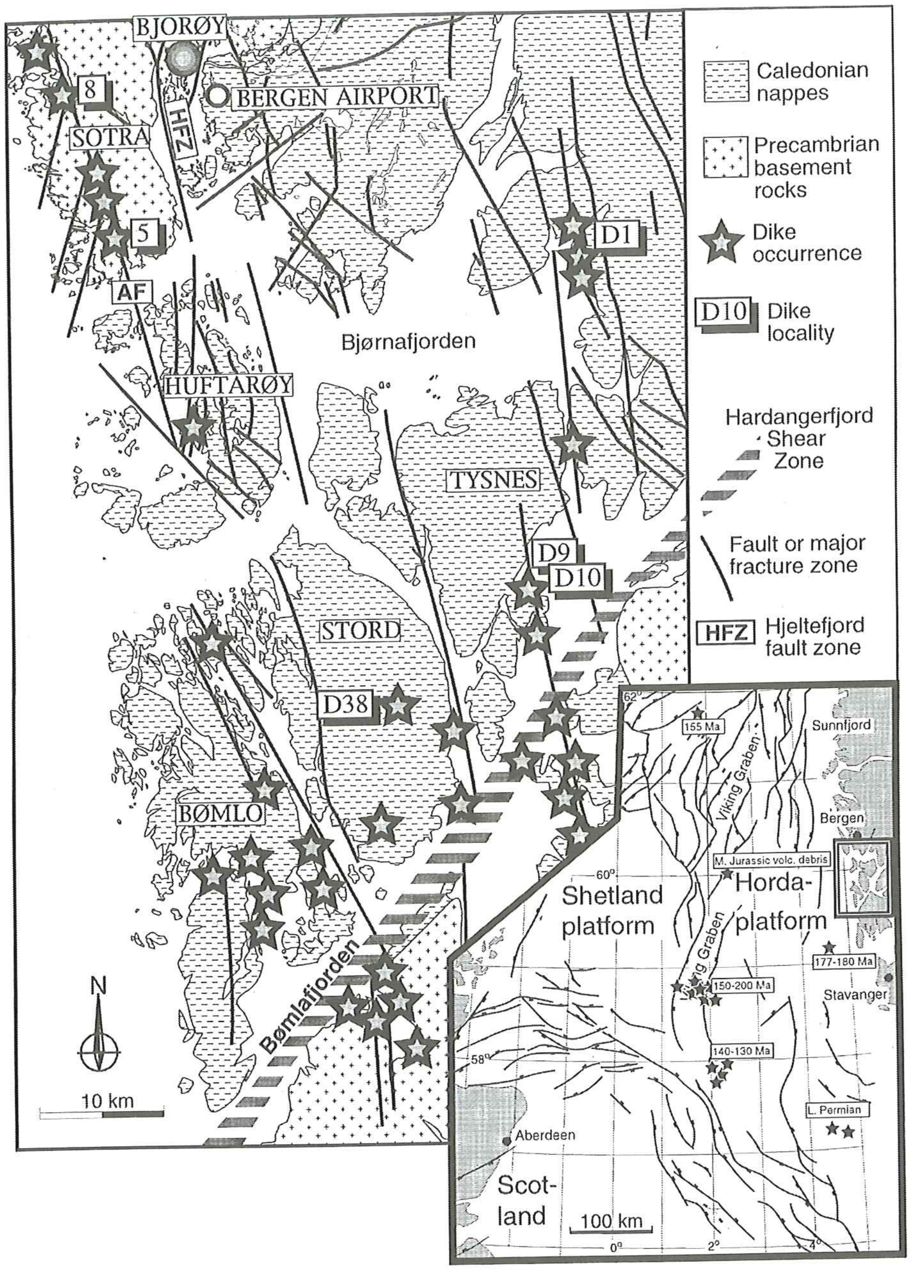

Fig. 1. Geological map of the Sunnhordland–Sotra area south of Bergen. Dike localities (stars) indicate the occurrence of one or several dikes. D-numbers are those used by Færseth et al. (1976); 5 and 8 are dikes dated by Løvlie & Mitchell (1982). Location of North Sea igneous activity is taken from Latin et al. (1990).

method. From a study of 15 dikes in Sunnhordland, Færseth et al. (1976) concluded that at least three episodes of intrusion had occurred in the Permian-Jurassic time interval (at 281, 226 and 168 Ma) (ages recalculated using decay constants of Steiger & Jaeger (1977), time-scale of Gradstein & Ogg (1996)). On Sotra just north of Sunnhordland, Permian ages (~250–270 Ma) were obtained by Løvlie & Mitchell (1982) from two dikes (5 and 8 in Fig. 1). Several dolerite dikes in the Sunnfjord area to the north also appear to be of Permian (250–270 Ma) age, based on paleomagnetic data (Torsvik et al. 1997). Together, these dike suites represent the youngest igneous activity recognized in western Norway. Their apparent ages and geographic positions indicate a close relationship with the tectono-magmatic evolution of the North Sea rift system, and their exact ages, here additionally constrained by $^{40}Ar/^{39}Ar$ analyses, are therefore of interest to both petroleum geologists and academics.

Ties to the North Sea rift system

The North Sea rift system experienced two main episodes of extension: a Permo-Triassic phase and a late Jurassic phase (e.g. Gabrielsen et al. 1990; Roberts et al. 1993). The basaltic dikes have repeatedly been referred to regarding the timing of early rifting in the North Sea, which by some is considered to be Triassic (Roberts et al. 1995) and by others thought to date back to the Permian (Færseth et al. 1995).

