Journal of Structural Geology 30 (2008) 918–928

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Emplacement of a Silurian granitic dyke swarm during nappe translation in the Scandinavian Caledonides

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ARTICLE INFO

Article history:
Received 19 April 2006
Received in revised form 10 March 2008
Accepted 18 March 2008
Available online 4 April 2008

Keywords:
Granitic dykes
U–Pb TIMS
Caledonian
Nappe
Strain marker

ABSTRACT

This paper investigates the geometry, deformation history and age of the synkinematic granitic Årdal dyke complex in the Upper Jotun Nappe, SW Norway. The typically subparallel north-trending dykes are folded and boudinaged, reflecting emplacement and deformation in a top-to-southeast non-coaxial strain field. The synmagmatic strain field is interpreted to reflect thrusting of the nappe at 427 ± 1 Ma, the zircon U–Pb TIMS age of the Årdal dyke complex. The Upper Jotun Nappe is a displaced part of the Baltic Shield; the age is therefore a minimum age for initiation of Caledonian thrusting of crystalline Baltica crust in western Norway.

1. Introduction

Granitic magmatism is commonly associated with active orogens, where the location and mode of granite emplacement will be influenced by the prevailing strain field. Syntectonic granites thus offer an opportunity to constrain the strain field at the time of emplacement (e.g., Holdsworth and Strachan, 1988; Gleizes et al., 1997; Spanner and Kruhl, 2002). As the timescale of granitic magmatism is typically short compared to the evolution of an orogen, this provides a snapshot of the strain field at a precise point in time (Harris et al., 2000; Petford and Clemens, 2000; Petford et al., 2000). Combined geochronological and structural studies of syntectonic granites therefore represent a powerful tool in the reconstruction of orogenies.

The Upper Jotun Nappe in the Jotun Nappe Complex, part of the Caledonian allochthon of south-western Norway (Fig. 1), was recently confirmed as a displaced part of the Baltic Shield (Lundmark et al., 2007). It hosts the synkinematic, granitic Årdal dyke complex, previously thought to be of Proterozoic age (Koestler, 1982). The dyke complex was recently re-dated to 427 ± 1 Ma (Lundmark and Corfu, 2007), linking it to the Scandian collisional phase of the Caledonian orogeny (Stephens and Gee, 1985; Hacker et al., 2003). The Årdal dyke complex thus offers an opportunity to investigate the local Caledonian strain field and the involvement of the Baltic Shield in the Caledonian orogeny in south-western Norway. In this study, granitic dykes at two localities in the Upper Jotun Nappe are dated to verify the geographical extent of the Årdal dyke complex and further constrain the timing of its emplacement, and the geometry and strain history of the dyke complex are examined.

2. Regional geology: south-western Norway and the Jotun Nappe Complex

During the Palaeozoic Caledonian orogeny Baltica collided with Laurentia, and southeast directed thrusting resulted in the emplacement of a series of nappes on top of the Baltic Shield (Stephens and Gee, 1985). These have traditionally been divided into four units according to their inferred origin: the Lower and Middle Allochthon represent oceanward parts of Baltica basement and its cover sequence, the Upper Allochthon consists of the outermost margin of Baltica and remains of the Iapetus Ocean, and the Uppermost Allochthon comprises rocks of Laurentian affinity (Roberts and Gee, 1985). The present-day geology of Norway is dominated by the erosional remnants of these thrust sheets. A brief summary of the current understanding of the timing of Caledonian collisional tectonics in western Norway is given in Hacker and Gans (2005) and Hacker et al. (2003).

One of the most prominent sets of thrust sheets in south-western Norway is the far-travelled Jotun Nappe Complex (Milnes and Koestler, 1985; Hossack and Cooper, 1986; Milnes et al., 1997). The complex consists mainly of displaced slices of crystalline continental crust and is generally assigned to the Middle Allochthon,

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doi:10.1016/j.jsg.2008.03.008

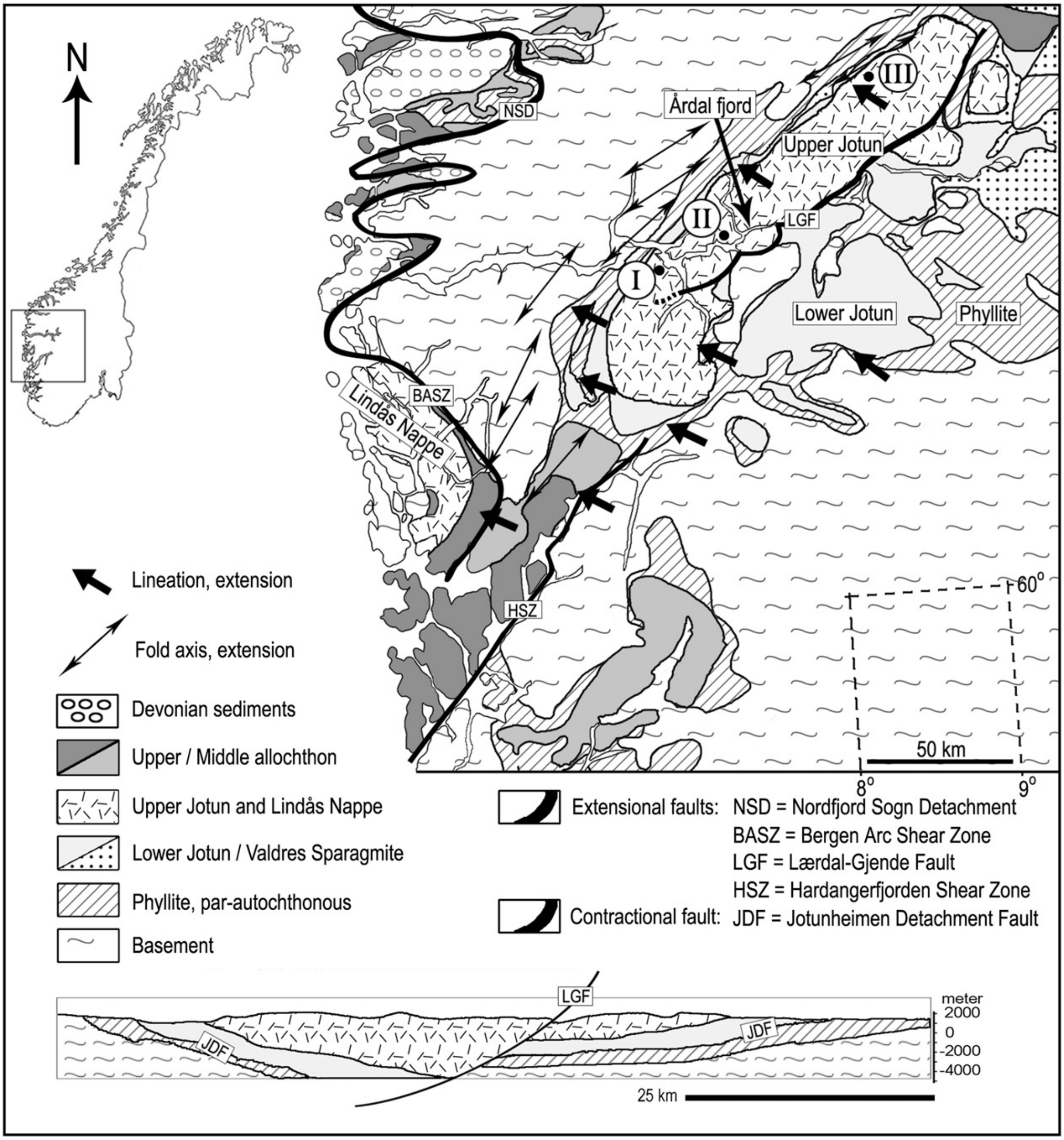


Fig. 1. Geology of south-western Norway (simplified after Gee et al., 1985; Lutro and Tveten, 1996; Fossen and Holst, 1995; Fossen and Dallmeyer, 1998). Localities are: (I) Fresvik, (II) Kaupanger, (III) Galdhøpiggen. The cross-section represents an idealised traverse normal to the strike of the Jotun Nappe Complex to the southeast of Galdhøpiggen. Fold axes and lineations relate to late-Caledonian top-to-northwest extension.

implying an origin in the imbricated Baltoscandian margin. This interpretation was recently confirmed by the similar Precambrian tectonometamorphic histories of the nappe complex and the Western Gneiss Region, the present outer edge of the Baltic Shield below, and to the northwest, of the nappe complex (Lundmark et al., 2007). The Jotun Nappe Complex is separated from the Baltic Shield by a décollement zone of Neoproterozoic and early Palaeozoic parautochthonous phyllitic and quartzitic rocks (Milnes et al., 1997). Top-to-southeast kinematic indicators within the décollement zone, relating to the collisional phase of the Caledonian orogeny, were largely overprinted by top-to-northwest extensional structures during late-Caledonian orogenic collapse, initiated shortly before 400 Ma (e.g., Fossen, 1992; Andersen, 1998; Dunlap and Fossen, 1998).

