Age constraints on the late Caledonian (Scandian) deformation in the Major Bergen Arc, SW Norway

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Fossen, H. & Dunlap. W.J.: Age constraints on the late Caledonian (Scandian) deformation in the Major Bergen Arc, SW Norway. *Norwegian Journal of Geology*, Vol. 86, pp. 59- 70. Trondheim 2006. ISSN 029-196X.

The Ulven Syncline in the Bergen Arcs contains some of the youngest rocks involved in Caledonian orogenic deformation in West Norway. The pelitic Vaktdal Formation contains a Middle Llandovery (439-436 Ma) fauna, providing a maximum age of deposition and deformation of the overlying psammitic Skarfjell Formation. New $^{40}Ar/^{39}Ar$ step heating data for biotites from two lamprophyric rocks in the Skarfjell Formation give a minimum age of the Skarfjell Formation of 417 Ma. According to most recent time scales, this indicates that the Skarfjell Formation is Silurian in age. Furthermore, a ~410 Ma $^{40}Ar/^{39}Ar$ age of metamorphic muscovite from the phyllitic Vaktdal Formation is interpreted as a deformation age. Compared to the known timing of Paleozoic events in West Norway, this age indicates that the Ulven Syncline formed in the Early Devonian during the Scandian phase of the Caledonian orogeny.

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Introduction

The complete closing of the proto-Atlantic Iapetus ocean and collision of Baltica with the Laurentian continent is commonly referred to as the Scandian phase of the Caledonian orogenic evolution (e.g. Gee 1975). Oceanic and continental terranes were amalgamated as an impressive orogenic wedge was formed above the Baltican basement in Scandinavia.

In West Norway, the Scandian phase gave way to widespread extensional tectonics and related deposition of Middle Devonian molasse deposits, constrained by both stratigraphic (Kiær 1918; Jarvik 1949), radiometric (Chauvet & Dallmeyer 1992; Fossen & Dunlap 1998) and structural data (Séranne & Séguret 1987; Fossen 1992; Osmundsen & Andersen 1998). On the other end, the *initiation* of the Scandian orogenic phase is constrained by fossil bearing metasediments deposited in arc settings prior to the final closure of the proto-Atlantic Iapetus ocean. The youngest reported fossiliferous rocks involved in Caledonian contraction in West Norway are the possible Wenlockian (~425 Ma; timescale by Gradstein et al. 2004 used throughout this paper) rocks of the Herland Group in Sunnfjord (Andersen et al. 1990). These rocks are overlain by what is interpreted to be an obduction melange (Sunnfjord melange) in the hanging wall of the Nordfjord-Sogn Shear Zone (Andersen et al. 1990). Unfortunately, the fossiliferous fauna in these rocks is at the present time poorly documented, and the significance of these rocks when it comes to constraining the Scandian time span is somewhat uncertain.

Farther south, the Ulven Syncline represents one of several modified synclinal structures in which Ordovician-Silurian sediments are pinched between blocks of their ophiolitic/island arc-type substrate in the Major Bergen Arc (Thon 1985a; Ingdahl 1989). The Ulven Syncline is a well-preserved example of these pinched-out synclines, and contains a Silurian fossiliferous succession. The age of the upper and non-fossiliferous quartzitic Skarfjell Formation is, however, unknown. Some of the cleavages and minor folds in the underlying phyllites of the Vaktdal Formation are rare or absent in the overlying quartzitic Skarfjell Formation. It has been suggested that these fabrics formed prior to the deposition of the sediments of the Skarfjell Formation (Sturt 1983; Saltnes 1984). This interpretation makes the Skarfjell Formation significantly younger than the underlying Silurian metasediments, calling for a subsequent phase of post-Early Devonian contractional deformation in this part of the Caledonides (Sturt 1983; Saltnes 1984). In this paper we briefly review the nature and timing of the deformation in the Ulven Syncline and discuss structural and orogenic implications in the light of new $^{40}Ar/^{39}Ar$ dates.