The North Sea rifting history was accompanied by other magmatic activity, particularly near the triple junction area located between Stavanger and Aberdeen (Fig. 1, inset

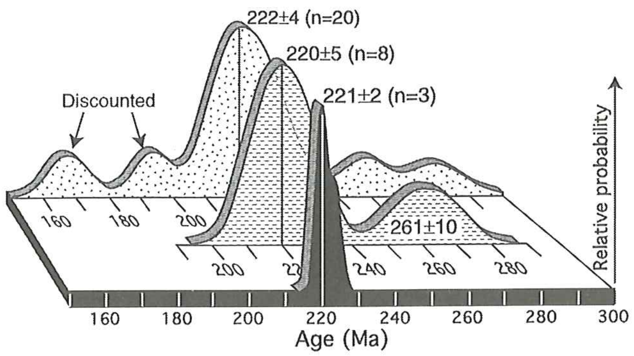

Fig. 2. Probability plot showing results of K-Ar and $^{40}Ar/^{39}Ar$ dating of dolerite dikes from Sunnhordland. Front: $^{40}Ar/^{39}Ar$ plateau ages of the three dikes redated in this study (Table 1). Middle: Amphibole K-Ar ages from 5 dikes, recalculated from Færseth et al. (1976). Back: Whole-rock ages from 15 dikes, recalculated from Færseth et al. (1976). The three data sets consistently show very distinct peaks at about 220 Ma. In addition, two amphibole dates from one of the dikes show a ~260 Ma age, giving rise to the additional peak in the central graph. The two Jurassic whole-rock ages are discarded as ages of intrusion because of alteration (see text for discussion). All errors involved in the calculation of the plots were 2σ. Weighted mean and 2 s.d. errors of Triassic probability peaks are shown.

map). Almost all documented igneous activity in the region occurred in the Jurassic and Cretaceous, except for some Permian occurrences west of Denmark (e.g. Latin et al. 1990 and references therein). It is, however, likely that the apparent absence of Triassic magmatism in the North Sea rift system is related to the low number of wells penetrating the Triassic sequence, as compared to the overwhelming number of wells in the Jurassic strata.

New sampling

We have collected amphibole-bearing porphyritic samples of the alkaline dikes in Sunnhordland-Sotra for $^{40}Ar/^{39}Ar$ dating. Only some of the dikes contain amphibole (amphibole from five dikes were analyzed by Færseth et al. (1976), using the K-Ar method). We have sampled three amphibole-bearing dikes for the current project, including the dike that yielded the youngest K-Ar age (D10), the dike which it intrudes (D9), and a third dike (D38) from the same region. For all the dikes, we can confidently relate them to the previous sample locations of Færseth et al. (1976), which allows us to use the same sample designations.

Sample D9 is from a very dark, alkaline, subvertical dike consisting of continuous left-stepping and SSE-striking segments. The dike is nearly 1 m wide, and contains olivine and amphibole phenocrysts. The length of the dike is not known since it enters the sea to the south (>20 m). Færseth et al. (1976) reported a Late Triassic age of 224 ± 7 Ma for this dike, based on one whole-rock K-Ar analysis (all errors in this article are quoted at the 2σ level unless otherwise noted).

Sample D10 is from a dike with 5 mm-long amphibole phenocrysts set in a very fine-grained light-grey matrix. Petrographic observations indicate that the groundmass of

Fig. 3. Field occurrence of dikes D9 and D10. D10 intruded along the margin of D9 and locally cross-cuts D9 to follow the western margin. A third dike, which is very similar to D9, occurs on the right side of the photograph. The hammer lies on the chilled margin of the latter dike. Width of D9 is 20 cm. Note that, for clarity, D9 has been given more contrast than the other dikes. For location, see Fig. 1. CR = country rock.

the D10 dike is partially altered to clay minerals, whereas the amphibole phenocrysts are completely fresh. The color and composition of this dike differ from D9 and most of the other dikes examined by Færseth et al. (1976). D10 intruded along D9 as shown in Fig. 3, and is therefore younger. The brown amphibole needles in this sample were not analyzed by Færseth et al. (1976), but a Jurassic whole-rock K-Ar age of 168 ± 6 Ma was reported for this dike and interpreted as the age of intrusion.

Sample D38 is from a NNW-trending, dark-grey, porphyritic dike on the summit of Kattnakken mountain. The D38 dike is similar in texture and composition to dike D9, and Færseth et al. (1976) presented an amphibole K-Ar age for D38 of 226 ± 7 Ma.

New $^{40}Ar/^{39}Ar$ geochronology

Amphibole separates from the three alkaline Sunnhordland dikes have been dated by the $^{40}Ar/^{39}Ar$ step heating