The polydeformed and polymetamorphosed Jotun Nappe Complex has traditionally been divided into two units, the Lower and the Upper Jotun Nappes, based on differences in metamorphic grade (Battey and McRitchie, 1973; Lutro and Tveten, 1996). The importance of this division was underlined by the recent re-dating of the Årdal dyke complex, present only in the overlying Upper Jotun Nappe, to 427 ± 1 Ma (Lundmark and Corfu, 2007), thus confirming juxtaposition of the two units during the Caledonian orogeny.

The Lower Jotun Nappe, separated from the Upper Jotun Nappe by complex shear zones, is dominated by para- and orthogneisses, generally of syenitic to monzonitic (ca. 1.69 Ga) or gabbroic compositions (ca. 1.25 Ga), metamorphosed up to amphibolite facies conditions during the Sveconorwegian orogeny (ca. 910 Ma;

Schärer, 1980). An overturned basement-cover contact links the late Precambrian Valdres Sparagmite to the Lower Jotun Nappe. The allochthonous sparagmites (meta-arkoses and conglomerates) are commonly correlated with the (par-) autochthonous cover of the Baltic Shield (Hossack et al., 1985; Nickelsen et al., 1985; Milnes et al., 1997).

The Upper Jotun Nappe consists mainly of variably retrograded granulite facies rocks; the north-eastern parts are dominated by ca. 1.65 Ga orthogneisses (Lundmark et al., 2007), while the central and southern parts are dominated by a ca. 965 Ma anorthosite–gabbro-troctolite suite (Lundmark and Corfu, 2008). Sveconorwegian regional high-grade metamorphism was locally followed by late-Sveconorwegian amphibolite facies retrogression/hydration, anatexis and shearing, which in the Hurrungane area was dated to ca. 950 Ma (Lundmark et al., 2007).

The Jotun Nappe Complex is cut by the northeast trending, ca. 20–45° northwest dipping extensional Lærdal-Gjende Fault (Fig. 1), which along with numerous minor top-to-northwest faults in the nappe complex marks the final stage of the Devonian orogenic collapse. The polyphase fault is marked by an up to 200 m thick zone of top-to-northwest extensional cataclasites (Milnes and Koestler, 1985; Andersen et al., 1999). The fault becomes less marked to the southwest and eventually dissolves in an array of extensional shear zones/faults. It has been suggested that the Lærdal-Gjende Fault represents a shallow level, late phase expression of the 600 km long ductile Hardangerfjorden Shear Zone (Fossen and Hurich, 2005). Reactivation of the Lærdal-Gjende Fault has taken place on several occasions, most importantly during the Permian (Andersen et al., 1999).

3. The Årdal dyke complex

3.1. General features

Typically north trending and eastward dipping leucogranitic dykes, often incorrectly referred to as trondhjemites in the literature (cf. Lundmark and Corfu, 2007), intrude the variably retrograded granulite facies rocks of the Upper Jotun Nappe. The dyke complex is centred on the Årdalfjord (Fig. 1), where the granites locally are the dominant rock type. To the northeast and southwest of the Årdalfjord, the dykes gradually become less frequent. The dykes typically range in width from centimetres to several tens of metres, with thicknesses in excess of 200 m inferred for poorly exposed dykes north of the Årdalfjord. The dykes cross-cut each other and include pegmatitic and aplitic varieties. The geographical extent of the Caledonian granites has been uncertain. Away from the central area occupied by the dyke swarm, the appearance of the granite tends to change as it becomes coarser grained and the content of mafic minerals decreases. Coincidentally, pre-Caledonian felsic dykes and pegmatites, rare or absent in the central parts occupied by the dyke complex, are common in this outer region (cf. Lundmark et al., 2007). Some of these, when retrograded, can easily be confused with the Caledonian dykes.

3.2. Geochronology

To determine the geographical extent of the Årdal dyke complex, coarse grained dykes to the northeast and southwest of the main complex were dated. Handpicked zircons from two crushed leucogranitic dykes at localities I and III (Fig. 1) were dissolved, spiked with $^{205}Pb/^{235}U$ and dated using isotope dilution thermal ionisation mass spectrometry (ID-TIMS; for details of analytical procedure see Lundmark and Corfu, 2007 and references therein). At locality I along the road to Fresvik (*UTM 3865E6740N*) a ca. 3 dm wide, gently south dipping dyke cut by a top-to-southeast shear zone was sampled. The dyke has a northwest dipping foliation defined by biotite, and cuts the fabric of the augen gneiss country rock. The second sample was collected at locality III ca. 5 km northeast of Galdhøpiggen (*UTM 4657E6838N*), and is representative of ubiquitous thin, felsic dykes in the generally highly sheared gneisses in the area. The dykes range from parallel to oblique to the main gneissic foliation and are in general themselves sheared and/or folded. The dated sample, leucocratic granite with sporadic coarse biotite and cm-sized potassic feldspar, represents the latest generation, which cuts across the sheared rocks without being visibly deformed. The samples yield ages of 427.6 ± 1.3 Ma and 427.5 ± 1.9 Ma respectively (Table 1; Fig. 2A,B), overlapping with the previous 427.1 ± 0.7 Ma titanite and zircon age from the main dyke complex in the Kaupanger (locality II) area (Lundmark and Corfu, 2007). This links the dated dykes to the Årdal dyke complex, extending the confirmed presence to include most of the Upper Jotun Nappe. The overlapping ages also indicate a relatively brief magmatic event, as the age difference between the main dyke complex and the last, undeformed dykes cannot be resolved.

Table 1
U–Pb isotopic data and ages, Årdal dyke complex

Fraction[a]	Weight (μg)[b]	U (ppm)[b]	Th/U[c]	Pbcom (pg)[b,d]	$\frac{^{206}Pb}{^{204}Pb}$[e]	$\frac{^{207}Pb}{^{235}U}$[f]	2 sigma (abs)[f]	$\frac{^{206}Pb}{^{238}U}$[e]	2 sigma (abs)[f]	rho[f]	$\frac{^{207}Pb}{^{206}Pb}$[f]	2 sigma (abs)[f]	$\frac{^{206}Pb}{^{238}U}$ (Ma)[f]	$\frac{^{207}Pb}{^{235}U}$ (Ma)[f]	$\frac{^{207}Pb}{^{206}Pb}$ (Ma)[f]
Fresvik (Locality I)															
Z1 eu fr	9	1047	0.01	7.3	5550	0.5233	0.0021	0.06822	0.00027	0.82	0.05563	0.00013	425.4	427.3	437
Z2 sr	1	536	0.24	1.4	3478	1.4312	0.0062	0.14075	0.00052	0.88	0.07375	0.00015	848.9	902.1	1035
Z3 eu fr [4]	2	2498	0.04	0.8	27131	0.5246	0.0016	0.06865	0.00019	0.94	0.05542	0.00005	428.0	428.2	429
Z4 eu	<1	>653	0.03	2.4	1176	0.5253	0.0033	0.06850	0.00026	0.62	0.05562	0.00028	427.1	428.7	437
Z5 sh fr [5]	5	799	0.03	2.0	8590	0.5256	0.0023	0.06913	0.00028	0.91	0.05515	0.00010	430.9	428.9	418
Galdhøpiggen (Locality III)															
Z6 eu fr	2	224	0.02	1.1	1780	0.5295	0.0031	0.06917	0.00026	0.71	0.05551	0.00023	431.2	431.5	433
Z7 eu tip [5]	1	230	0.00	0.9	1134	0.5268	0.0044	0.06901	0.00032	0.64	0.05537	0.00036	430.2	429.7	427
Z8 eu tip	1	248	0.01	0.9	1179	0.5340	0.0044	0.06905	0.00031	0.65	0.05610	0.00036	430.4	434.5	456
Z9 eu fr	1	481	0.01	4.4	493	0.5204	0.0052	0.06863	0.00029	0.59	0.05500	0.00045	427.9	425.4	412
Z10 eu sh	19	86	0.01	4.3	1634	0.5256	0.0039	0.06849	0.00021	0.45	0.05566	0.00037	427.0	428.9	439
Z11 eu fr	18	249	0.01	19.7	999	0.5229	0.0020	0.06852	0.00014	0.61	0.05535	0.00017	427.2	427.1	427

[a] fr, fragment; eu, euhedral grain; sh, subhedral grain; sr, subrounded grain; [*N*], number of grains in multi-grain fractions.

[b] Weight and concentrations are known to about 10% for samples larger than 5 μg and not better than 50% for small single grains.

[c] Th/U model ratio inferred from 208/206 ratio and age of sample.

[d] Pbcom, total common Pb in sample corrected for spike and fractionation (initial + blank).

[e] Raw data corrected for fractionation.

[f] Corrected for fractionation, spike, blank and initial common Pb; error calculated by propagating the main sources of uncertainty.