Geologic setting and previous work

The Bergen Arc System

Our understanding of the Bergen Arc System changed considerably throughout the previous century (e.g. Kolderup & Kolderup 1940; Kvale 1960; Sturt & Thon

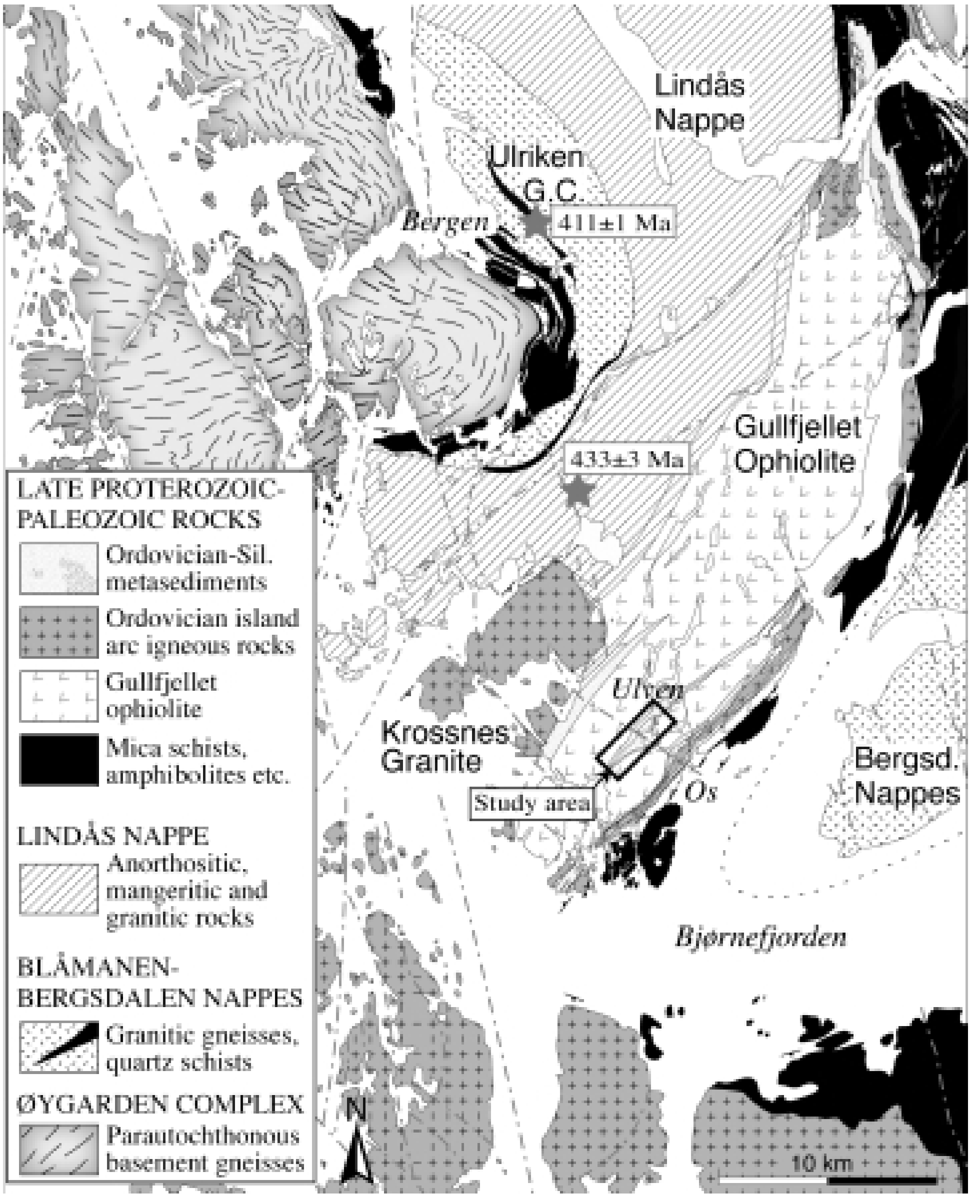


Fig. 1. Geologic map of the southern part of the Bergen Arc System, showing the location of the Ulven study area. Ulriken G.C. = Ulriken Gneiss Complex. Stars indicate $^{40}Ar/^{39}Ar$ dates published in Fossen & Dunlap (1998).

1978), and interpretations have continued to evolve as recent mapping and dating have allowed more refined models to be constructed. The Bergen Arcs are now regarded as a sequence of Caledonian nappes that occupy a major depression in the Baltic basement, (Sturt & Thon 1978) (Fig. 1). The depression is bounded by the extensional Bergen Arc Shear Zone to the east (Wennberg et al. 1998), which formed during orogenic collapse through crustal extension after the cessation of Caledonian thrusting (Fossen 1992).