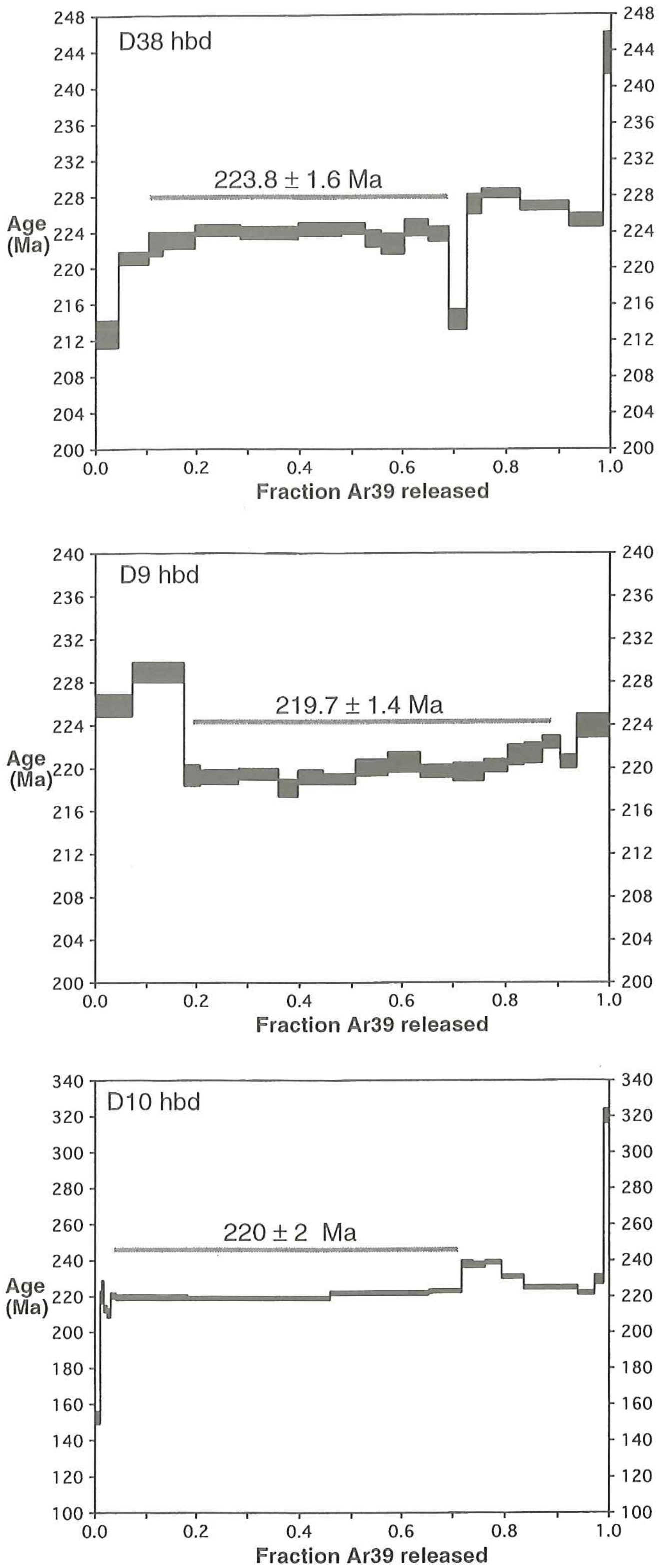

Fig. 4. $^{40}Ar/^{39}Ar$ age spectra for amphibole from dikes D9, D10 and D38 (Sunnhordland). Note change in scale of vertical axes.

method (e.g. McDougall & Harrison 1989). The analytical procedure used is identical to that of Dunlap & Fossen (1998) and Fossen & Dunlap (1998). The advantage of using amphiboles for the dating of the dikes is that they are much more resistant to thermally induced argon loss than other potassium-bearing minerals and whole rocks, and thus amphiboles are likely to yield the age of dike intrusion. The advantage in employing the step heating method over the K-Ar method is that any age gradients can potentially be revealed as the argon gas is incrementally evolved from the samples by increasing the temperature in a stepwise manner, and analyzing each aliquot of gas separately. In this way it is possible to determine if the isotopic system has been disturbed subsequent to intrusion by reheating events, maintenance of elevated temperatures long after intrusion, or by alteration of the original igneous minerals. Additional advantages of the $^{40}Ar/^{39}Ar$ method are that only one aliquot of sample is needed, and the required sample size is much smaller (only a few milligrams). The results (Table 1) have been plotted as age spectra in Fig. 4.

Amphibole D38 yields an age spectrum that is somewhat erratic, rising from a minimum age of 213 Ma, and reaching a second minimum of 215 Ma at 72% of gas release. The intervening gas from steps 3 to 12 defines a plateau age at 224 ± 2 Ma. The total gas age of 224 ± 2 Ma is similar to the plateau age. The K/Ca plot for the sample (Fig. 5c) indicates that a high K phase or phases dominate the initial gas release. Not surprisingly, the mineral separate for D38 exhibits fragments of groundmass attached to the amphibole fragments (estimated 4–5% by volume). We ascribe the steadily rising apparent ages in the initial gas release to be the result of the gas being derived both from this groundmass contaminant and from the amphiboles. By 1100°C and step two we believe that the groundmass contaminant was largely outgassed of its argon. The last few steps in the spectrum yield mostly older apparent ages, but we prefer to ascribe the age of intrusion to the plateau at 224 Ma. An isochron age of 224 ± 2 Ma (Fig. 6) is consistent with this interpretation.

D9 amphibole, which has a total gas age of 222 ± 2 Ma, yields the oldest evolved age in the first two steps of the degassing spectrum at 229 Ma (gas evolved at 900 and 1100°C) (Fig. 4). These steps are associated with the highest evolved K/Ca (Fig. 5), as would be expected if the argon was derived from a high-K phase or phases. Petrographic examination of the mineral separate reveals that many of the amphibole fragments have thin skins of groundmass material still attached (estimated 2–3% of separate volume). We believe that the elevated ages in the first two steps are derived from excess argon trapped in the groundmass material. This material is likely to be extensively degassed by 1100°C. Subsequent steps define a plateau over steps 3 to 15, covering some 70% of gas release, at 220 ± 2 Ma, which is consistent with the 219 ± 1 Ma isochron age for this sample, presented in Fig. 6, and identical to the plateau age defined by the D10 amphibole (see below).

