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The age and tectonic significance of dolerite dykes in western Norway

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Abstract: Coast-parallel dykes in SW Norway, primarily of Permo-Triassic age, have been linked regionally to the early tectonic evolution of the Norwegian continental shelf. We demonstrate from palaeomagnetic data (mean declination=206.1°, inclination= − 30.1°, α_{95}=11.8°) that dolerite dykes in the coastal Sunnfjord region of Western Norway and immediately west of the Devonian Basins are also of Permian (*c.* 250–270 Ma) age, and not lower- or pre-Devonian as previously advocated. The Sunnfjord dykes appear to be contemporaneous with dykes from SW Norway at Sotra (262 ± 6 Ma) and the oldest dykes from Sunnhordland (260–280 Ma), and geochemical data attest to a transition from sub-alkaline to alkaline magmatism at the dawn of the Mesozoic.

The Sunnfjord dykes are not simple records of E–W extension and magma intrusion, but instead represent significant mid–late Permian time markers within a complex zone of fault activation and rejuvenation. Late Mesozoic–Cenozoic magnetic overprinting (mean declination=348.6°, inclination= +68.9°, α_{95}=12°) and metamorphic alteration documented by these dykes are directly dependent upon proximity to major E–W brittle faults south of the Hornelen Devonian Basin, hence some motion and related fluid activity do post-date dyke intrusion. The E–W high-angle normal or oblique-slip faults can be regionally traced offshore to the Øygarden Fault Zone. Onshore, these faults truncate the Hornelen low-angle detachment, which in turn cuts folded Devonian strata. These observations, along with evidence for Permian and Late Jurassic–Cretaceous extension from the nearby Dalsfjord region, demonstrate important reactivation of a Late to post-Caledonian detachment and high-angle fault system in Western Norway.

Keywords: Norway, Permian, dykes, faults, reactivation.

Recent interpretation of seismic reflection data from offshore Western Norway (Fig. 1a) indicates that Permian extension was significantly greater and more regionally important than the Mesozoic (Jurassic–early Cretaceous) extension (Christiansson *et al.* 1995; Færseth *et al.* 1995). In onshore areas, Permian low-angle fault-rejuvenation in western Norway (Torsvik *et al.* 1992; Osmundsen 1996; Eide *et al.* 1997) and coast-parallel Permo-Triassic dykes in Southwest Norway (Færseth *et al.* 1976; Løvlie & Mitchell 1982) further attest to the importance of Late Palaeozoic rifting in the region (Fig. 1a).

Relatively abundant, coast-parallel, predominantly N–S-trending dykes, from the Sunnfjord area of Western Norway have also been noted since early mapping in the area commenced (Reusch 1881), but their age(s) and tectonic significance were never thoroughly investigated. The majority of these dykes were affected by E–W high-angle faults south of the Hornelen Devonian Basin (Fig. 1b); thus, Skjerlie & Tysseland (1981) interpreted the dykes as Lower Devonian or older because the faults were traditionally and regionally interpreted as primary controlling elements of Devonian sedimentation (Steel 1976; Norton 1986; Seranne & Seguret 1987). However, in more recent studies, these faults have been found to contain Late Palaeozoic and Mesozoic rejuvenation components (Torsvik *et al.* 1988, 1992; Wilks & Cuthbert 1994). The importance of establishing the age of the Sunnfjord dolerite dykes is therefore two-fold. First, they represent an important coast-parallel magmatic event which probably ties to the offshore tectonic development (pre-syn-rift?). Second, the dyke ages provide an important time-marker for subsequent faulting or rejuvenation of E–W high-angle structures in Western Norway.

Regional setting

The west Norwegian geological infrastructure is largely a product of the Scandian Orogeny that resulted from continental collision between Baltica and Laurentia and subsequent, extensional post-orogenic tectonics. In the Sunnfjord area, the continental collision can be accurately timed to the Mid-Silurian by the stratigraphic and deformational history of the Herland Group on Atløy (Fig. 1b) (Andersen *et al.* 1990). The collision hallmarks included high, pre-collision plate velocities (Torsvik *et al.* 1996), whole-scale subduction of Baltic continental crust and ensuing rapid Late Silurian–Lower Devonian exhumation of an orogen that contains high- and ultra-high pressure (HP–UHP) metamorphic rocks (Andersen *et al.* 1991, 1994; Dewey *et al.* 1993; Dobrzhinetskaya *et al.* 1995; Eide & Torsvik 1996). Extensional and erosional unroofing along the central parts of the orogen eventually resulted in formation of high-angle faults in the exhumed middle and upper crustal complexes. These faults subsequently controlled the formation of the Devonian Old Red Basins of Western Norway (Osmundsen & Andersen 1994) and were rooted in an array of lower-angle, extensional detachments that presently floor the eastern margins of the Devonian Basins (Andersen & Jamtveit 1990). The principal Nordfjord–Sogn Detachment

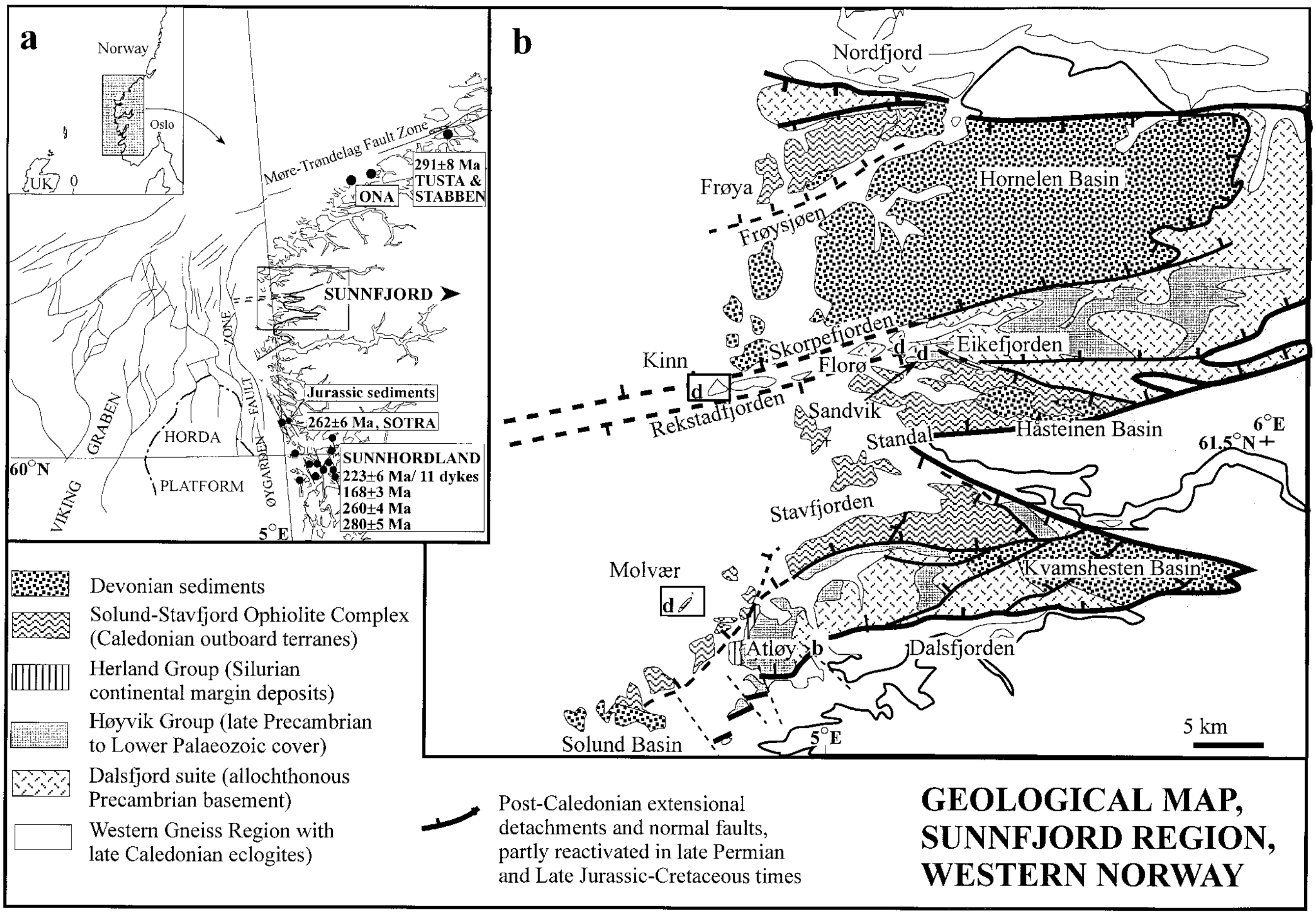

Fig. 1. (a) Sketch map of western Norway (see inset map for location in Norway), principal offshore structural elements and location of Permo-Triassic coast-parallel dykes. (b) Geological map of the Sunnfjord region, western Norway (see inset in a) and Sunnfjord dyke sampling localities (marked d). Fault-rock localities (Dalsfjord Fault) from the Atløy-Askvoll region (see text) are marked b.