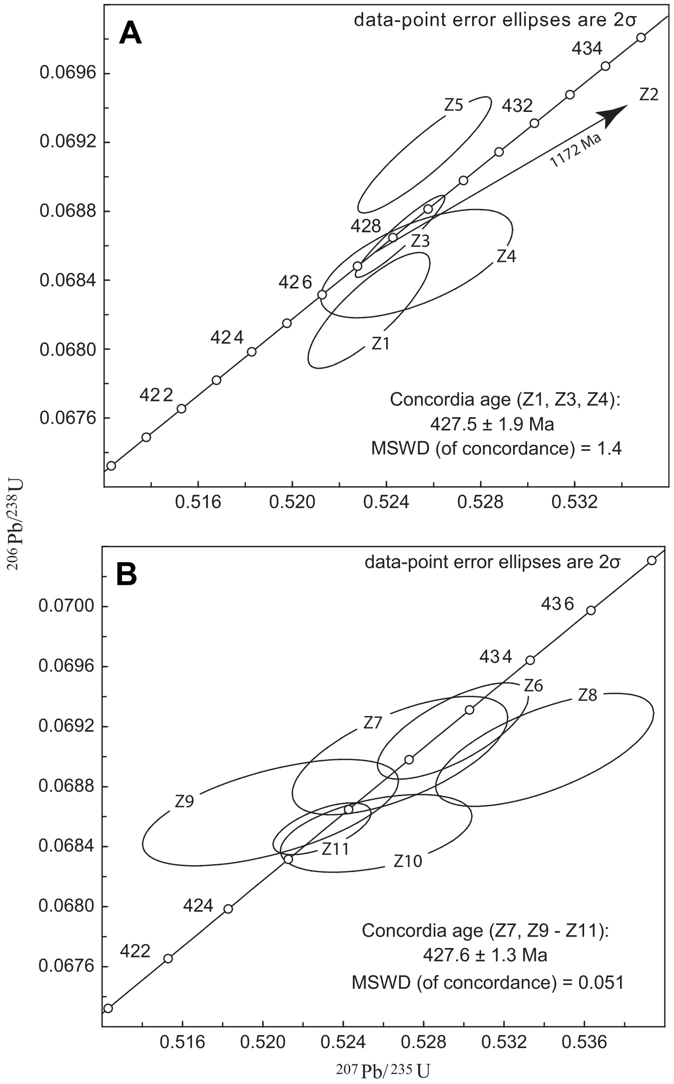


Fig. 2. Concordia diagrams. (A) Locality I, Fresvik. Point Z5 is reversely discordant, while Z2 (not shown) has an inherited component. Points Z1, Z3 and Z4 yield a concordant age of 427.5 ± 1.9 Ma. Omitting point Z1, which may reflect minor recent lead-loss, produces no significant change to the age. (B) Locality III (Galdhøpiggen). Points Z6 and Z8 show components of inheritance, remaining points yield a concordant age of 427.6 ± 1.3 Ma.

3.3. Locality I, Fresvik

Locality I is situated to the southeast of the main dyke swarm, where the dykes are exposed along road cuts in the Djupedal area on the road to Fresvik (Fig. 1). The country rock is a variably (re-)hydrated garnet bearing granulite augen gneiss. The leucogranitic dykes, ca. 0.5–20 cm wide, are generally northeast striking and dip towards southeast (Fig. 3A); the (sub-) parallel dykes are oblique to the gneissic fabric of the country rock and are locally emplaced in top-to-southeast shear zones.

In one instance, a ca. 1 dm wide Caledonian dyke is hosted by a shear zone lined by deflected foliations defining a top-to-southeast shear sense (Fig. 4A). The shear zone (and the dyke) is parallel to the other dykes in the area, and cross-cuts ca. 890 Ma neosomes (Lundmark and Corfu, 2008) in the country rock. The deflected foliations, and deformation of a pre-Caledonian, garnet bearing felsic dyke (possibly related to the neosomes; Fig. 4A) are not mirrored in the Caledonian dyke; the shear zone is therefore pre- to synmagmatic.

A northwest dipping foliation defined by biotite is present in the dykes (Fig. 3B) but typically difficult to measure due to the small width of most dykes in the area, the relatively coarse grain size, and the lack of sufficient mafic minerals in the leucocratic dykes to easily visualize the fabric. The dykes are cut at a low angle by decimetre to metre scale top-to-southeast post-emplacement shear zones that are sub-parallel to the dykes, but more gently dipping. A ca. 155° trending mineral elongation lineation is developed on top-to-southeast shear surfaces and in a mylonite zone (Fig. 3B). The strike of the foliation in the dykes is parallel to the strike of the dykes, and normal to the lineation (maximum density in stereoplot; Fig. 3A,B), relations consistent with top-to-southeast non-coaxial strain.

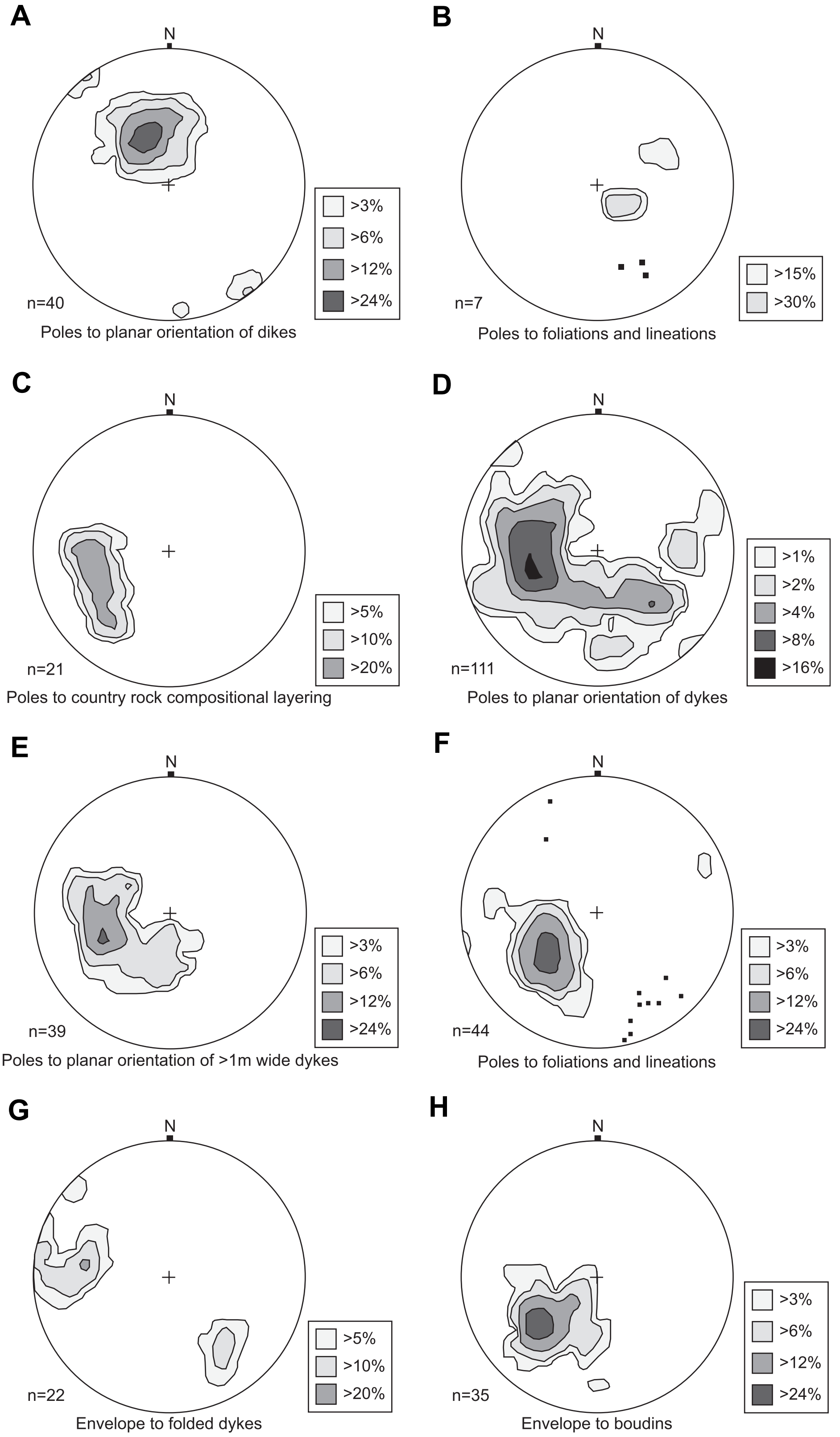
During non-coaxial shear the minimum compressive stress (σ_3) is oblique to the shear direction, presenting a potential weakness for magmas to exploit if they intrude as self-propagating dykes, whereas Riedel, P and C shear faults represent fault controlled pathways. At this locality, the angle between the dip of the dykes and the orientation of the foliation is ca. 130°, similar to the $\geq$120° angle expected if synthetic Riedel faults controlled emplacement of the dykes. The prevalence of one of the conjugate faults (normally the synthetic faults) is a common feature of non-coaxial shear zones (e.g., Anderson, 1951; Christie-Blick and Biddle, 1985). The inferred C shear direction at Fresvik approximately matches the observed, post-emplacement synthetic faults that cross-cut the dykes at a low angle with a dip of ca. 10–25°.