The Proterozoic rocks of the Lindås nappe, flanked in the west by the Blåmanen Nappe (Ulriken Gneiss Complex and Rundemanen Formation) occupy the core of what appears to be a synformal structure (Kvale 1960). These nappe units overly the mostly Lower Paleozoic rocks of the Major and Minor Bergen Arcs. Whereas rocks of the Lindås and Blåmanen Nappes are considered Proterozoic in age (Sturt et al. 1975; Austrheim & Griffin 1985; Fossen 1988a), the Major and Minor Bergen Arcs comprise tectonic fragments of an Ordovician outboard terrane (Thon 1985b; Dunning & Pedersen 1988). These Ordovician rocks are now imbricated and tectonically intercalated with slices of Proterozoic and probably Lower Paleozoic rocks of continental affinity. Strain gradients are high, and the locally intense fabrics are related to emplacement of the outboard terrane onto the Baltican continental margin during the main collisional (Scandian) phase of the Caledonian orogeny (e.g. Færseth et al. 1977).

The Gullfjellet Ophiolite and arc-related rocks

The Gullfjellet Ophiolite (Thon 1985b) constitutes a major portion of the Major Bergen Arc. It contains gabbro (489 ± 3 Ma U/Pb zircon age; Dunning &

Pedersen 1998), sheeted dikes and basaltic units that are considered elements of a classical ophiolite pseudo-stratigraphy (Thon 1985b). Pelitic and subordinate psammitic units are considered to represent the original caprock to the ophiolite, and both were intruded at an early (Ordovician) stage by various arc-related granitoid intrusions. The oldest of these intrusions is the so-called quartz augen gneiss (Kolderup & Kolderup 1940), dated at 482 +6/-4 (U/Pb zircon age; Dunning & Pedersen 1988), whereas the Krossnes Granite may be the youngest (430 ± 6 Ma Rb/Sr whole rock age; Fossen & Austrheim 1988). This granite is among the youngest components of a suite of mostly magmatic rocks that extend southward from the Bergen Arcs, named the Sunnhordland Batholith (Andersen & Jansen 1987). This batholith developed on oceanic crust into a gradually more mature arc system during the Ordovician time period (Andersen & Jansen 1987; Pedersen & Dunning 1997).

The deformation of the ophiolite complex is highly heterogeneous. High-strain zones up to one kilometer thick contain metasediments that unconformably overlie the afore-mentioned ophiolitic rocks (with the possible exception of the latest granitoids). These sediments have a similar, although somewhat differently developed stratigraphy, generally consisting of a basal polymictic conglomerate, an overlying marble, phyllites and locally a quartzite or quartzite conglomerate (Ingdahl 1989). The marbles contain Ashgillan (mid-Ordovician?) fossils, providing a minimum age for the unconformity against the underlying ophiolite/island arc terrane (Thon 1985a).

The ophiolitic rocks are believed to have gone through a tectonothermal event prior to deposition of the late Ordovician sedimentary succession. Although the discordant relations along the unconformity presented as evidence for a pre-depositional event are indeed ambiguous (Ingdahl 1989), independent information favor the existence of a tectonometamorphic break. Such information includes a preserved pre-Scandian metamorphic mineral assemblage (Fossen 1988b) and the fact that the 430 ± 6 Ma Krossnes Granite intruded polydeformed metasediments of the Major Bergen Arc (Fossen & Austrheim 1988). Pre-Scandian deformation is also known from other parts of the outboard terrane in western Norway. Of particular interest to us is the fact that Scandian deformation and metamorphism by far dominate, and it is this deformation in the Ulven area that will be described here in some detail.

The Ulven Syncline and lamprophyric intrusions

Three synclinal zones of Upper Ordovician-Silurian metasediments are recognized in the Major Bergen Arc, named the Os, Hegglandsdal and Ulven synclines