(Norton 1986) juxtaposes the late-Caledonian HP rocks of the Lower Plate and low- to medium-grade Precambrian to Silurian allochthonous units of the Upper Plate (Fig. 1b) (Dewey *et al.* 1993; Andersen *et al.* 1994).

With the exception of the Håsteinen Basin which is mostly unconformable on its substrate, the Devonian Basins in western Norway are presently bounded by low-angle detachments to the east, reactivated faults along their northern and southern margins, and depositional unconformities to the west (Fig. 1b). Within the detachments and other major shear zones, kinematic indicators demonstrate top-west displacement; associated stretching lineations and magnetic fabrics have an E–W orientation (Chauvet & Seranne 1989; Swensson & Andersen 1991; Torsvik *et al.* 1992). Most of the penetrative deformation in the hanging- and footwalls of the detachments have been traditionally explained as syn-kinematic features related to post-orogenic extensional collapse (Seranne & Seguret 1987; Seguret *et al.* 1989). However, the structure of Devonian Basins, as well as their Upper and Lower Plate substrates, are dominated by inversion and E–W folding; these structures are arguably related to a phase of N–S shortening. Based on palaeomagnetic studies, Torsvik *et al.* (1988) demonstrated that N–S shortening continued into the Late Devonian and possible Early Carboniferous, although detailed structural studies in the footwall of the main detachment indicate that N–S shortening may have been related to sinistral transtensional deformation that had already begun in the Devonian (Krabbendam pers. com. 1996).

Sunnfjord dykes

The Sunnfjord dykes (Reusch 1881; Kolderup 1928; Kildal 1969; Skjerlie & Tysseland 1981) intrude the Late Precambrian and early Palaeozoic sequences of the basement and allochthons, but have not been observed to cut the Devonian Basins. Dykes trend 350°–060° (but mostly N–S) with steep WNW or vertical dips and vary in thickness from 0.1 to 10 m (Skjerlie & Tysseland 1981). Detailed sampling profiles from eight dykes and contacts at Molvær (Fig. 2a) and Kinn (Fig. 2b) were drilled in the field, whereas two dykes at Florø and Sandvik (Fig. 1b) were hand-sampled for logistic and archaeological reasons.

The Sunnfjord dykes have chemical compositions similar to continental tholeiites (Skjerlie & Tysseland 1981), but exhibit variable primary igneous textures and degrees of secondary alteration. Primary igneous textures appear to be logically correlated with dyke width and corollary differences in intrusive cooling rates, whilst secondary alteration depends upon the proximity of the dykes to the E–W Skorpe- and Rekstadfjorden Faults (Fig. 1b).

The least altered dykes occur on the Molvær isles (Figs 1b & 2a) where they intrude a highly deformed sequence of

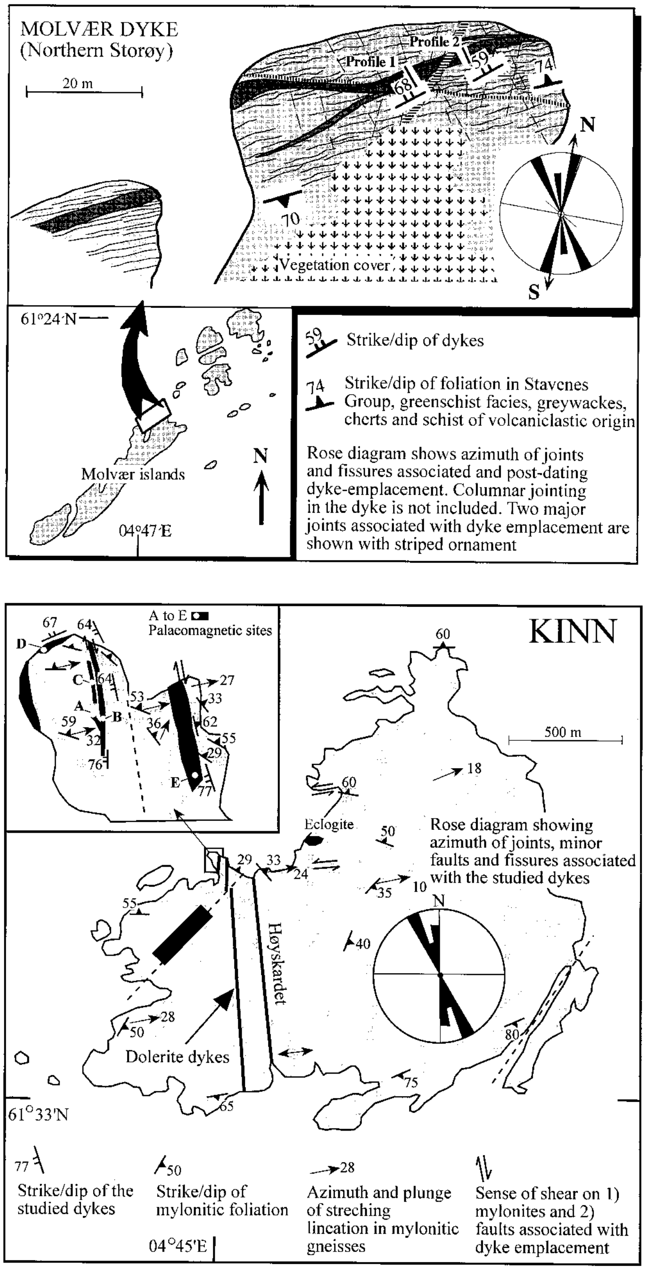

Fig. 2. Geological sketch map from (a) the Molvær isles and (b) Kinn (see Fig. 1b). Structural data from central and southern Kinn from Lutro (1991).

greenschist-facies schists, including meta-greywackes, graphitic schists, meta-cherts and meta-tuffaceous rocks of the Stavenes Group. The latter represents the volcano-sedimentary cover to the late Ordovician Solund–Stavfjord Ophiolite Complex (Furnes *et al.* 1990) both of which were obducted onto the Middle Silurian Herland Group during the initial stages of the Scandian orogeny (Andersen *et al.* 1990). The relationships between the Molvær dykes and the wall-rock structure indicate that dyke emplacement was partly controlled by the orientation of the main foliation of the Stavenes Group and a NNE-trending joint system that at least locally predates the Molvær dykes. A pre-existing, roughly E–W trending (0.1–0.5 m wide) zone of cataclastic brecciation controlled a 15 m long, E–W segment of the dyke (Fig. 2a). A separate set of NW-trending fractures apparently post-date the dykes at Molvær.

Except for jointing, the Molvær dykes are essentially unmetamorphosed and display glassy chilled margins and columnar jointing; both features indicate shallow intrusion levels and rapid cooling against the wall-rock. The dykes are hypocrystalline basalts with phenocrysts of plagioclase, clinopyroxene, and oxides in a groundmass that largely comprises grey-green, fresh glass. The opaque phases comprise abundant titanomagnetite and some accessory pyrite. Titanomagnetite grains range in size from the limit of optical resolution up to several hundred microns. Grain are elongated and often skeletal, indicative of fairly rapid cooling. Close inspection of the grains (Fig. 3a) shows that ilmenite lamellae are present on a very fine scale, indicating high-temperature oxidation to class II of Ade-Hall *et al.* (1971). The lamellae are closely spaced and always less than 1 μm in width, causing a partitioning which should have a marked effect on the domain state of the larger grains.