We conclude that the most likely explanation for the observations is top-to-southeast non-coaxial strain during and after the intrusion of the dykes, giving rise to synthetic Riedel faults that served as conduits for the granitic magma. Both the Caledonian dykes and the shear zones are typically enveloped by hydrated zones, easily distinguished by a colour change in the country rock from light brown to black as the garnet/pyroxene/amphibole assemblage is transformed into a biotite-dominated mineral assemblage. Locally, the post-emplacement faults have transformed the gneiss into biotite schist.

3.4. Locality II, Kaupanger

Locality II is situated above the village of Kaupanger, close to the geographical centre of the dyke swarm. Here, a ca. 1.5 km northwest striking transect through the Upper Jotun Nappe along road cuts gives an exceptionally good exposure of the Årdal dyke complex. The country rock is a banded metatroctolite, locally coronitic, with northeast dipping mafic and felsic (anorthosite) layers (Fig. 3C) that vary in width from a few millimetres to approximately one metre. The Caledonian dykes range in width from 0.5 cm to ca. 100 m and are typically northwest striking and northeast dipping (Fig. 3D,E). Despite the overlapping orientations of the dykes and the compositional layering of the metatroctolite in stereographic plots (Fig. 3C,E; only $\geq$1 m wide dykes, thin dykes are generally reoriented by post-emplacement deformation), the dykes are typically oblique to the layering, albeit at a small angle. Given the marked anisotropy of the metatroctolite, we conclude that the orientation of the dykes was primarily determined by an external stress field, consistent with the observation at other localities that the dykes typically are (sub-)parallel and, as at Fresvik, generally oblique to the fabric of the country rocks.

Shearing is ubiquitous; most thin dykes are either folded or drawn out into boudins, depending on their orientations, and dykes of all sizes exhibit a foliation defined by biotite grains (Fig. 3F–H and Fig. 5). The deformation primarily reflects top-to-southeast, heterogeneous simple shear parallel to the compositional layering of the country rock (Fig. 4B and Fig. 5). An associated mineral elongation lineation on shear surfaces trends ca. 153° and plunges to the southeast (Fig. 3F). As at Fresvik, the strike of the foliation in



A: Poles to planar orientation of dikes

B: Poles to foliations and lineations

C: Poles to country rock compositional layering

D: Poles to planar orientation of dykes

E: Poles to planar orientation of >1m wide dykes

F: Poles to foliations and lineations

G: Envelope to folded dykes

H: Envelope to boudins

Fig. 3. (A–H) Stereographic plots (lower hemisphere, equal area projection). Data plotted as poles to planes, except for lineations. Contours show % data per % area. (A) and (B) depict data from Fresvik, (C)–(H) depict data from Kaupanger.

the dykes is parallel to the strike of the dykes and normal to the lineation, a geometry compatible with top-to-southeast non-coaxial strain. Deformation of the metatroctolite is primarily confined to mafic layers and is associated with a mineralogical change from a competent assemblage of garnet, pyroxene and amphibole to biotite schist, where shear bands (S-C fabrics) consistently indicate a top-to-southeast shear sense. The effect of hydration is also readily seen in the felsic layers, where the plagioclase changes

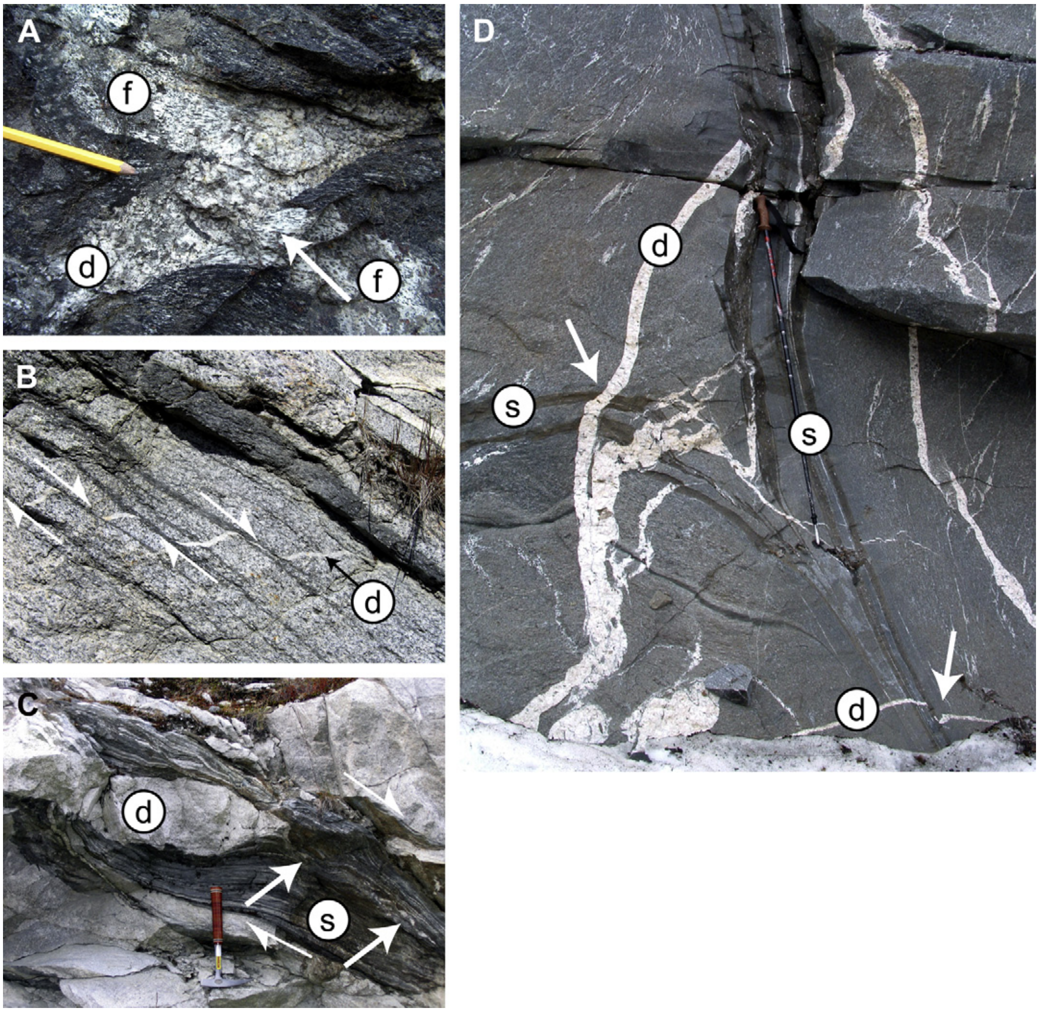


Fig. 4. (A) Locality I, Fresvik. North-facing road cut. A Caledonian dyke (d) intrudes a top-to-southeast shear zone, cross-cutting a garnet bearing felsic dyke (f) that shares the pre-Caledonian fabric of the country rock. The geometry and style of the shear zone points to a Caledonian age, while absence of corresponding shearing in the dyke indicates that shearing was pre- to synmagmatic. (B) Locality II, Kaupanger. South-facing road cut. A cm-wide Caledonian dyke (d) in metatroctolite. The dyke is progressively deformed as it traverses thin, mafic layers that have been transformed into biotite schist. Arrows indicate top-to-southeast shear sense. The section is ca. 50 cm long. (C) Locality II, Kaupanger. South-facing road cut. A syntectonic Caledonian dyke (d) interacts with a mylonitic shear zone (s). The dyke cross-cuts part of the mylonitic fabric, but is also deformed by the shear zone. Arrows indicate top-to-southeast shear sense and the position of the deformed and drawn out dyke. (D) Locality III, Galdhøpiggen. North-facing rock face. Caledonian syntectonic granitic dykes (d) in gneiss interact with a convergent set of mylonites (s). Arrows indicate a dyke cross-cutting a mylonite and a mylonite cross-cutting a dyke. Walking pole for scale.

colour from lilac to white. The local minimum strain can be estimated by matching the offset of a given dyke as it gets deformed in successive mafic layers to the length of the section measured. For the ca. 4 m wide section depicted in Fig. 5, the minimum angular shear (ψ) is 11°, the equivalent of a minimum shear strain (γ) of 0.2. The section is gauged to be typical of the locality.

An atypical but illustrative field example demonstrates the emplacement of the dykes under semi-brittle conditions in a top-to-southeast non-coaxial strain field, and the sequence of events. The emplacement of a thin granitic dyke (1; Fig. 6A) was followed by top-to-southeast deformation, primarily confined to the mafic layers of the country rock (see top left corner of Fig. 6A; cf Fig. 4B). Next, a second dyke intruded the country rock (2; Fig. 6A); three segments are parallel to the country rock layering, while two segments cross-cut the layering at a high angle. Gently deflected compositional layers in the host rock along the cross-cutting segments indicate top-to-northwest shearing. Further top-to-southeast strain induced a foliation defined by biotite in the dyke (cf. Fig. 3F). A critical observation to explain the geometry of the dyke is that, contrary to the norm, the main segments of the dyke are parallel to the compositional layering of the country rock.