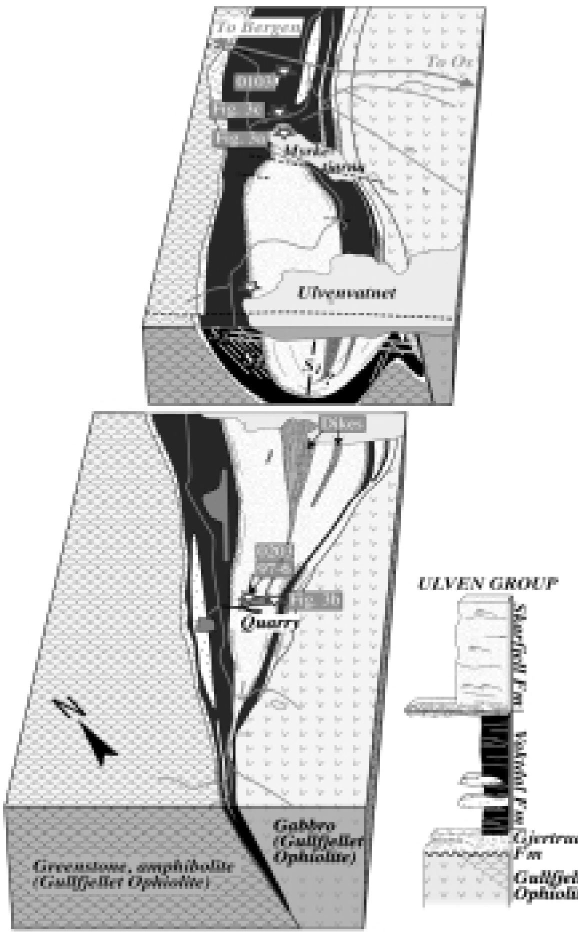


Fig. 2. Block diagram of the Ulven Syncline and stratigraphy of the Ulven Group. Sampling localities are indicated.

(Ingdahl 1989). These metasediments, which show large stratigraphic and petrological similarities, are considered to be remnants of a sedimentary cover to the Gullfjellet Ophiolite and related arc-type rocks. The synclinal zones are preserved in several kilometer-wide high-strain zones in the ophiolitic basement. The unusually low strains recorded in the widest parts of the Ulven syncline are an anomaly that has lead to the preservation of fossils and primary structures that are elsewhere obliterated.

The Ulven Syncline (Ryan & Skevington 1976) contains the youngest Paleozoic rocks of the three zones and of the Bergen Arc system as a whole. A primary, although strained unconformity exists between the ophiolitic basement and the greenish polymictic conglomerates and impure sandstones of the Gjertrudsberg Formation. Overlying the basal conglomerates and sandstones are the phyllites and intercalated quartz schists of the Vaktdal Formation.

The youngest metasedimentary rock in the Ulven Syncline is a quartzite with beds of quartz(ite) conglomerate (Skarfjell Fm.) (Fig. 2), occupying the core of the syncline. Cross bedding is common in the quartzite, showing that the quartzitic rocks young toward the core of the syncline. The contact with the underlying phyllites (Vaktdal Formation) is abrupt, and secondary cleavages in the phyllites are generally absent in the more competent conglomerates and quartzites of the Skarfjell Formation. This has led to speculations that the contact represents a regionally significant unconformity, where the Skarfjell Formation is younger than the age of some of the deformation in the Vaktdal Formation, and that the Skarfjell Formation and its deformation is post-Early Devonian in age (Sturt 1983; Saltnes 1984).

Metamorphosed and variably foliated lamprophyric intrusive rocks occur more or less parallel to the subvertical bedding and foliation in the quartzite southwest of Ulvenvatnet, and thus represent the youngest rock in the syncline. In places the lamprophyric rocks are seen to cut bedding at low angles, indicating that they at least locally intruded as dikes. The lamprophyres contain clusters of biotite that represent primary phenocrysts. In most places, alligned biotite grains are for the most part localized along domains that define the foliation. The heterogeneous nature of the deformation has however left some parts of the dikes almost unstrained.

Fossils have not been found in the Skarfjell Formation. Hence, no upper age constraint exists for the Ulven Group and the lamprophyric rocks. Graptolite and coral faunas are preserved in the underlying phyllitic Vaktdal Formation (Reusch 1882). The interpretation by Kolderup & Kolderup (1940) that the upper Vaktdal Formation is of Late Llandovery age was disregarded by Ryan & Skevington (1976), who found no evidence for a post-Middle Llandovery fauna. We thus consider the maximum age of the non-fossiliferous Skarfjell Formation and the lamprophyric rocks to be Middle Llandovery (~436-439 Ma).

Deformation of the Ulven Group

The main (D1) deformation (The Ulven syncline)

The folding of the Ulven Group into its synclinal structure is the large-scale effect of the first and main phase of deformation (D1). It affects bedding, soft sediment deformation structures and early quartz veins (Fig. 3a-c). The Ulven Syncline is an upright to slightly overturned structure with a steeply dipping axial surface (Fig. 2). The hinge is gently SW plunging, as are stretching lineations measured in the Skarfjell Formation. Some observations of what are interpreted to be F1 fold axes support this view.