A basaltic dyke at Sandvik, just south of the Rekstadfjorden Fault (Fig. 1b), intrudes Late Precambrian quartzites and appears fresh in hand-specimen, but has undergone some low-grade metamorphic alteration. Plagioclase is pervasively pseudomorphed by sericite, while clinopyroxene is generally unaltered or may have minor epidote, biotite or amphibole replacement products. The dominant opaque phase is abundant class II titanomagnetite (Fig. 3b) with accessory pyrite. Slight to moderate low-temperature oxidation, with granulation and some replacement of opaque phases along grain edges is evident.

The Kinn dykes (Figs 1b & 2b) intrude highly deformed orthogneisses which locally preserve eclogite facies assemblages correlated with the Western Gneiss Region. Dyke margins are variably brecciated and in outcrop, these dykes are part of an intrusive network that comprises a large, coarse-grained gabbroic dyke- or sill-like mass with numerous, associated, narrow, branching aphanitic to porphyritic basaltic dykes. The main gabbro body (Site E in Fig. 2b) has a coarse-grained, subophitic texture, although clinopyroxene now occurs as sub- to euhedral grains with preserved cores replaced progressively or completely by amphibole. Coarse-grained opaque grains are typically up to several hundred microns in size. Titanomagnetite of high-temperature oxidation class II is again the dominant phase (Fig. 3c). The grains exhibit coarse ilmenite lamellae, and often contain smaller inclusions of pyrite. Low temperature alteration of individual titanomagnetite grains varies from slight to heavy, with replacement of oxides by non-opaque phases resulting in many cases. Fine-grained oxides occur on pseudomorphic amphibole.

The thinner basaltic Kinn dykes probably once had a texture similar to that of Molvær, but are now completely altered to lower greenschist facies. A glassy groundmass comprises amphibole and chlorite, in addition to amphibole pseudomorphs after clinopyroxene. Two distinct generations of oxides are present: (1) Primary titanomagnetite grains with maximum sizes in excess of 100 μm with well-developed ilmenite lamellae indicating high-temperature oxidation to class II (Fig. 3d). The lamellae pattern is on a coarser scale than e.g. the Molvær dykes. (2) A pervasive cross-hatched pattern of elongate magnetite particles, apparently formed during secondary metamorphism of the rock (Fig. 3e). The pattern is best seen in transmitted light (Fig. 3f), and secondary magnetite appears to follow microfractures.

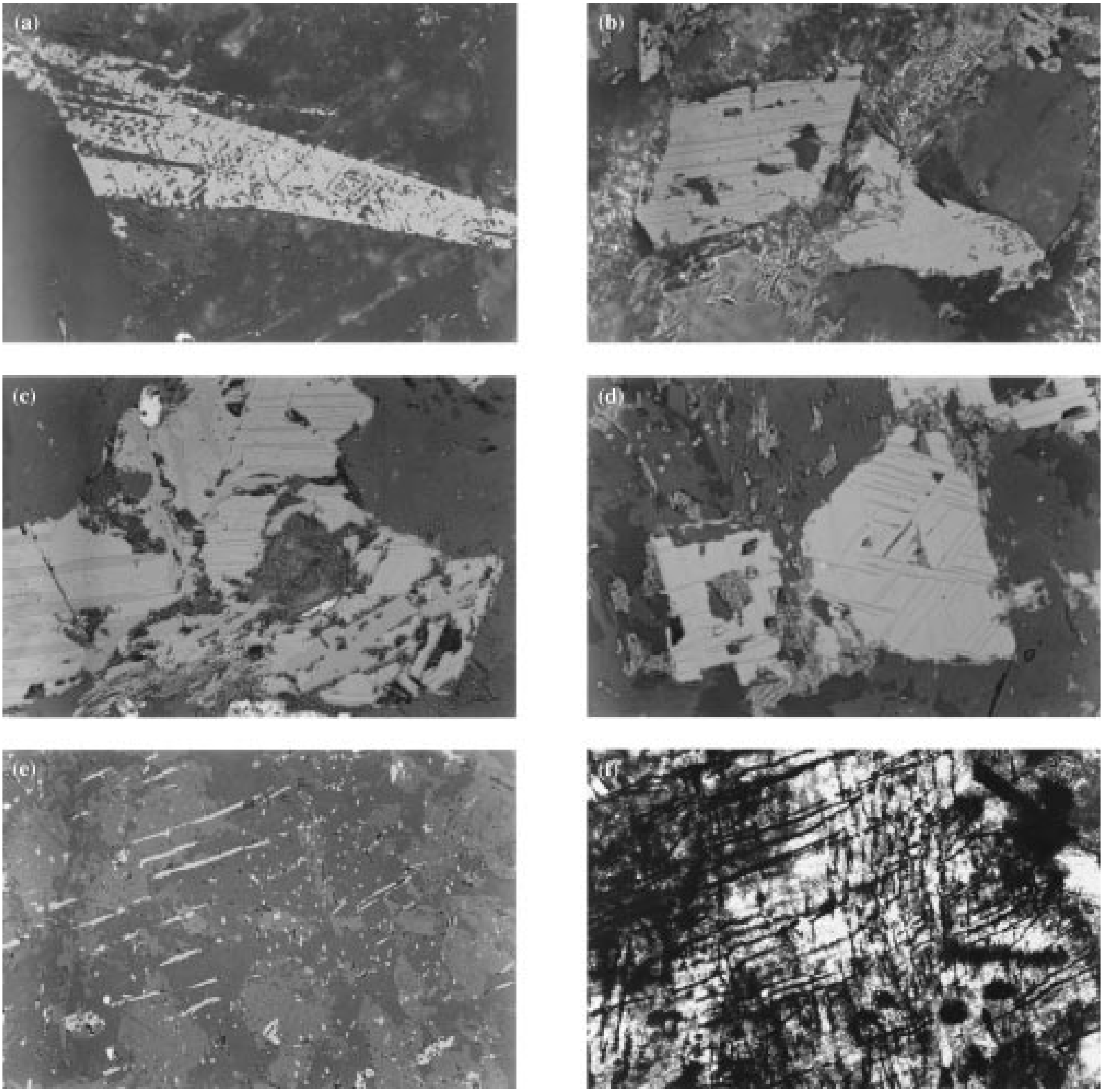

Fig. 3. Reflected light (a–e) and transmitted light (f) photomicrographs of opaque grains. See text for further descriptions. (a) Molvær dyke titanomagnetite (TM) grain. Frame width=130 μm. Note very fine-scale ilmenite lamellae. (b) Sandvik dyke TM grain. Frame width=130 μm. (c) Broad Kinn dyke TM grain (location E). Frame width=325 μm. (d) Thinner Kinn dyke TM grain (location A). Frame width=130 μm. (e, f) From same micrograph as (d) viewed in reflected and transmitted light, respectively, showing cross-hatched pattern of secondary magnetite. Frame width=325 μm.

Palaeomagnetic experiments

The natural remanent magnetization (NRM) was measured with a JR5A magnetometer and remanence stability was tested by thermal and two-axis tumbler alternating field (AF) demagnetization. Characteristic remanence components were calculated using least squares analysis. NRM intensities and bulk-susceptibilities are listed in Table 1.

Thermo-magnetic analysis was performed on a horizontal translation balance, and all tested samples, independent of dyke alteration state or location within a single dyke, yield Curie-temperatures of 580°C, i.e. titanium-poor titanomagnetite or almost pure magnetite (Fig. 4a). Heating and cooling curves are practically identical and indicate minimal thermo-chemical alterations during the experiments.