The apparent age of D10 amphibole rises rapidly from a minimum age of 153 Ma to define a plateau from 4 to 71% of gas release at 220 ± 2 Ma (Fig. 4). Subsequent steps rise

Table 1. Analytical data for $^{40}Ar/^{39}Ar$ incremental heating experiments, corrected for mass spectrometer discrimination, line blanks, and for the decay of ^{37}Ar and ^{39}Ar during and after irradiation. Corrections for interfering nuclear reactions have only been made for the radiogenic argon ($^{40}Ar^*$) to K-generated ^{39}Ar ratio ($^{40}Ar^*/^{39}Ar_K$). Amounts of ^{39}Ar are derived from the measured sensitivity of the mass spectrometer. Relative isotope amounts for a given age spectrum are precise, but absolute amounts may have uncertainties of ~5–10%. Totals are the %^{39}Ar weighted means of the analyses except for the integrated age, which must be calculated from the integrated $^{40}Ar^*/^{39}Ar_K$. Flux monitor: Australian National University GA1550 Biotite (97.9 Ma, J determined by interpolation). $\lambda = 5.543 \times 10^{-10}$ a^{-1}. ^{37}Ar decay factor: ~4. Correction factors: $(40/39)_k = 0.0270$; $(36/37)_{Ca} = 0.00035$; $(39/37)_{Ca} = 0.000786$.

$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$ (10^{-3})	$^{36}Ar/^{39}Ar$ (10^{-3})	^{39}Ar (10^{-16} mol)	Cumulative ^{39}Ar (%)	%$^{40}Ar^*$	$^{40}Ar^*/^{39}Ar_K$	Calculated Age (Ma) ± 1 s.d.	Temp °C	K/Ca
D-10 Amphibole, ANU29 #95280, 250–125 μm, J = 0.004180 ± 0.4%									
49.46	1.272	96.29	8.554	1.0	42.7	21.14	152.8 ± 3.6	800	0.413
51.54	2.980	70.72	3.207	1.4	60.0	31.00	219.8 ± 3.5	900	0.176
47.99	1.454	55.56	3.501	1.8	66.0	31.73	224.7 ± 4.1	1000	0.362
42.06	2.358	41.76	7.088	2.6	71.2	29.99	213.1 ± 2.1	1100	0.223
48.58	3.242	65.62	5.148	3.2	60.7	29.58	210.3 ± 2.5	1130	0.162
43.91	3.617	44.94	8.549	4.2	70.5	31.07	220.3 ± 1.7	1160	0.145
35.93	3.902	18.47	121.2	18.4	85.9	30.95	219.5 ± 1.1	1190	0.134
32.38	4.029	6.874	234.2	45.8	94.9	30.84	218.7 ± 1.0	1230	0.130
32.47	4.170	5.806	165.3	65.2	96.0	31.26	221.6 ± 1.0	1260	0.126
35.74	4.160	16.07	55.09	71.6	87.8	31.51	223.2 ± 1.0	1280	0.126
44.31	3.904	37.21	18.43	73.8	76.0	33.79	238.4 ± 2.1	1290	0.134
43.86	3.777	35.96	20.52	76.2	76.6	33.70	237.8 ± 1.5	1300	0.139
42.26	3.855	30.22	27.52	79.4	79.8	33.83	238.6 ± 1.0	1310	0.136
38.48	3.887	21.15	35.50	83.6	84.7	32.70	231.1 ± 1.1	1320	0.135
36.55	3.972	17.60	46.78	89.1	86.8	31.83	225.3 ± 0.9	1330	0.132
39.09	4.042	26.34	41.49	93.9	81.1	31.80	225.2 ± 1.1	1340	0.130
39.53	4.087	29.47	27.55	97.1	79.0	31.32	222.0 ± 1.4	1350	0.128
52.34	4.008	69.00	15.84	99.0	61.8	32.44	229.5 ± 2.1	1380	0.131
95.40	2.549	166.9	8.622	100	48.5	46.40	319.8 ± 1.6	1450	0.206
					Totals	31.48	223.0 ± 1.2		0.192
D-38 Amphibole, ANU29 #95277, 150–90 μm, J = 0.004140 ± 0.4%									
41.34	1.014	37.95	47.61	4.6	73.1	30.22	212.7 ± 1.6	900	0.518
34.93	0.9774	11.97	62.39	10.7	90.1	31.49	221.1 ± 0.7	1100	0.538
34.98	2.202	11.83	28.27	13.4	90.6	31.75	222.8 ± 1.3	1140	0.239
33.26	3.483	6.349	64.26	19.6	95.4	31.80	223.1 ± 0.9	1170	0.151
33.09	3.942	5.436	90.60	28.3	96.3	31.97	224.2 ± 0.7	1190	0.133
32.93	4.135	5.193	116.7	39.6	96.6	31.91	223.9 ± 0.7	1205	0.127
33.46	4.212	6.773	86.91	48.0	95.2	31.98	224.3 ± 0.6	1215	0.125
34.43	4.221	10.03	47.22	52.6	92.6	31.99	224.4 ± 0.6	1220	0.124
34.40	4.271	10.50	34.30	55.9	92.2	31.83	223.3 ± 0.9	1230	0.123
34.48	4.324	11.01	44.84	60.2	91.8	31.75	222.8 ± 1.1	1240	0.121
35.10	4.396	12.31	48.57	64.9	90.9	32.01	224.5 ± 1.0	1250	0.119
35.56	4.492	14.22	40.92	68.8	89.4	31.91	223.8 ± 0.8	1260	0.117
35.58	4.343	19.00	36.93	72.4	85.4	30.48	214.4 ± 1.1	1270	0.121
37.36	4.601	18.69	28.69	75.2	86.4	32.41	227.1 ± 1.2	1280	0.114
34.64	4.509	8.848	75.89	82.5	93.7	32.59	228.3 ± 0.5	1300	0.116
35.02	4.647	10.88	98.48	92.0	92.1	32.38	227.0 ± 0.5	1330	0.113
35.74	5.116	14.36	70.07	98.8	89.5	32.12	225.2 ± 0.7	1360	0.102
67.43	3.953	111.6	12.79	100	51.6	34.93	243.7 ± 2.3	1450	0.133
					Totals	31.91	223.8 ± 0.8		0.174
D-9 Amphibole, ANU29 #95279, 250–104 μm, J = 0.004041 ± 0.4%									
43.85	1.167	37.16	90.63	7.2	75.2	32.99	225.8 ± 1.0	900	0.450
41.77	0.5534	28.23	129.8	17.5	80.1	33.48	228.9 ± 0.9	1100	0.952
34.95	2.729	11.13	41.74	20.9	91.3	31.99	219.3 ± 1.0	1140	0.192
33.22	3.589	5.722	92.28	28.2	95.9	31.97	219.2 ± 0.6	1170	0.146
33.22	3.817	5.588	96.55	35.8	96.1	32.02	219.5 ± 0.5	1190	0.138
33.39	3.934	7.013	46.57	39.5	94.9	31.80	218.1 ± 0.8	1200	0.133
33.65	4.012	7.321	63.68	44.6	94.7	31.97	219.2 ± 0.7	1210	0.131
34.35	4.052	9.862	78.29	50.8	92.7	31.93	219.0 ± 0.5	1220	0.130
33.44	4.150	6.254	79.01	57.1	95.7	32.10	220.0 ± 0.7	1230	0.126
33.74	4.164	7.003	79.51	63.4	95.1	32.18	220.6 ± 1.0	1240	0.126
34.02	4.199	8.382	80.21	69.8	93.9	32.05	219.7 ± 0.6	1250	0.125
33.68	4.232	7.295	74.65	75.7	94.8	32.04	219.7 ± 0.9	1260	0.124
34.59	4.427	10.23	57.67	80.2	92.5	32.12	220.2 ± 0.6	1270	0.118
34.90	4.954	10.91	42.01	83.6	92.2	32.29	221.2 ± 0.9	1280	0.106
35.64	5.393	13.51	43.52	87.0	90.3	32.31	221.4 ± 0.9	1295	0.097
36.01	4.786	13.94	45.13	90.6	89.9	32.47	222.4 ± 0.6	1315	0.110
36.47	4.726	16.41	39.29	93.7	88.0	32.19	220.6 ± 0.6	1340	0.111
46.56	5.085	49.02	79.19	100	70.0	32.70	223.9 ± 1.1	1450	0.103
					Totals	32.33	221.5 ± 0.8		0.190