The dilation of zigzag dykes, as described by Hoek (1991), is normal to the envelope and oblique to the segments of the dyke (Fig. 6B). Zigzag dykes typically form due to the presence of a structural weakness oblique to the overall direction of extension (σ_3). The structural weakness, for example a strong anisotropy in the country rock, reorients the dilation, i.e., the dyke. To achieve overall extension normal to σ_3, a set of fractures develops at an angle to the structural weakness, making room for a second set of dyke segments. In a qualitative application of this model to the dyke described above, we suggest that top-to-southeast shearing was accompanied by a preferred direction of dilation (σ_3), approximated by the two-dimensional displacement vector (arrows in Fig. 6C), at an angle to the structural weakness, i.e., the compositional layering in the country rock, leading to formation of a zigzag dyke. The oblique set of top-to-northwest faults approximately matches the inferred direction of antithetic Riedel faults, suggesting that the angle of the oblique fractures was not coincidental, but also reflects a top-so-southeast non-coaxial strain field.

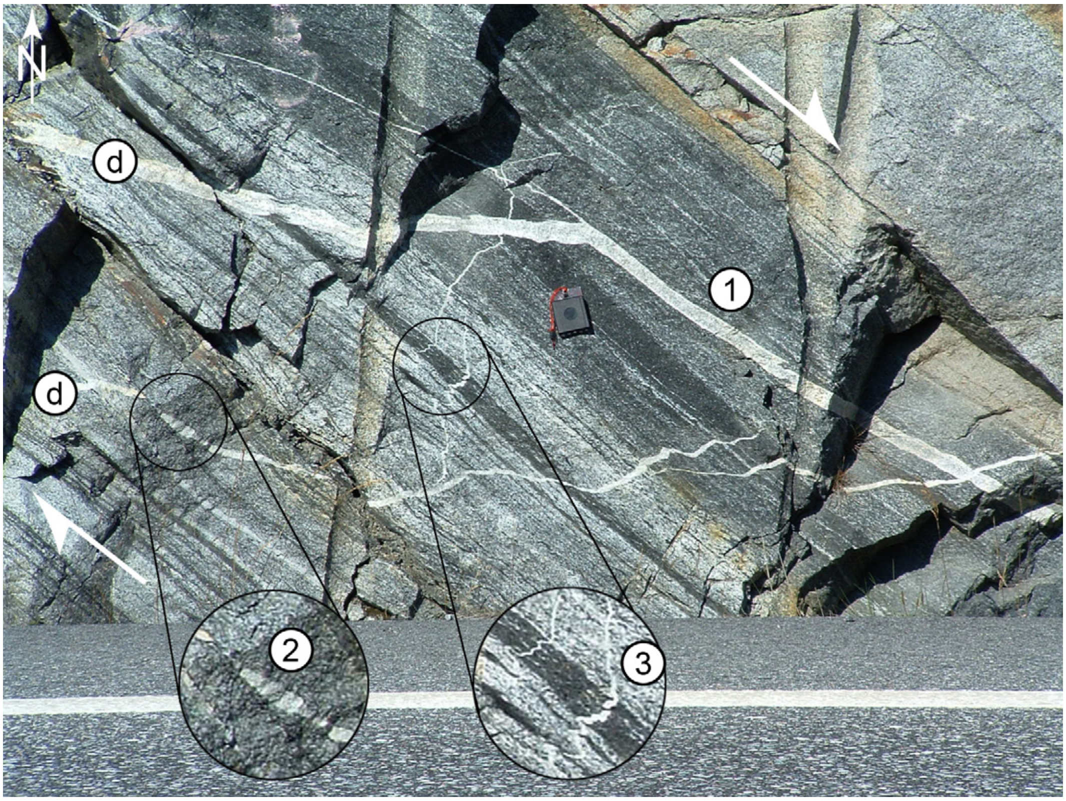


Fig. 5. Locality II, Kaupanger. South-facing road cut. Caledonian dykes (d) emplaced obliquely to the compositional layering of the metatroctolite. Post-emplacement deformation is generally parallel to the compositional layers and concentrated to the mafic parts of the country rock, producing drawn out (2) and folded (3) dykes. Arrows indicate shear sense. Compass for scale. Modified after Lundmark and Corfu (2007).

Subsidiary shear zones cutting across the compositional layering of the country rock also deform the dykes, and are locally intruded by them; some of these synmagmatic shear zones indicate a top-to-northwest shear sense, some are mylonitic (Fig. 4C). Sparse, 1–2 cm wide mylonites developed in the anorthositic layers contain remnants of lilac plagioclase, are cut by the Caledonian dykes and are not associated with hydration; these are tentatively correlated to Sveconorwegian mylonites elsewhere in the Upper Jotun Nappe (cf. Lundmark et al., 2007). Top-to-northwest (reactivation of) shear zones, typically coinciding with the development of a green chlorite dominated mineral assemblage, post-date all other deformational structures and are related to late- to post-Caledonian extension.

We conclude that the observations above are consistent with top-to-southeast non-coaxial strain during emplacement of the dyke complex, followed by later top-to-northwest, brittle deformation. A comparison of the angle between the orientations of the dykes ($\geq$1 m wide) and the foliations (maximum density in stereoplot; Fig. 3E,F) yields ca. 168°. The closest match is the ca. 148° ($\gamma = 0.2$) angle expected if emplacement of the dykes was controlled by synthetic P faults.

3.5. Locality III, Galdhøpiggen

Locality III is situated in the north-western part of the Upper Jotun Nappe (Fig. 1). Good exposures are few and far apart, and fewer Caledonian dykes are observed than at the previously described localities. Here, the leucogranitic dykes are generally coarse grained, ranging in width from half a centimetre to a few decimetres. The discordant dykes intrude a garnet bearing, light brown gneiss. Pre-Caledonian leucosomes and pegmatites (likely of Sveconorwegian age, cf. Lundmark et al., 2007) are common, and are generally oriented parallel to the gneissic foliation of the country rock. The pegmatites act as zones of weakness that control the orientation of mylonitic shear zones (similar features were described by Koestler, 1988). The Caledonian dykes generally strike east and dip to the south, but the pattern of largely straight, (sub-)parallel dykes at the previously described localities is less developed. Some mylonitic shear zones can be identified as synmagmatic with respect to the Caledonian granites, both deforming and being cross-cut by the dykes (Fig. 4D). In places, ductile folding on the scale of tens of metres can thus be determined to be coeval with intrusion of the leucogranitic dykes. The sense of shear, marked by deflected foliations, drawn out and boudinaged dykes and rotated porphyroclasts is mostly top-to-south with accompanying north–south lineations. As observed at localities I and II, some dykes intrude along shear zones, and some dykes are enveloped by ca. 1 dm wide, biotite-rich, hydrated zones. Thin dykes cross-cut many top-to-south deformational structures, indicating that the bulk of the top-to-south strain coincided with the main magmatic event at this locality.

4. Interpretation

4.1. Caledonian deformation, hydration and magmatism in the Upper Jotun Nappe

The Upper Jotun Nappe is dominated by dry, granulite facies rocks; a conspicuous lack of Caledonian deformation, apart from discrete mylonite zones and brittle extension related faults, has been reported from most of the nappe (Bryhni and Sturt, 1985; Milnes and Koestler, 1985; Milnes et al., 1997). This contrasts sharply with the localities described above. As illustrated at Kaupanger, the deformation style is typically semi-brittle, with faults

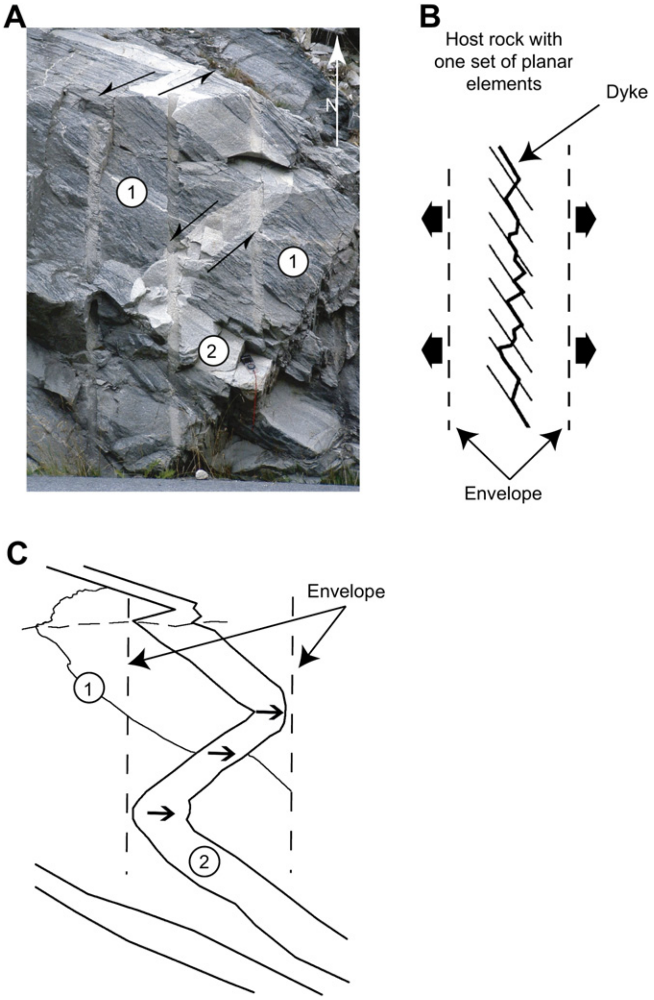


Fig. 6. Locality II, Kaupanger. South-facing road cut. The dykes are slightly tilted to the northeast. (A) A thin granitic dyke (1) deformed by top-to-southeast layer parallel deformation (top left corner) is offset by two top-to-north-west antithetic faults accommodating a ca. 5 dm thick leucogranitic dyke (2). The geometry of the leucogranitic dyke is determined by the faults and the compositional layering of the country rock. (B) The presence of a structural weakness in the country rock oblique to the overall extension can result in formation of a zigzag dyke (modified after Hoek, 1991). Dilation is normal to the envelope of the zigzag dyke. (C) The overall dilation of the Caledonian zigzag dyke is indicated by the two-dimensional displacement vector (arrows), parallel to the minimum compressive stress (σ_3) and normal to the envelope of the dyke, but oblique to the compositional layering of the country rock. The typical orientation of dykes in the area is represented by a dyke in the lower left corner.