Isothermal remanent magnetization (IRM) acquisition curves are dominated by magnetic phases which saturate in fields of 150–300 mT, and remanence coercive forces (H_{cr}) vary from 15 to 40 mT. High H_{cr} and probable pseudo-single domain (PSD) magnetite are observed from the pristine

Table 1. *Sampling details, mean NRM intensity and susceptibility and characteristic remanence components for the Sunnfjord dykes (mean sampling coordinates: 61.5°N and 4.8°E)*

	Strike/dip	Width (m)	NRM	Sus	Dec°	Inc°	*N*	α_{95}	*k*	Component
Molvær dykes										
Dyke A	232°/59°	2.0	495 ± 247	45 949 ± 4873	355.8	63.2	12	7.6	33.8	M-C
					220.1	− 36.5	18	4.6	57.8	P
Dyke B	232°/59°	0.4	562 ± 97	35 281 ± 1837	329.8	73.8	3	17.5	50.8	M-C
					220.4	− 20.6	6	23.7	8.4	P
Dyke C	232°/68°	0.6	1070 ± 388	36 019 ± 4259	213.3	− 36.0	7	3.3	345.5	P
Contact schist			1.4 ± 0.9	529 ± 24	204.0	− 28.6	6	2.9	550.0	P
Sandvik dyke	036°/90°	1.5	1507 ± 67	77 868 ± 5535	342.6	+73.2	13	10.1	17.8	M-C
					191.5	− 32.8	8	8.2	46.7	P
Kinn dykes										
Dyke A	267°/63°	0.2	721 ± 250	55 862 ± 5117	069.0	+84.2	8	10.3	29.6	M-C
Dyke B	175°/64°	1.4	784 ± 219	53 927 ± 4699	030.4	+68.8	8	16.2	12.7	M-C
Dyke C	158°/70°	0.25	825 ± 227	57 577 ± 2738	038.7	+69.4	2	(38.4)	(44.4)	M-C
					188.3	− 22.8	3	(56)	(5.9)	P
Dyke D	240/67°	3.5+	792 ± 129	52 754 ± 5220						
Dyke E	170°/77°	9.0	854 ± 109	59 868 ± 7297	342.8	+53.1	3	26.3	23.1	M-C
Contact gneiss			260 ± 118	13 162 ± 9706	357.0	+60.2	3	28.5	19.7	M-C
Florø dyke	010°/90°	2.3	4889 ± 695	81 331 ± 4361	299.7	+42.3	5	8.5	82.2	M-C
Combined					348.6	+68.9	9*	12.0	19.4	M-C
					206.1	− 30.1	6*	11.8	33.3	P

NRM=natural remanent magnetization (mA/M); Sus=susceptibility (10^{-6} SI); Dec°, Inc°=mean declination and inclination; n=number of samples/sites*; α_{95}=95% cone of confidence; *k*=precision parameter; component interpretation: M-C, Mesozoic–Cenozoic; P, Permian.

Molvær dykes whilst the altered Kinn and Florø dykes show minimum values. This may partly indicate magnetite 'softening' with increased alteration, but properties of the magnetically harder Molvær dykes are clearly the result of smaller grains and finer lamella structure, i.e. due to primary mineralogic difference. Hysteresis analysis and saturation remanence to saturation magnetization (J_{rs}/J_s) and coercivity (H_{cr}/H_c) ratios show a clear trend towards a multidomain (MD) state from Molvær to Kinn dykes (Fig. 4b). J_{rs}/J_s is normally regarded as the best measure of grain size ranges, from 0.5 for uniaxial SD grains down to <0.02 for true MD magnetite (Dunlop 1986). Increasing titanium content raises the MS/PSD transition to 0.1. H_{cr}/H_c is theoretically between 1 and 2 for SD grains and increases with grain size. In practice true SD values for J_{rs}/J_s are very rare and in the Day diagram (Fig. 4b, Day *et al.* 1977), values most commonly fall in the PSD range. J_s values are around 1 Am^2 kg^{-1} for the Kinn, Florø and Molvær dykes and just below 2 Am^2 kg^{-1} for the Sandvik dyke, indicative of magnetite contents of *c.* 1% and 2% respectively.

Molvær dykes

The pristine Molvær dykes (Fig. 2) are characterized by two remanence components: (1) a low to intermediate unblocking component (denoted M-C) with northerly declinations and steep positive inclinations and, (2) a high unblocking component (denoted P) with SW declinations and negative inclinations (Fig. 5a; Table 1). Component P is characterized by discrete thermal unblocking between 560 and 580°C or by isolation in AF fields above 15–19 mT (Fig. 5b). Median destructive ($M_{1/2}$) AF fields range between 12 and 20 mT. In many instances the M-C component is not randomized before 550°C (Fig. 5a), but dyke margin samples and the baked contact schist (Fig. 5c) are less influenced by the M-C component. Maximum susceptibilities are recorded in the widest dyke A (Fig. 5d) and marginal samples show lower values than the interior and centre, which may attest to grain-size contrasts. However, titanomagnetite concentration and degree of high-temperature titanomagnetite oxidation are important

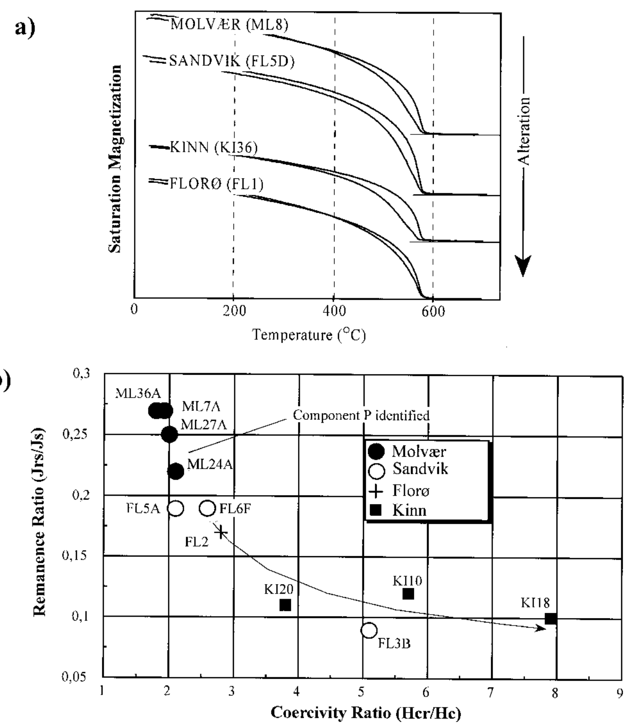

Fig. 4. (a) Thermomagnetic curves from the Sunnfjord dykes which are all identical with $T_c \approx 580$°C and reversible heating and cooling curves (b) J_{rs}/J_s and H_{cr}/H_c ratios. In the Day diagram, only the encircled samples with high J_{rs}/J_s and low H_{cr}/H_c reveal the P-component (probably primary Permian).