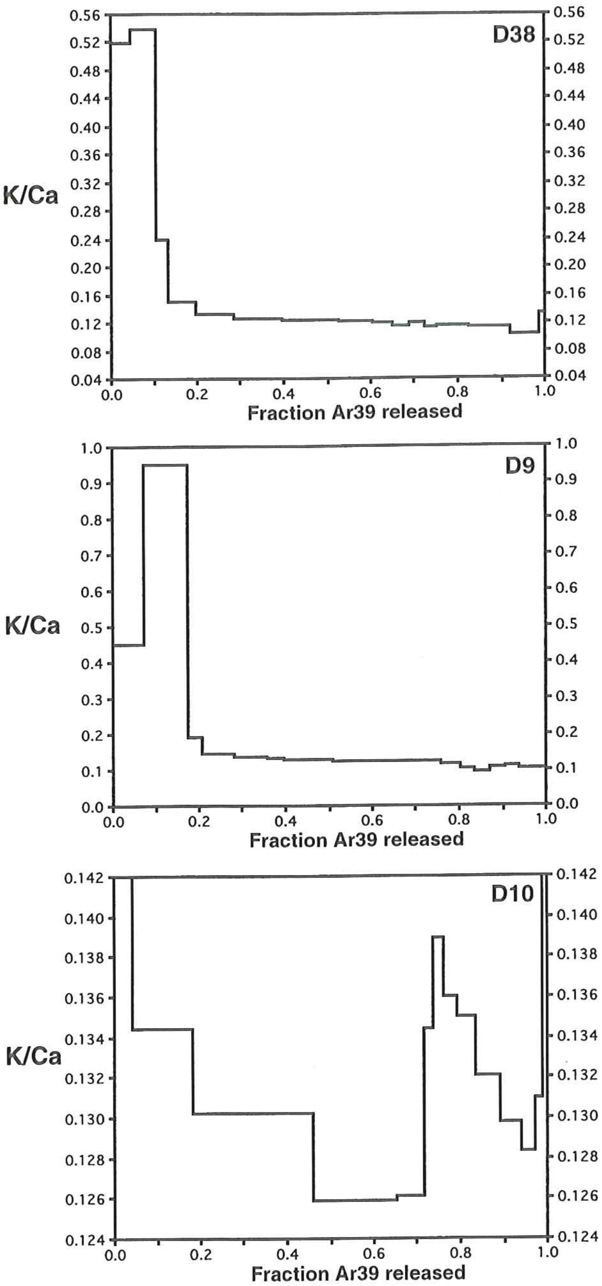

Fig. 5. K/Ca distribution for the amphibole separates analyzed by the $^{40}Ar/^{39}Ar$ method. See text for discussion.

in age to a maximum of 239 Ma, but then decline to another minimum at 221 Ma. This increase in apparent age above the plateau is associated with melting of the amphiboles at ~1300°C during the step heating experiment. Note also the associated increase in K/Ca (Fig. 5). We do not believe that mineral inclusions could be responsible for these increases, because they are volumetrically insignificant (estimated at <0.01% by volume). Whatever the cause of the increase in age, however, the well-defined isochron age of 222 ± 3 (Fig. 6) and the total gas age of 223 ± 2 Ma indicate that these older steps have little influence on the overall interpretation. It thus seems likely that the age of intrusion is that of the plateau (and isochron) at ~220 Ma.