cross-cutting felsic and mafic layers alike in the country rock, or ductile and confined to hydrated mafic layers in the country rock. On a larger scale, hydration and associated deformation of the metatroctolite are essentially confined to areas where the Caledonian dykes are present. At Kaupanger, with its multitude of dykes, wholesale hydration has left behind only lenses of the pre-Caledonian mineral assemblage, typically in uncommonly thick mafic and felsic layers of the country rock. The locally important influence of Caledonian magmatism and the associated metamorphism on the country rock is also reflected in the U–Pb systematics of zircon and titanite. Silurian lead loss and titanite growth in massif anorthosite in the central Upper Jotun Nappe is dated to 425 ± 5 Ma (Lundmark and Corfu, 2008), overlapping with the age of the Årdal dyke complex. The Caledonian influence on the U–Pb system is less pronounced in the north-eastern parts of the nappe (Lundmark et al., 2007), corresponding to a decreasing number of dykes, and is all but absent from the Lower Jotun Nappe, which lacks Silurian magmatism (Schärer, 1980).

The geographical correlation between Caledonian magmatism on one hand and hydration and top-to-southeast deformation of the country rock on the other, is suggestive of a scenario where deformation, magmatism and hydration fed of each other in a cycle of reaction softening as heat and fluids introduced by the magmatism facilitated further deformation, leading to increased access to fluids, and more deformation (e.g., Brodie and Rutter, 1985). At Galdhøpiggen, undeformed late dykes and the absence of biotite schist suggest lower fluid availability, possibly reflecting a longer distance to the base of the Upper Jotun Nappe, or the smaller volume of Caledonian magmatism.

4.2. The relationship between the Kaupanger and Fresvik localities

Zircon U–Pb ages from localities I, II and III show that the Caledonian dykes were emplaced simultaneously, within analytical error, across the Upper Jotun Nappe. A pattern of (sub-)parallel synkinematic dykes, deformed by top-to-southeast shearing normal to the strike of the dykes is observed at both Kaupanger and Fresvik. It is reasonable to interpret this as reflecting a common strain history from the time of dyke emplacement and during the top-to-southeast phase of deformation. However, whereas observations at Fresvik indicate roughly horizontal top-to-southeast shear strain, the dykes and structures at Kaupanger are tilted to the northeast (Fig. 3A–H). To account for this present-day mismatch, it is necessary to speculate concerning the events post-dating the top-to-southeast deformation.

Kaupanger is situated in the hanging wall, in the area of maximum displacement, of the mainly Devonian, top-to-northwest extensional Lærdal-Gjende Fault (Andersen et al., 1999), whereas Fresvik is situated close to the south-western fault termination (Fig. 1). This suggests that displacement in the Kaupanger area was greater than in the Fresvik area. If the structures at the two localities initially represented the same strain field, a semi-quantitative restoration of the structures in the Kaupanger area to the pre-fault state can be attempted, assuming rigid body block rotation.

The Lærdal-Gjende Fault is, in the area of interest, approximated to a hinged normal fault, dipping 45° to the northwest. Top-to-northwest extensional lineations and corresponding fold axes in the Caledonian décollement zone in the region are approximately normal and parallel to the Lærdal-Gjende Fault trace, respectively, indicating extension towards ca. 302° (Fig. 1; Fossen and Holst, 1995).

Restoring the hanging-wall (the Kaupanger area) by 45° eliminates the secondary tilt of the dykes and structures at Kaupanger, and aligns them with those recorded in the Fresvik area (Fig. 7A–F). A post-restoration mismatch between the foliations at the two localities testifies to the limitations of our assumptions, but is consistent with the downwards rotation of the hanging-wall implied in the cross-section in Fig. 1 (suggesting rotation about an axis parallel to the fault trace). All the same, the crude restoration achieves a reasonable fit between the structures observed at the localities, which suggests that movements along the Lærdal-Gjende Fault were indeed the main reason for the present-day mismatch.

The 45° restoration implies ca. 10 km of vertical displacement along the Lærdal-Gjende Fault in the Kaupanger area (assuming zero displacement at Fresvik), roughly of the same magnitude as previous estimates of ca. 6–8 km of vertical displacement (Lutro and Tveten, 1996; Andersen et al., 1999).

A comparison to the pattern of intrusions and deformation observed at Galdhøpiggen, the northernmost locality, which typically shows a top-to-south direction of shear deformation, suggests larger block movements, likely reflecting the presence of additional extensional faults, such as the Utladalen Fault (Milnes and Koestler, 1985), to the northeast of Kaupanger.

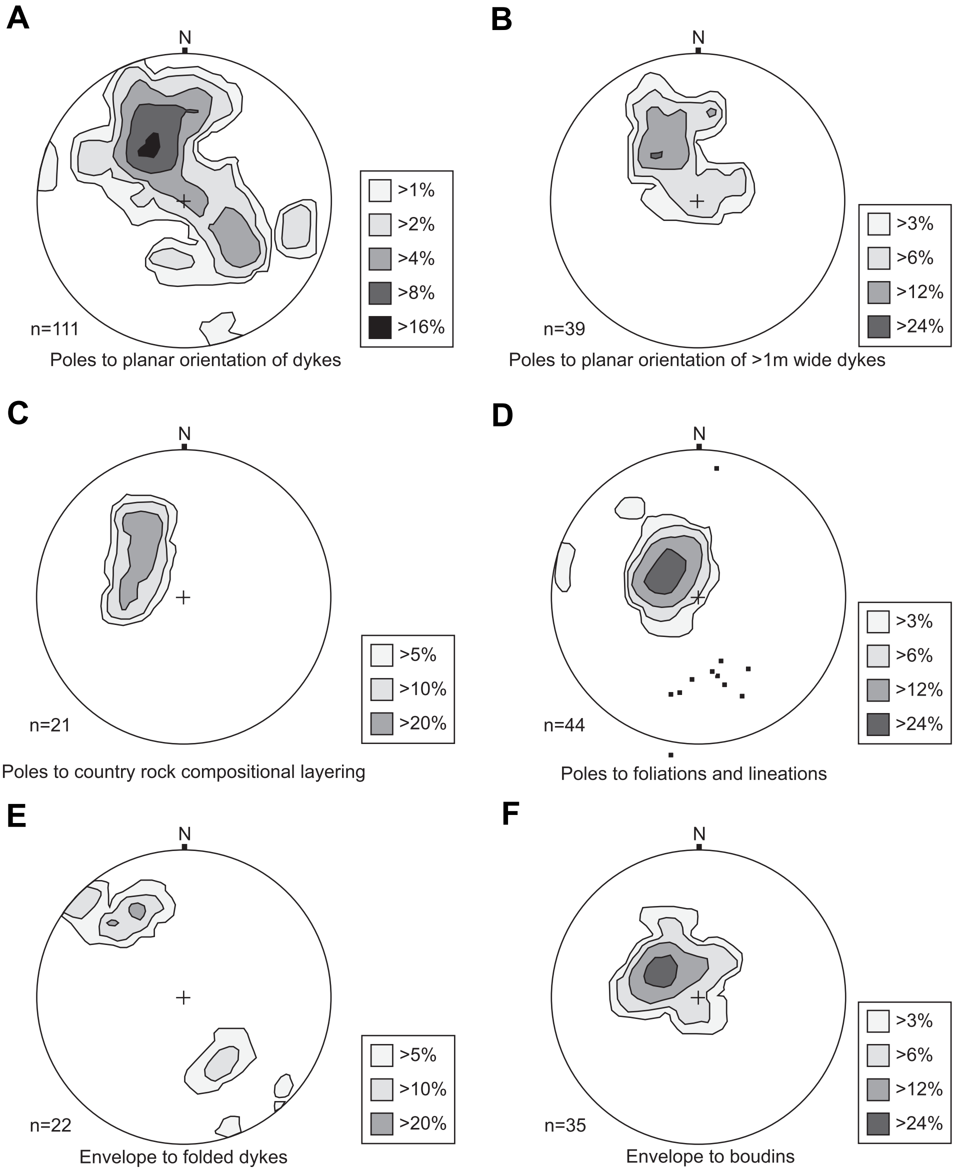


Fig. 7. (A–F) Locality II, Kaupanger. Stereographic plots (lower hemisphere, equal area projection). Contours show % data per % area. All data restored to the inferred pre-extensional fault configuration by 45° rotation about an axis parallel to the lineation in the décollement zone and normal to the fault plane that is assumed to dip 45° to the northwest.