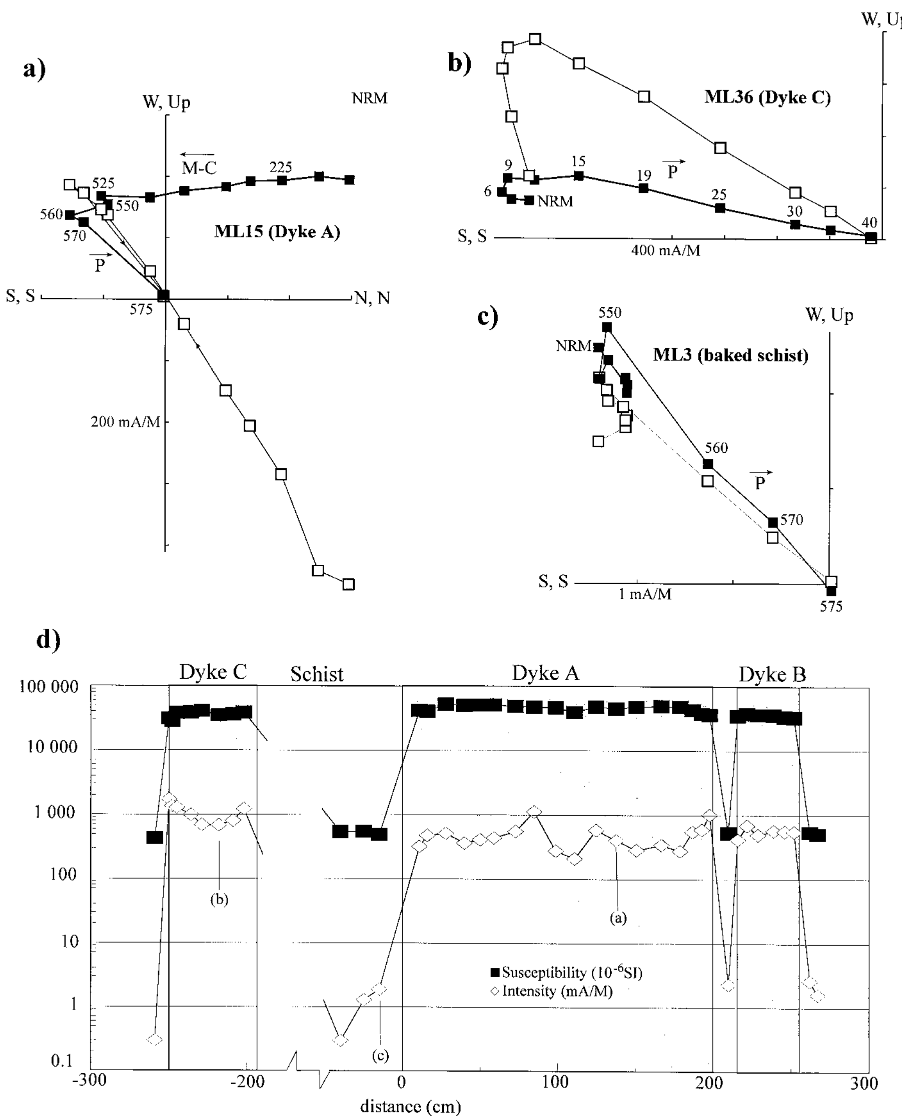

Fig. 5. Thermal (a) and alternating field (b) demagnetization of Molvær dyke samples and (c) thermal demagnetization of a baked contact sample. (d) Intensity and susceptibility profile (note logarithmic scale) through the tested dykes and contact (distance in centimetres). In orthogonal vector plots, solid (open) symbols represent projections onto the horizontal (vertical) plane.

factors. NRM intensities are also clearly influenced by overprints (M-C), but the narrow dyke C (Profile 2 in Fig. 2a), which is least affected by the M-C component, exhibits a pattern of high NRM with low susceptibility along the margins. This probably reflects a relatively undisturbed primary cooling pattern of a fine-grained margin and coarser-grained interior. The P component in the contact schist closely corresponds to the dyke components but schists sampled outside the baked region did not yield sensible palaeomagnetic results due to low intensity and viscous directional behaviour.

Sandvik dyke

The Sandvik dyke (Fig. 1b) is directionally more complex than the Molvær dykes. Most commonly the M-C component is identifiable whereas the P component is not isolated. Southerly directional trends show that the high unblocking component P is always present (identified in Fig. 6a), but 'stable end-directions' are often difficult to observe (Fig. 6b) due to the combined effect of overlapping unblocking-spectra and the fact that the P component often resides within an extremely narrow temperature interval (570–580°C). $M_{1/2}$ is considerably lower than the Molvær dykes, generally 1–5 mT, except in a subordinate number of samples where the P component was identified and $M_{1/2}$ was 10–12 mT.

Kinn dykes

These dykes were tested in considerable detail due their relatively complex textural characteristics (Fig. 3), but demagnetization behaviour is similar to, but less stable than those from Sandvik. All samples show pronounced southerly directional movement during demagnetization (Fig. 6b), but the high unblocking P component is difficult to isolate and only poorly identified in three samples from one dyke at temperatures above 550–570°C (Fig. 6c, Table 1). Low $M_{1/2}$ (2–4 mT) prevails, and the low to intermediate M-C components are comparable to those from Molvær and Sandvik (Fig. 7a).

Florø dyke

The Florø dyke has significantly higher NRM intensity (Table 1) and only M-C components are identified. A few samples from this strongly altered dyke were thermally tested; they all show identical and almost uni-vectorial directional behaviour (Fig. 6d), but with somewhat more westerly declinations than M-C components from the other dykes (Fig. 7a).

Magnetic interpretation

Palaeomagnetic results from Sunnfjord dykes reveal a high unblocking component (P) with SSW declinations and negative inclinations, which is partially or entirely (Florø) overprinted by components (M-C) with N or NNW declinations and positive inclinations (Fig. 7a). Component P can be interpreted as mid–late Permian (*c.* 250–270 Ma) with a late Mesozoic–Cenozoic (M-C), probably Cretaceous or younger, overprint (Fig. 7a). The Sunnfjord dyke pole (P) is almost identical to fault-rocks ('green breccia' of Torsvik *et al.* 1992) from Atløy (Fig. 8), formed during low-angle faulting on the Dalsfjord Fault (Fig. 1b), and isotopically dated to 250–260 Ma (Eide *et al.* 1997). The Permian magnetic signature in the Sunnfjord dykes represents either a primary intrusion age or a regional overprint. We prefer the former explanation because extensive palaeomagnetic studies of the Devonian Basins and substrate (including an anorthosite locality 200 m from the Sandvik dyke; Site 25 in Torsvik *et al.* 1988) in the Sunnfjord area essentially yield pre-Permian magnetic ages.

Alteration and magnetic resetting of the Sunnfjord dykes is clearly related to movements along the prominent E–W faults south of the Hornelen Devonian Basin (Fig. 1b). Just south of the Rekstadfjorden Fault, at Sandvik, Permian directions are partially recovered whereas within the fault-zone, remagnetization prevails (Kinn), and at Florø (Fig. 1b) the Permian direction is entirely obliterated. These magnetic characteristics are represented by respective differences in mineralogy and degree of metamorphism, manifested first by primary igneous textural characteristics and grain sizes, and second, by the effects of subsequent metamorphic (hydrothermal) alteration on the magnetomineralogy. The M-C overprint plots near the present earth's magnetic field direction and may partly have a viscous and recent origin.

The Sunnfjord dykes all share a similar primary magnetic phase, i.e. abundant titanomagnetite of oxidation class II (Fig. 3) which explains the high Curie temperatures and unblocking temperatures. Differences in magnetic hardness partly arise from differences in grain-size and coarseness of the lamellae. The Molvær dykes show signs of fairly rapid cooling with commonly skeletal and very fine scale lamellae, while the broadest Kinn dyke (Dyke E) has the largest grains and coarsest lamellae. Varying degrees of low-temperature alteration of the primary titanomagnetite phase are evident in all dykes, and the thinner Kinn dykes (and Florø dyke) have a second significant magnetic phase (magnetite), clearly associated with later, lower greenschist-facies metamorphism (Fig. 3e & f).

A regional dyke perspective

Permo-Trassic dykes are observed in several areas in coastal western Norway, and the oldest dated dykes are located at

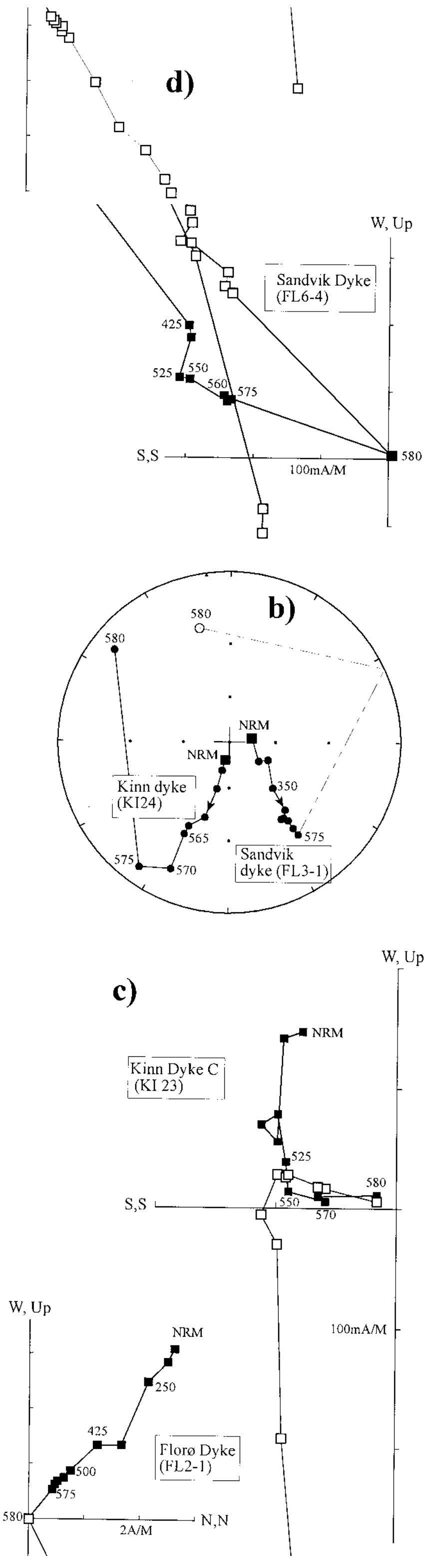

Fig. 6. Thermal demagnetization samples from the Sandvik (a, b), Kinn (b, c) and Florø dykes (d). In the stereoplot, closed (open) symbols denote positive (negative) inclination. See Fig. 5 for further legend.