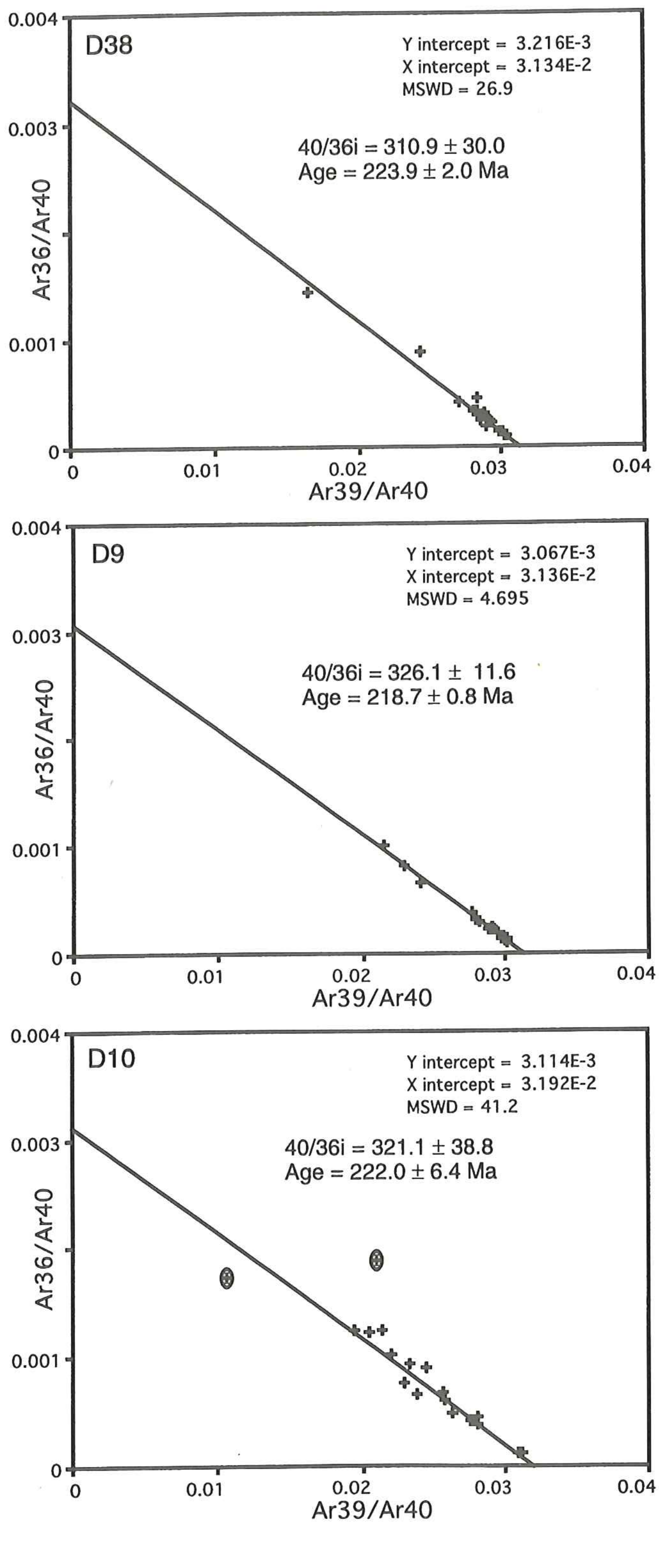

Fig. 6. Inverse isochron plot of $^{40}Ar/^{39}Ar$ data from the three dikes dated in this study. The isochron ages are indistinguishable from the plateau ages presented in Fig. 4. Two data points were disregarded for dike D10; the gas associated with these two deleted steps is largely unradiogenic and is adversely affected by system blanks, thus they are not useful in calculating the isochron age.

In view of the significantly younger K-Ar age reported for the D10 whole rock by Færseth et al. (1976) and a whole-rock age of about 162 Ma, which was obtained by Eide and co-workers in a parallel study to the present one,

Table 2. K-Ar data. ANU#, Australian National University catalogue number; K, potassium. $\%^{40}Ar^*$ is percent radiogenic argon 40. Decay constants are $\lambda e = 0.581$ E-10/y and $\lambda\beta = 4.962$ E-10/y.

No.	ANU#	Material	K wt %	Rad ^{40}Ar, 10^{-9} mol/g	$\%^{40}Ar^*$	Age Ma $\pm 1\sigma$
D10	95280	Whole rock	4.100 (mean of 3)	1.308	75.0	175.0 ± 3.2

ANU#, Australian National University catalogue number; K, potassium. $\%^{40}Ar^*$ is percent radiogenic argon 40. Decay constants are $\lambda e = 0.581$ E-10/y and $\lambda\beta = 4.962$ E-10/y.

we decided to run a conventional K-Ar analysis on a split of our sample of the D10 dike, the results of which are presented in Table 2. Our whole-rock sample has yielded a K-Ar age of 175 ± 6 Ma, which is within error of the 168 ± 6 Ma age determined by Færseth et al. (1976).