4.3. The Årdal dyke complex as strain marker: the relation between the Upper Jotun Nappe and the Caledonides of south-western Norway

The large scale translation of thrust sheets during the contractional phase of the Caledonian orogeny was approximately normal to the trend of the orogen (Soper et al., 1992). Important variations exist along the orogen and between the different levels of the thrust stack. For the Jotun Nappe Complex, however, the direction was towards ca. 160° throughout the orogeny (Hossack, 1983; compilation in Soper et al., 1992). The restored orientation of the top-to-southeast strain recorded in the Årdal dyke complex match the ca. 160° direction of transportation. Furthermore, the strike of the Årdal dykes is parallel to the inferred Caledonian orogenic front northwest of the present day nappe complex, and the synmagmatic top-to-southeast strain field is compatible with the envisaged collisional strain field. Thus, the strain history of the nappe as recorded by the Årdal dyke complex matches the emplacement history of the Upper Jotun Nappe envisaged from regional constraints. The good fit between the observations in the nappe and the inferred overall orogenic setting is somewhat surprising, suggesting that in spite of the far-travelled nature of the nappe, translation following emplacement of the dyke complex was relatively straightforward.

4.4. The strain field at 427 Ma in the Upper Jotun Nappe and the timing of contractional thrusting in the Caledonian orogen

The synkinematic Årdal dyke complex provides a snapshot of the prevailing strain field in the Upper Jotun Nappe at 427 ± 1 Ma. Since the nappe represents a displaced part of the Baltic Shield (Lundmark et al., 2007), the top-to-southeast non-coaxial strain at this time suggests either the onset of nappe formation in the Baltic Shield, or deformation of an already established nappe during top-to-southeast translation. Either way, the Årdal dyke complex provides a minimum age for the involvement of Baltica basement in western Norway in the collision.

Based on the isotopic and geochemical signatures of the Årdal dyke complex, and zircon inheritance, Lundmark and Corfu (2007) suggested that the magma source was anatexis of Rb-depleted sediments, and that the dyke complex is correlated with similar, approximately coeval granites in the Middle Allochthon Lindås Nappe (Wennberg et al., 2001; Kühn et al., 2002) and the Upper Allochton Lifjorden complex (Skjerlie et al., 2000). The inferred sedimentary source of the granites, and the presence of related granites in nappes of both continental and oceanic affinities coupled with the absence of similar granites in the exposed Baltica basement, led the authors to suggest that the granites were emplaced as the different nappes overrode melting sediments during translation.

This implies that the synmagmatic strain field recorded by the Årdal dyke complex reflects southeast-ward translation of the Upper Jotun Nappe, and that nappe translation controlled the geometry of the dyke complex; the 427 ± 1 Ma age is thus a minimum age for thrusting. Thus, tectonic compression in an essentially contractional setting during intrusion of the Årdal dykes is set against the locally important space creation required by the granitic intrusions, a situation investigated by several authors (e.g. Brown and Solar, 1998, and references therein). The present study shows that at some point during the translation of the nappe the forces driving ascent of the magma (likely a combination of buoyancy and tectonic forces) became strong enough to exploit the weaknesses created by the Caledonian shear systems.

The age of top-to-southeast thrusting in south-western Norway has been deduced from ^{40}Ar/^{39}Ar data from phyllites in the décollement zone underlying the Jotun Nappe Complex. The data fall into two age groups, interpreted to represent southeast directed thrusting at 415–408 Ma, and top-to-northwest reactivation of the detachment fault at 402–394 Ma, with a rapid change from a contractional to an extensional setting around 408–402 Ma (Fossen and Dunlap, 1998). Assuming a thrust displacement of 300 km for the Upper Jotun Nappe (minimum estimate by Hossack and Cooper, 1986), and a time span of thrusting extending from at least 427 to 410 Ma, an average thrust velocity of ca. 1.8 cm/yr is implied. This can be seen in the context of a northward latitudinal velocity component of Baltica of ca. 8–10 cm/yr at the beginning of the collision with Laurentia (Torsvik et al., 1996). The inferred Palaeozoic Upper Jotun Nappe thrust velocity is thus of the same order of magnitude as the present-day convergence rate of ca. 1.8 ± 0.2 cm/yr across the Himalaya (Bilham et al., 1997; Paul et al., 2001).

5. Conclusions

The 427 ± 1 Ma Årdal dyke complex was emplaced in the Upper Jotun Nappe, a displaced part of the Baltic Shield, during a short lived magmatic event. The geometry of the dyke complex was primarily controlled by Caledonian pre- to synmagmatic faults reflecting a top-to-southeast non-coaxial strain field. The strain field is interpreted to reflect nappe translation, and the age of the Årdal dyke complex is therefore a minimum age for Caledonian thrusting of crystalline Baltica crust in western Norway. Rheological changes induced by the magmatism permitted further hydration and deformation of the country rocks in the vicinity of the dykes in a continued top-to-southeast non-coaxial strain field, possibly reflecting continued translation of the Upper Jotun Nappe and its emplacement on top of the Lower Jotun Nappe. The final major modification of the architecture of the nappe complex was the development of top-to-northwest faults related to Devonian collapse of the orogen, tilting the Kaupanger area ca. 45° to the northeast relative to the Fresvik area. The constraints on the timing of contractional thrusting in the Caledonian orogen that follow from this interpretation suggest nappe thrust velocities during the Palaeozoic Caledonian orogeny comparable to thrust velocities in the present day Himalayan orogen.

Acknowledgements

The study was funded by the Norwegian Research Council, grant 147535. Laboratory assistance was provided by Gunborg Bye-Fjeld. Field assistance was provided by Edina Pózer Bue. Professors A. Andresen, R.H. Gabrielsen and T.B. Andersen at Oslo University gave valuable suggestions and comments. The manuscript was further improved by the helpful suggestions from reviewers N. Petford and H. Fossen.

References

Andersen, T.B., 1998. Extensional tectonics in southern Norway: An overview. Tectonophysics 285 (3), 333–351.

Andersen, T.B., Torsvik, T.H., Eide, E.A., Osmundsen, P.T., Faleide, J.I., 1999. Permian and Mesozoic extensional faulting within the Caledonides of central south Norway. Journal of the Geological Society (London) 156 (6), 1073–1080, doi:10.1144/gsjgs.156.6.1073.

Anderson, E.M., 1951. The Dynamics of Faulting. Oliver and Boyd, Edinburgh, UK. 1–206.

Battey, M.H., McRitchie, W.D., 1973. A geological traverse across the pyroxene-granulites of Jotunheimen in the Norwegian Caledonides. Norsk Geologisk Tidsskrift. Supplement 53 (3), 237–265.

Bilham, R., Larson, K.M., Freymueller, J.T., 1997. GPS measurements of present-day convergence across the Nepal Himalaya. Nature (London) 386, 61–64, doi:10.1038/386061a0.

Brodie, K.H., Rutter, E.H., 1985. On the relationship between deformation and metamorphism, with special reference to the behavior of basic rocks. In: Thompson, A.B., Rubie, D.C. (Eds.), Metamorphic Reactions; Kinetics, Textures, and Deformation. Springer, New York, pp. 138–179.

Brown, M., Solar, G.S., 1998. Granite ascent and emplacement during contractional deformation in convergent orogens. In: Extraction, Transport and Emplacement of Granitic Magmas 20; 9–10. Pergamon, Oxford/New York, pp. 1365–1393.

Bryhni, I., Sturt, B.A., 1985. Caledonides of southwestern Norway. In: Gee, D.G., Sturt, B.A. (Eds.), The Caledonide Orogen. Scandinavia and Related Areas, Vol. 1. John Wiley and Sons, Chichester, UK, pp. 89–107.

Christie-Blick, N., Biddle, K., 1985. Deformation and basin formation along strike-slip faults. In: Biddle, K., Christie-Blick, N. (Eds.), Strike-Slip Deformation, Basin Formation, and Sedimentation. SEPM Special Publication, vol. 37. SEPM, Tulsa, pp. 1–34.

Dunlap, W.J., Fossen, H., 1998. Early Paleozoic orogenic collapse, tectonic stability, and late Paleozoic continental rifting revealed through thermochronology of K-feldspars, Southern Norway. Tectonics 17 (4), 604–620.

Fossen, H., 1992. The role of extensional tectonics in the Caledonides of South Norway. Journal of Structural Geology 14 (8–9), 1033–1046.

Fossen, H., Dallmeyer, R.D., 1998. ^{40}Ar/^{39}Ar muscovite dates from the nappe region of southwestern Norway; dating extensional deformation in the Scandinavian Caledonides. Tectonophysics 285 (1–2), 119–133.