a)

b)

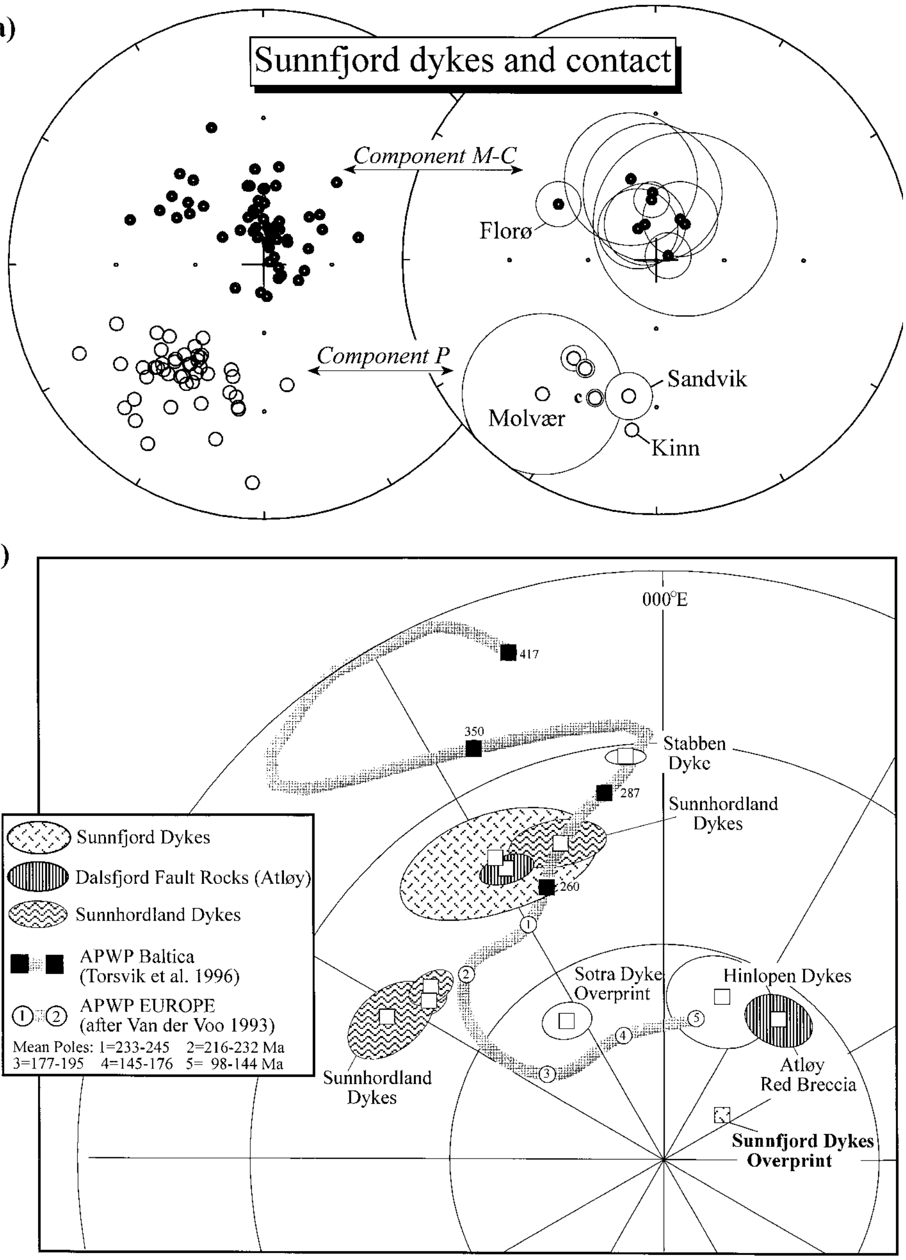

Fig. 7. (a) Characteristic remanence components from the Sunnfjord dykes, sample (left) and dyke-contact mean directions (right diagram with α_{95} confidence circles), respectively. (b) Apparent polar wander paths (APWP) for Baltica and Europe, selected poles from Western Norway (Table 2) and the Sunnfjord mean poles (component P and M-C, Tables 1–2). Sunnfjord M-C pole is shown without error confidence ellipses (d*p*/d*m*). For comparison, we also include a pole from the *c.* 145 Ma Hinlopen dolerites (Halvorsen 1989). Equal area polar projection.

Tustna-Stabben (Fig. 1a) and within the eastern part of the Møre Trøndelag Fault Zone. The palaeomagnetic pole from the E–W Stabben syenitic dykes (Sturt & Torsvik 1987) plots at the Lower Permian part of the Baltica APWP (Fig. 7b) and a Rb–Sr age of 291 ± 8 Ma obtained from the nearby island of Tustna (Råheim 1974) fits well with the magnetic age estimate. South of the Møre Trøndelag Fault Zone, N–S-trending basaltic dykes are observed on the island of Ona (Fig. 1a; Robinson pers. comm. 1995) but presently lack isotopic age constraints.

Isotopic age data are not yet available for the Sunnfjord dykes, but the palaeomagnetic data strongly suggest a mid-late Permian age (*c.* 250–270 Ma; Fig. 7a). Two ultrapotassic dykes from the same region (Dalsfjord area) are dated between 256–262 Ma (K/Ar whole rock; Furnes *et al.* 1982). These dykes, however, are highly altered with a strong magnetic fabric, and palaeomagnetic testing proved unsuccessful (Torsvik unpublished data 1992). Their unusual strike (E–W) and geochemistry are also markedly different from the sub-alkaline tholeiitic Sunnfjord dykes (Fig. 8b). Following Furnes *et al.* (1982) we regard it reasonable to conclude that the K/Ar whole rock ages from these dykes relate to strong hydrothermal alteration, probably linked to movement along the Dalsfjord Fault. The exact intrusion-crystallization age of these dykes is therefore uncertain.

Further southward along the coast, six concordant ages from two dykes on the island of Sotra (west of Bergen; Fig. 1a) yield a mean age of 262 ± 6 Ma (Fig. 8a; Løvlie & Mitchell 1982). Unpublished geochemical data suggest a continental tholeiitic affinity, conceivably similar to the Permian-aged Sunnfjord dykes (Furnes pers. comm. 1996). The palaeomagnetic data from the Sotra dykes, however, are clearly discordant with the Permian isotopic ages (Fig. 7b). The Sotra dykes are located along a major NNW–SSE lineament and the

Table 2. *Post-Carboniferous palaeomagnetic data from Western Norway (Figs 1 and 7b) that are discussed in the text*

Site Rock Unit (Geo.Lat., Geo.Long.)	Dec°	Inc°	α_{95}	Pole Lat.	Pole Long	d*p*	d*m*	Isotopic age	Magnetic age estimate	Ref.
NW Norway										
Stabben Dykes (63.3°N, 8.5°E)	192.0	− 12.0	2.4	− 32.1	354.4	1.0	2.0	291 ± 8 Ma (Rb/Sr)	Early Permian	1, 2
Central western Norway										
Sunnfjord Dykes (61.5°N, 4.8°E)	206.1	− 30.1	11.8	− 41.0	330.7	7.3	13.1		Mid–late Permian (Component P)	3
Sunnfjord Dykes (61.5°N, 4.8°E)	348.6	+68.9	12.9	− 79.0	053.9	17.3	20.4		<Cretaceous (Component M-C)	3
Atløy 'green breccia' (61.3°N, 5°E)	205.0	− 33.0	3.2	− 43.2	331.5	2.0	4.0	253 ± 5 Ma ($^{40}Ar/^{39}Ar$)	Mid–Late Permian	4, 5
Atløy 'red breccia' (61.3°N, 5°E)	342.0	+58.0	3.2	− 64.8	039.5	3.0	5.0	<130 Ma ($^{40}Ar/^{39}Ar$)	L. Jurrassic–E. Cretaceous	4, 5
SW Norway										
Sotra Dykes (60.0°N, 5°E)	019.5	+59.1	2.3	− 66.0	325.0			262 ± 6 Ma (K/Ar)	Jurrasic ?	6
Sunnhordland Dykes (59.8°N, 5.5°E)	198.0	− 27.0	5.8	− 43.0	342.0			280–164 Ma (K/Ar)	Permian	7, 8
Sunnhordland Dykes (59.8°N, 5.5°E)	047.8	+48.9	5.0	− 46.0	297.0				Triassic	7
Sunnhordland Dyke-UH (59.8°N, 5.5°E)	040.0	+48.0	2.5	− 49.2	306.3			280 ± 5 Ma (K/Ar)	Triassic	9, 8
Sunnhordland Dyke-SA (59.8°N, 5.5°E)	041.0	+50.0	1.9	− 50.2	303.8			223 ± 6 Ma (K/Ar)	Triassic	9, 8