Discussion and comparison with other data

Triassic ages

Færseth et al. (1976) present both whole-rock and amphibole K-Ar dates. As stated in their original paper, fair agreement between the five amphibole dates and whole-rock dates from the same samples suggest that these five age estimates are more reliable than those where only whole-rock data exist. Four of these five pairs of data types indicate dike intrusion at about 220 Ma (Fig. 2). This grouping correlates well with the new $^{40}Ar/^{39}Ar$ plateau ages of amphiboles presented in this work, together making a very strong case for dike intrusion at around 220 Ma.

As stated by Færseth et al. (1976), the fact that amphibole and whole-rock K-Ar ages are similar for the five dikes where ages on both such materials were determined, gives us reason to believe that most of the other whole-rock dates also closely date the times of intrusion. In general, this assumption appears to hold; the probability distribution of the whole-rock data set shows a clear peak which coincides with those defined by both the paired K-Ar set and the new $^{40}Ar/^{39}Ar$ plateau ages. It is therefore reasonable to conclude that the majority of the dated dikes intruded at ~220 Ma.

Permian ages

Færseth et al. (1976) interpreted the first of three episodes of intrusion to have occurred at around 280 Ma. However, one of the dikes (D63) yielded consistent whole-rock and amphibole K-Ar ages of ~260 Ma and is considered by us to be more reliable than the whole-rock ages of ~280 Ma (D60).

Whole-rock K-Ar data from two of the Sotra dikes may date their intrusion at ~261 and ~254 Ma (Løvlie & Mitchell 1982). The fact that seven samples from one dike give such consistent results is strong evidence for this. If partial loss of radiogenic argon from the whole-rock system had occurred, then we would not expect such consistency in these results, mainly because the K mostly resides in the groundmass; the portion of the sample generally susceptible to alteration. In addition, the Permian K-Ar ages for one amphibole and one whole rock of the alkaline dikes from Sunnhordland (Færseth et al. 1976) present a compelling case for limited intrusion of Permian dikes at about the same time as those on Sotra. $^{40}Ar/^{39}Ar$ data from a plagioclase separate of one of the Sotra dikes is presented by Eide & Torsvik (1998). A poorly defined $^{40}Ar/^{39}Ar$ isochron intercept age of $241 + 11$ Ma was obtained. However, the strong saddle shape of the age spectrum indicates excess argon contamination, possibly indicating that this is a maximum age for dike intrusion.

Unpublished fission track analysis of apatite from the southern (254 Ma) K-Ar multisampled Sotra dike shows indications of a Permian age for the longest traces (J. P. Stiberg, pers. comm.). The dike has an apparent apatite fission track age of 198 ± 20 Ma, a mean track length of 12.84 ± 0.18 μm and a standard deviation of 1.30. Considering that the average length of induced fission tracks is known to be 16.2 μm, a corrected age of 250 ± 20 Ma can be calculated. This age is compatible with the existing K-Ar and $^{40}Ar/^{39}Ar$ ages (the younger apparent fission track age may indicate later burial or thermal increase).

Considering the existing data, a Permian pulse of tension and magmatism in the Sotra–Sunnhordland dike population is reasonably well documented. The ages of these dikes appear to be in the range 250–260 Ma, which concurs with paleomagnetic dates from the Molvær dikes further north (Torsvik et al. 1997).

Jurassic ages

Among the original K-Ar whole-rock data of Færseth et al. (1976), two low-age outliers (D1 and D10) were presented. One (D1) was discarded by Færseth et al. (1976) because the field occurrence is brecciated and veined. The 168 ± 6 Ma K-Ar whole-rock age of D10, on the other hand, was regarded as the time of intrusion. Eide & Torsvik (1998) have determined a Jurrasic $^{40}Ar/^{39}Ar$ whole-rock age for material from this same site, which is not surprising in the light of the previously published K-Ar whole-rock age. On the contrary, we have shown that the amphibole phenocrysts from the same outcrop are ~220 Ma old, an age which is indistinguishable from most K-Ar and $^{40}Ar/^{39}Ar$ amphibole ages of dikes from the area. Several explanations and interpretations can possibly explain this inconsistency between the young whole-rock and older amphibole ages.

The dated amphiboles could be xenochrysts derived from the wall rock of the D9 dike. However, this interpretation can be discarded because of the distinctly different color (pleochroism), characteristic shape, and even distribution of amphiboles in D10.

There could be excess argon in the amphiboles – a well-demonstrated phenomenon and problem in dating rocks by the $^{40}Ar/^{39}Ar$ method, particularly with whole rocks. In this case, however, there must be just enough excess argon in the amphiboles to match the age (~220 Ma) of most other dated dikes in the area, which is a highly unlikely albeit possible situation. Another argument *against* excess argon contamination is that the age spectrum for amphibole D10 does not show the characteristic pattern of excess argon uptake, wherein the initial and final steps of the age spectrum would be expected to show strongly elevated ages. The isochron for the D10 amphiboles lends further support for the absence of excess argon in that no anomalously old outliers with significant gas volumes are found, and the isochron age is almost identical to that of the plateau age. The only other possibility is that excess argon is homogeneously distributed within the D10 amphiboles, a phenomenon that has not been shown to occur.

An argument presented in favor of a Jurassic age is the anomalous geochemistry of dike D10 as compared with other dikes in Sunnhordland (Færseth et al. 1976). However, this anomaly could simply mean that the source of this dike was different from that of the other dikes, which does not require D10 to be of an entirely different age.