Fossen, H., Dunlap, W.J., 1998. Timing and kinematics of Caledonian thrusting and extension collapse, southern Norway; evidence from (super 40) Ar/(super 39) Ar thermochronology. Journal of Structural Geology 20 (6), 765–781.

Fossen, H., Holst, T.B., 1995. Northwest-verging folds and the northwestward movement of the Caledonian Jotun Nappe, Norway. Journal of Structural Geology 17 (1), 3–15.

Fossen, H., Hurich, C.A., 2005. The Hardangerfjord shear zone in SW Norway and the North Sea; a large-scale low-angle shear zone in the Caledonian crust. Journal of the Geological Society of London 162 (4), 675–687.

Gee, D.G., Kumpulainen, R., Roberts, D., Stephens, M.B., Thon, A., Zachrisson, E., 1985. Scandinavian Caledonides tectonostratigraphic map. In: Gee, D.G., Sturt, B.A. (Eds.), The Caledonide Orogen; Scandinavia and Related Areas. John Wiley and Sons, Chichester, UK, p. 1266.

Gleizes, G., Leblanc, D., Bouchez, J.L., 1997. Variscan granites of the Pyrenees revisited: their role as syntectonic markers of the orogen. Terra Nova 9 (1), 38–41, doi:10.1046/j.1365-3121.1997.d01-9.x.

Hacker, B.R., Gans, P.B., 2005. Continental collisions and the creation of ultrahigh-pressure terranes: Petrology and thermochronology of nappes in the central Scandinavian Caledonides. Geological Society of America Bulletin 117, 117–134, doi:10.1130/B25549.1.

Hacker, B.R., Andersen, T.B., Root, D.B., Mehl, L., Mattinson, J.M., Wooden, J.L., 2003. Exhumation of high-pressure rocks beneath the Solund Basin, Western Gneiss region of Norway. Journal of metamorphic Geology 21 (6), 613–629.

Harris, N., Vance, D., Ayres, M., 2000. From sediment to granite: timescales of anatexis in the upper crust. Chemical Geology 162, 155–167.

Hoek, J.D., 1991. A classification of dyke-fracture geometry with examples from Precambrian dyke swarms in the Vestfold Hills, Antarctica. Geologische Rundschau 80 (2), 233–248.

Holdsworth, R.E., Strachan, R.A., 1988. Structural age and possible origin of the Vagastie Bridge granite and associated intrusions, central Sutherland. Geological Magazine 125 (6), 613–620.

Hossack, J.R., 1983. A cross-section through the Scandinavian Caledonides constructed with the aid of branchline maps. In: Balanced Cross-Sections and their

Geological Significance; A Memorial to David Elliott. Pergamon, Oxford/New York, pp. 103–111.

Hossack, J.R., Cooper, M.A., 1986. Collision tectonics in the Scandinavian Caledonides. In: Collision Tectonics 19. Geological Society of London, London, UK, pp. 287–304.

Hossack, J.R., Garton, M.R., Nickelsen, R.P., 1985. The geological section from the foreland up to the Jotun thrust sheet in the Valdres area, South Norway. In: Gee, D.G., Sturt, B.A. (Eds.), The Caledonide Orogen. Scandinavia and Related Areas, Vol. 1. John Wiley and Sons, Chichester, UK, pp. 443–456.

Koestler, A.G., 1982. A Precambrian age for the Ofredal granodiorite intrusion, central Jotun Nappe, Sogn, Norway. Norsk Geologisk Tidsskrift 62 (3), 225–228.

Koestler, A.G., 1988. Heterogeneous deformation and mylonitization of a granulite complex, Jotun-Valdres Nappe Complex, central South Norway. Geological Journal 23 (1), 1–13.

Kühn, A., Glodny, J., Austrheim, H., Råheim, A., 2002. The Caledonian tectonometamorphic evolution of the Lindås Nappe; constraints from U–Pb, Sm-Nd and Rb-Sr ages of granitoid dykes. Norsk Geologisk Tidsskrift 82 (1), 45–57.

Lundmark, M., Corfu, F., 2007. The age and origin of the Årdal dyke complex, SW Norway: false isochrons, incomplete mixing and the genesis of Caledonian granites in basement nappes. Tectonics 26, TC2007, doi:10.1029/2005TC001844.

Lundmark, A.M., Corfu, F., 2008. Late-orogenic Sveconorwegian massif anorthosite in the Jotun Nappe Complex, SW Norway, and causes of repeated AMCG magmatism along the Baltoscandian margin. Contributions to Mineralogy and Petrology 155, 147–163, doi:10.1007/s00410-007-0233-5.

Lundmark, A.M., Corfu, F., Selbekk, R., Spürgin, S., 2007. The Proterozoic history of high-grade gneisses in the Jotun Nappe Complex in SW Norway; constraints from U–Pb geochronology. Precambrian Research 159 (3–4), 133–154, doi:10.1016/j.precamres.2006.12.015.

Lutro, O., Tveten, E., 1996. Geologisk kart over Norge, bergrunnskart Årdal M 1:250 000. Norges Geologiske Undersøkelse.

Milnes, A.G., Koestler, A.G., 1985. Geological structure of Jotunheimen, Southern Norway (Sognefjell-Valdres cross-section). In: Gee, D.G., Sturt, B.A. (Eds.), The Caledonide Orogen. Scandinavia and Related Areas, Vol. 1. John Wiley and Sons, Chichester, UK, pp. 457–474.

Milnes, A.G., Wennberg, O.P., Skår, Ø., Koestler, A.G., 1997. Contraction, extension and timing in the South Norwegian Caledonides; the Sognefjord transect. In: Burg, J.P., Ford, M. (Eds.), Orogeny Through Time. Geological Society of London, Special publication 121, London, UK, pp. 123–148.

Nickelsen, R.P., Hossack, J.R., Garton, M., Repetsky, J., 1985. Late Precambrian to Ordovician stratigraphy and correlation in the Valdres and Synnfjell thrust sheets of the Valdres area, southern Norwegian Caledonides; with some comments on sedimentation. In: Gee, D.G., Sturt, B.A. (Eds.), The Caledonide Orogen. Scandinavia and Related Areas, Vol. 1. John Wiley and Sons, Chichester, UK, pp. 369–378.

Paul, J., Buergmann, R., Gaur, V.K., Bilham, R., Larson, K.M., Ananda, M.B., Jade, S., Mukal, M., Anupama, T.S., Satyal, G., Kumar, D., 2001. The motion and active deformation of India. Geophysical Research Letters 28 (4), 647–650.

Petford, N., Clemens, J.D., 2000. Granites are not diapiric. Geology Today 16 (5), 180–184.

Petford, N., Cruden, A.R., McCaffrey, K.J.W., Vigneresse, J.L., 2000. Granite magma formation, transport and emplacement in the Earth's crust. Nature (London) 408, 669–673.

Roberts, D., Gee, D.G., 1985. An introduction to the structure of the Scandinavian Caledonides. In: Gee, D.G., Sturt, B.A. (Eds.), The Caledonide Orogen; Scandinavia and Related Areas. John Wiley and Sons, Chichester, UK, pp. 55–68.

Schärer, U., 1980. U–Pb and Rb-Sr dating of a polymetamorphic nappe terrain; the Caledonian Jotun Nappe, southern Norway. Earth and Planetary Science Letters 49 (2), 205–218.

Skjerlie, K.P., Pedersen, R.B., Wennberg, O.P., de la Rosa, J., 2000. Volatile phase fluxed anatexis of metasediments during late Caledonian ophiolite obduction: Evidence from the Sogneskollen granitic complex, west Norway. Journal of the Geological Society of London 157 (6), 1199–1213.

Soper, N.J., Strachan, R.A., Holdsworth, R.E., Gayer, R.A., Greiling, R.O., 1992. Sinistral transpression and the Silurian closure of Iapetus. Journal of the Geological Society (London) 149 (6), 871–880, doi:10.1144/gsjgs.149.6.0871.

Spanner, B.G., Kruhl, J.H., 2002. Syntectonic granites in thrust and strike-slip regimes: the history of the Carmo and Cindacta plutons (southeastern Brazil). Journal of South American Earth Sciences 15 (4), 431–444.

Stephens, M.B., Gee, D.G., 1985. A tectonic model for the evolution of the eugeoclinal terranes in the central Scandinavian Caledonides. In: Gee, D.G., Sturt, B.A. (Eds.), The Caledonide Orogen. Scandinavia and Related Areas, Vol. 1. John Wiley and Sons, Chichester, UK, pp. 953–978.

Torsvik, T.H., Smethurst, M.A., Meert, J.G., Vand, V.R., McKerrow, W.S., Brasier, M.D., Sturt, B.A., Walderhaug, H.J., 1996. Continental break-up and collision in the Neoproterozoic and Palaeozoic; a tale of Baltica and Laurentia. Earth-Science Reviews 40 (3–4), 229–258.

Wennbqerg, O.P., Skjerlie, K.P., Dilek, Y., 2001. Field relationships and geochemistry of the Ostereide dykes, western Norway; implications for Caledonian tectonometamorphic evolution. Norsk Geologisk Tidsskrift 81 (4), 305–320.