Ref, References: 1, Sturt & Torsvik (1987); 2, Råheim (1974)-recalculated age from the Tustna dyke; 3, this study (Table 1); 4, Torsvik *et al.* (1992); 5, Eide *et al.* (1997); 6, Løvlie & Mitchell (1982); 7, Løvlie (1981); 8, Færseth *et al.* 1976-recalculated ages; 9, Walderhaug (1993).

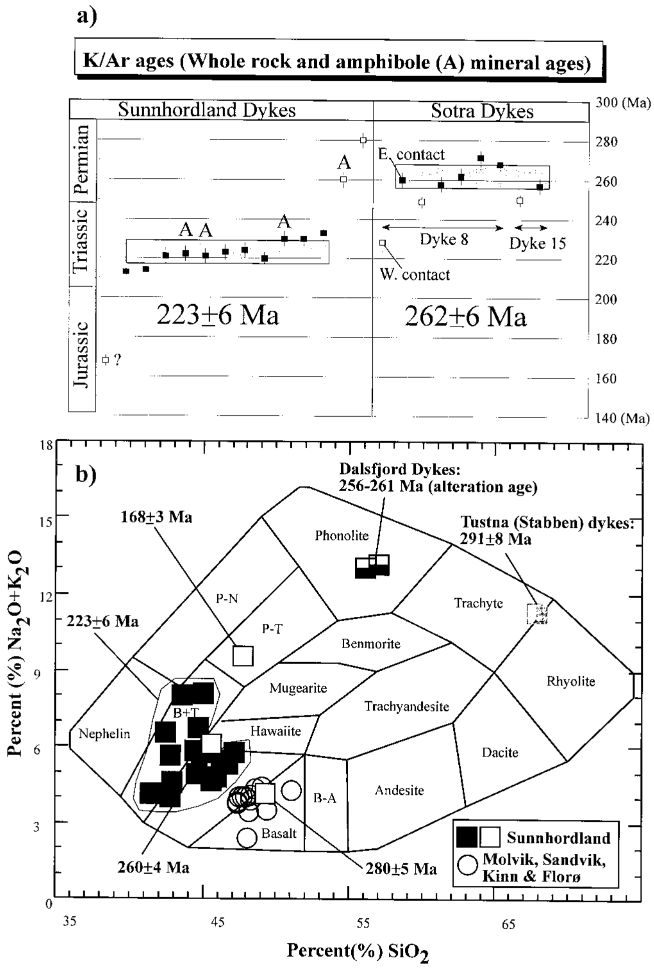

Fig. 8. (a) Recalculated K/Ar ages from 14 Sunnhordland dykes, Western Norway (after Færseth *et al.* 1976). Also included are K/Ar data from dykes (two profiles) from Sotra (Løvlie & Mitchell 1982). Concordant ages (with errors) are shaded. (b) Alkali–silica discrimination plot for the sub-alkaline Sunnfjord dykes (Molvær, Sandvik, Kinn & Florø; data from Skjerlie & Tysseland 1981), Sunnhordland dykes (mainly alkaline signature; data from Færseth *et al.* 1976). Also included for comparison, data from the Dalsfjord (Furnes *et al.* 1982) and Tustna dykes (Råheim 1974). B − A, basaltic andesite; B+T, basanite/tephrite; P − T, phonolitic tephrite; P − N, phonolitic nephelinite

palaeomagnetic pole probably represents a Jurassic re-magnetization. In this respect it is important to note that faulted and fractured Jurassic sediments have recently been discovered in a fjord close to these dykes (Fossen 1997).

In the Sunnhordland region (Fig. 1b), Færseth *et al.* (1976) obtained 11 concordant K/Ar whole-rock and amphibole ages from alkaline-basaltic dykes that yielded a mean age of 223 ± 6 Ma (recalculated ages, this study; Fig. 8a). With the addition of a few 'outlying' ages (280 ± 5, 260 ± 4 and 168 ± 3 Ma), they argued for three intrusive events, i.e. Permian, Mid-Triassic and Jurassic. In our opinion, the composite 223 ± 6 Ma isotopic age fits with the bulk palaeomagnetic poles from these dykes (Løvlie 1981, Walderhaug 1993) since they plot near the 216–232 Ma mean pole for Europe (Van der Voo 1993; Fig. 7b). From some dykes, Løvlie (1981), found a poorly defined Permian direction (see pole in Fig. 7b) and this may validate the 260–280 Ma K/Ar ages.

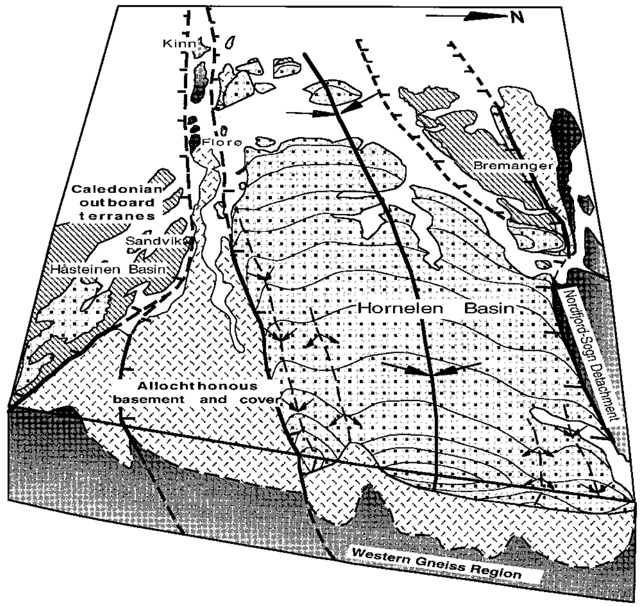

Fig. 9. Block diagram of the Hornelen Basin and substrate. The NNE–SSW section demonstrates age relationships between the basin-margin faults, Devonian basin fill, detachments and the regional east–west-trending folds in western Norway. Notice that the Nordfjord–Sogn Detachment capping the Western Gneiss Region is more intensely folded than the Hornelen Detachment. The low-angle and gently folded Hornelen Detachment truncates already folded Devonian sediments. The south-margin fault of the basin truncates all the other main structural elements in the area.

Færseth *et al.* (1976) noted that the 280 ± 5 Ma dyke differs in bulk- and rare earth element geochemistry from other Sunnhordland dykes; its sub-alkalic signature is comparable with the Sunnfjord dykes (Fig. 8b) and probably also to the Permian Sotra dykes. This argues for a Permian origin for some Sunnhordland dykes, although the 260 Ma Sunnhordland dyke does not follow the same chemical trend. The 168 Ma dyke age is troublesome since palaeomagnetic data from this dyke are similar to the 223 Ma dykes (Løvlie 1981; Walderhaug 1993) and new isotopic age data are clearly necessary to clarify the incongruities. On balance, available palaeomagnetic, isotopic and geochemical data from the entire group of dykes in Western Norway indicate probably two (mid–late Permian and mid-Triassic) intrusive events with subtle different magmatic signatures.