Jurassic dike intrusion occurred in southern Sweden (Scania basalts) which appears to match the whole-rock ages of dike D10 (Eide & Torsvik, 1998). On the other hand, Jurassic magmatic rocks in the North Sea region are dated by the $^{40}Ar/^{39}Ar$ method to late Jurassic–early Cretaceous (154 ± 2, 152 ± 3, 148 ± 2, 144 ± 1, ~135, 133 ± 2, and 132 ± 3 Ma; Latin et al. (1990) and references therein), related in time to the well-established late Jurassic–early Cretaceous rift phase. These ages are younger than the whole-rock ages obtained for dike D10.

The most important observation with regard to the different $^{40}Ar/^{39}Ar$ ages for D10 is, in our opinion, the previously unnoted fact that the groundmass of D10 is altered, while the amphiboles are pristine. It is well known that the fine-grained groundmass in volcanic and sub-volcanic rocks is susceptible to loss of radiogenic argon upon alteration, such that an apparent K-Ar age can only be considered a minimum age of intrusion (e.g. McDougall & Harrison 1989). The fact that a $^{40}Ar/^{39}Ar$ step heating experiment on altered whole-rock material might yield a plateau is not grounds for interpreting the age as meaningful. In the case of fine-grained igneous rocks, it should be demonstrated that argon has quantitatively been retained. Normally, a number of replicate analyses from different sampling sites would be required to make a case (e.g., Løvlie & Mitchell 1982). In contrast, fresh amphibole phenocrysts from such rocks are well known for retaining radiogenic argon even when the groundmass does not. We interpret these results to indicate that the D10 groundmass has not retained its radiogenic argon during the alteration process, and that the K-Ar and $^{40}Ar/^{39}Ar$ apparent ages of the whole rock are geologically meaningless.

The whole-rock ages of 235 ± 5 (dike D5 with K-Ar whole-rock age of ~222 Ma) and 241 ± 6 Ma (D60, K-Ar whole-rock age of ~280 Ma) presented by Eide & Torsvik (1998) are difficult to interpret. If the ages represent the times of intrusion, they indicate dike intrusion during the interval 250–230 Ma, and show that the K-Ar whole-rock dates are unreliable for at least these two additional cases. Unfortunately, Eide & Torsvik's data show strong U-shaped age spectra, indicating a high level of excess argon contamination (McDougall & Harrison 1989). In these cases the saddles ('plateaus') are unlikely to have geologic meaning, and are likely to be too old, simply because the contamination is so marked. The fact that these samples yield 'plateaux' and 'isochrons' is not grounds for interpreting the ages as meaningful.

Regional perspectives

The apparent absence of Jurassic dikes on the Norwegian mainland is consistent with the general impression from the North Sea basin that Jurassic magmatism is concentrated in the central parts of the rift structures where extension is anomalously high (Latin et al. 1990). In particular, the late Jurassic extension was very mild in the North Sea region immediately west of Sunnhordland-Sotra (the Horda Platform), whereas Permo-Triassic extension was considerable in this region (Gabrielsen et al. 1990; Færseth et al. 1995).

The Permo-Triassic stretching history is likely to have caused upwelling and partial melting of the asthenosphere under the Horda Platform, and formation or reactivation of steep and deep-going fracture and fault systems in the Permian and Late Triassic enabled dike emplacement at high crustal levels. Steel & Ryseth (1990) identified the Early Triassic as a period of syn-rift sedimentation on the Horda Platform, and the rest of the Triassic period as a time of post-rift sedimentation. However, restoration of sections across the Horda Platform (Gabrielsen et al. 1990) has revealed the existence of a late Triassic phase of stretching which may be related to the intrusion of most of the Sunnhordland dikes. It is therefore likely that Permo-Triassic dikes or volcanic rocks also occur in the pre-Jurassic sequences in the Horda Platform to the west of the Sunnhordland-Sotra area.

The older group of dikes in Sunnhordland and Sotra (250–260 Ma) coincides in time with dolerite dike intrusion and reactivation of the Nordfjord–Sogn Detachment in the Sunnfjord region to the north (Eide et al. 1997; Torsvik et al. 1997), indicating that the Permo-Triassic phase dates back to the Early Permian. This is in agreement with recent K-feldspar $^{40}Ar/^{39}Ar$ geochronology (Dunlap & Fossen 1998), indicating increased denudation rates of southern Norway from the latest Carboniferous which may be related to crustal destabilization and North Sea rift initiation already at ~300 Ma.

Conclusions

Revision of existing K-Ar data and new $^{40}Ar/^{39}Ar$ step heating data for amphiboles from late coast-parallel dikes in the Sunnhordland–Sotra region indicates that most of the K-Ar data are reliable, although precision can be improved. Together, the existing data indicate that an Early Permian (250–260 Ma) pulse of magmatism was followed by more extensive dike intrusion along N–S to NNW–SSE lineaments in the early Late Triassic (~220 Ma). The ages demonstrate, as suggested by Færseth et al. (1976), that the N–S to NNW–SSE lineaments in Sunnhordland are Permian or older.

The new $^{40}Ar/^{39}Ar$ data discount the previously inferred Middle Jurassic age of one of the dikes within the Sunnhordland–Sotra fracture swarm, and the Jurassic whole-rock age obtained from this dike is attributed to secondary alteration of the groundmass. Unaltered amphibole phenocrysts from this dike yield what is considered to be a more reliable $^{40}Ar/^{39}Ar$ plateau age at 220 ± 2 Ma, perfectly consistent with other ages from Triassic dikes in Sunnhordland.

The Late Triassic phase of dike injection is likely related to crustal tension during rifting on the Horda Platform. Similarly, the Early Permian phase is connected to early rifting of the North Sea rift system.

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