Conclusions

Palaeomagnetic data from the Sunnfjord dykes in coastal western Norway suggest a mid–late Permian (250–270 Ma) age and not Early Devonian or older age as argued by earlier workers. The primary remanent signature is carried by deuterically oxidized titanomagnetite (class II); the documented strong Late Mesozoic–Cenozoic overprinting and metamorphic alteration up to lower greenschist facies relate to proximity to major E–W shear zones and faults south of the Hornelen Devonian Basin. This leads to the conclusion that some of the motion and related hydrothermal fluid flow along the faults post-date dyke intrusion. The Sunnfjord dykes are thus not simple records of E–W extension and magma intrusion, but rather represent significant time markers within a complex zone of fault activation and rejuvenation. Mapping

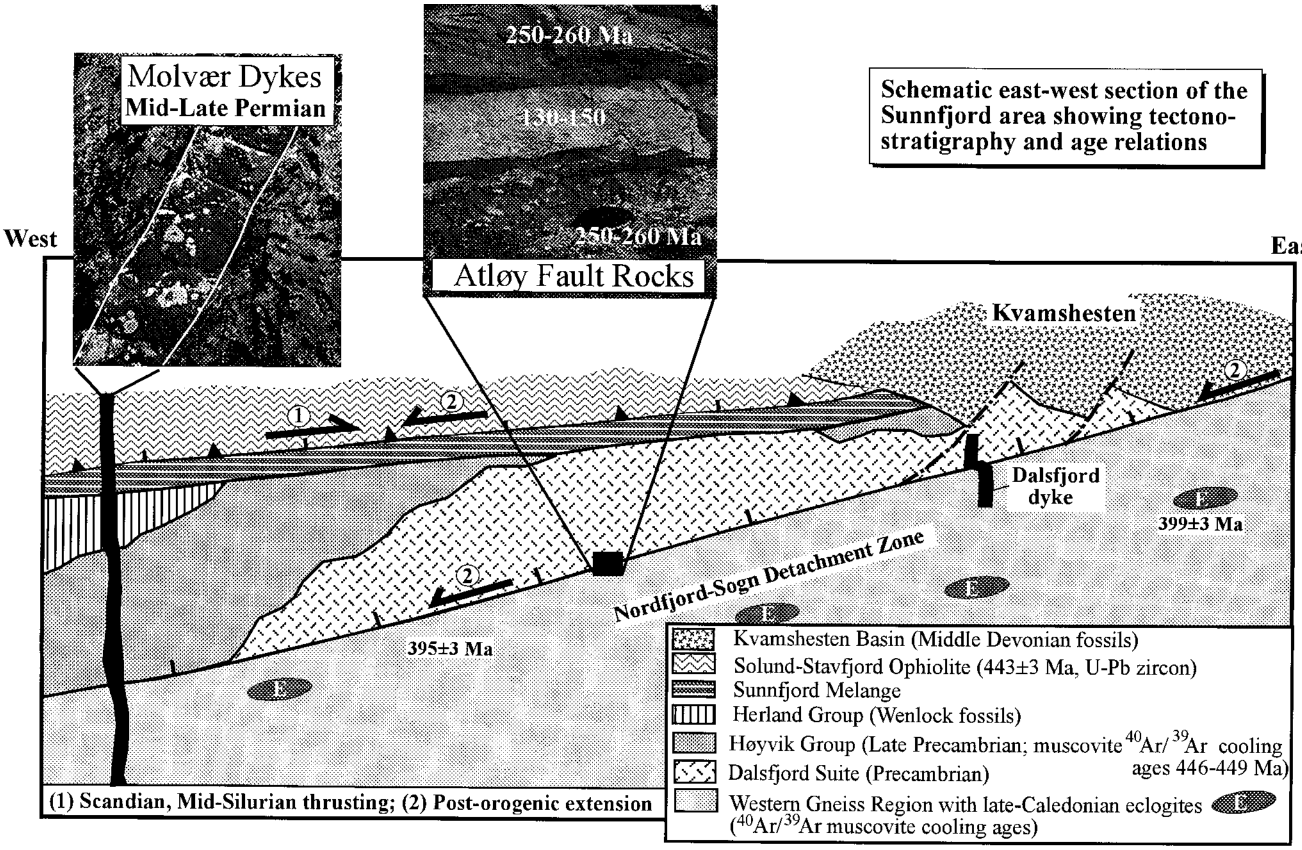

Fig. 10. Schematic (not to scale) east–west section of the Kvamshesten Devonian Basin and substrate. The profile illustrates the tectono-stratigraphy and the approximate position of the Molvær and Dalsfjord dykes. Notice that syn-depositional Devonian faults are truncated by the reactivated Nordfjord–Sogn Detachment, and that the Dalsfjord dyke is deformed by the fault. The relationship between the Molvær dykes and the main detachment can only be inferred from the relationships at Kinn, Florø and Sandvik. $^{40}Ar/^{39}Ar$ cooling ages of white micas are from Berry *et al.* (1993), Andersen *et al.* (1997) and Eide *et al.* (1997).

along the southern and eastern margin of the Hornelen Basin also shows that the south-margin fault of the basin truncates the east margin low-angle detachment, which in turn truncates the already folded youngest Devonian strata in the Hornelen Basin (Fig. 9). These observations of polyphase normal faulting reinforce previous analyses (Torsvik *et al.* 1988, 1992; Wilks & Cutbert 1994) and support the new palaeomagnetic data which demonstrate important reactivation of the Late to Post-Caledonian detachment and high-angle fault system in Western Norway. It is also noteworthy that the provenance for the Hornelen Devonian sediments is entirely from the Upper Plate lithologies (Nilsen 1968; Cuthbert 1991) and thus clearly demonstrates post-depositional rejuvenation of the main detachments and faults that presently bound the basins.

The importance of contractional and extensional rejuvenation of the Devonian on-shore structures in western Norway for the Late Palaeozoic and Mesozoic tectonic development of the offshore Horda Platform and the Viking Graben (Fig. 1a) is equivocal since correlation and integrated interpretation of the on- and off-shore structural features have hitherto been few and preliminary. Nonetheless, onshore tectonic models do serve as templates for understanding offshore structural geometries, and in our opinion the following sequence of Late Palaeozoic–Mesozoic events can be deduced from the onshore information.

(1) The Sunnfjord dykes are mid-late Permian in age and probably contemporaneous with the geochemically similar Sotra dykes (262 ± 6 Ma) and the oldest phase of magmatism in the Sunnhordland area (260–280 Ma). Collectively they attest to major Permo-Triassic rifting and a change from sub-alkaline (Permian) to alkaline (Triassic) magmatism.

(2) The Hornelen Basin is bounded by a shallow westward dipping detachment in the east and to the north and south by steep brittle E–W faults which cut the detachment (Fig. 9). These are post-depositional structures, although they probably lie close to the syn-sedimentary Devonian bounding faults. The E–W faults clearly affect the Permian aged Sunnfjord dykes and therefore record a protracted rejuvenation history and magnetic resetting during the Mesozoic–Cenozoic. Indeed, these faults are still seismically active.

(3) The E–W brittle faults can clearly be traced offshore to the Øygarden Fault Zone (Fig. 1a), the most extensive N–S structural element in offshore Norway, and probably representative of the main basin margin during Permo-Triassic and Jurassic extension (Færseth *et al.* 1995). Detailed offshore aeromagnetic studies which are underway will delineate if these E–W faults cut, or terminate at, the Øygarden Fault Zone.

(4) In the Dalsfjord region (Atløy, Fig. 1b) there is blatant onshore evidence for reactivation of the Nordfjord-Sogn Detachment (Fig. 10). Well-dated fault-rocks indicate that the Dalsfjord Fault, now flooring the Kvamshesten Devonian Basin, underwent periods of brittle low-angle (<15°) extensional reactivation during Permian and Upper Jurassic/Lower Cretaceous times (Torsvik *et al.* 1992; Eide *et al.* 1997).

Palaeomagnetic data from the oldest brittle fault rocks at Atløy (250–260 Ma) match the Sunnfjord dykes (Figs 7a & 8), and it thus appears that sub-alkaline magmatism and low-angle faulting were fairly contemporaneous, and in a predominantly E–W-oriented extensional stress field.

(5) South of the Solund Devonian Basin (Fig. 1), Færseth *et al.* (1995) argue that the Solund Fault (part of the Nordfjord-Sogn Detachment) continues offshore and represents a major structural barrier with opposing blocktilts. Although they find no direct evidence of post-Devonian faulting or reactivation, we observe that the Dalsfjord and probably also Solund Faults are 'young' tectonic features and the most important onshore faulting took place during the mid–late Permian times.

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