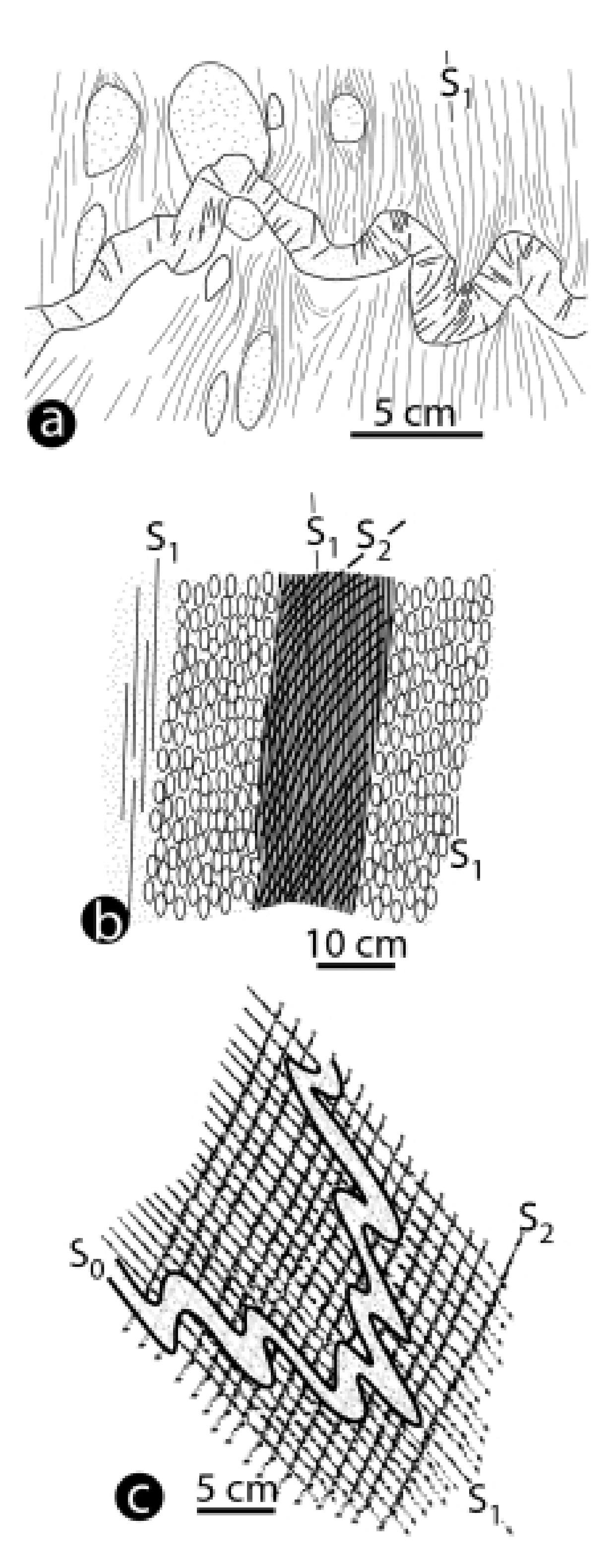


Fig. 3. Structural observations from the Ulven Syncline. a) S1 cleavage in the Skarfjell Fm. A folded quartz vein is oriented subparallel with bedding. Note cleavage refracton pattern characteristic of buckling (flattening across S1). b) Non-planar S2 crenulation cleavage overprinting S1 in phyllitic layer between two conglomerate layers at the base of the Skarfjell Formation. Ulven quarry. c) S0-S1-S2 relations in phyllite (Vaktdal Fm). Looking northeast in all cases.

Primary sedimentary structures are well preserved within the Skarfjell Formation in the study area. Strained conglomerate pebbles (Fig. 3b) are oriented with their flattening plane along the axial trace of the Ulven Syncline (Fig. 4a). An S1 cleavage is developed in sandy and mica-bearing parts of the Skarfjell Formation as well as in the lamprophyric rocks. Because this S1 cleavage is axial planar to the Ulven Syncline, it is inferred that the well-foliated lamprophyric rocks must have been folded together with the Skarfjell Formation during D1.

The S1 foliation in the Skarfjell Formation is correlated with a phyllitic cleavage in the underlying Vaktdal Formation. The cleavage has a fairly constant orientation in the Skarfjell and Vaktdal Formations in the northeastern fold closure near Myrketjørna (Fig. 2). Along the limbs, the cleavage is refracted according to the large difference in competence between the two formations. Refraction of S1 can also be seen on a more local (cm) scale (Fig. 3a). The S1 cleavage in the Vaktdal Formation is also affected by later domainal cleavages (see below).

D1 strain, as measured from deformed quartz(ite) pebbles, is generally low in the NW limb in the Ulvenvatnet area (Saltnes 1984). Strain appears to be higher in the narrower southeastern side of the syncline, where the fold appears to be attenuated or sheared out. Strain in the Ulvenvatnet area is also higher on the SE limb, as reflected by the difference in limb thickness (230 m on the NW limb vs. 105 m on the SE limb). The large variation in strain geometry (prolate to oblate shapes) that is recorded by the deformed conglomerate layers (Saltnes 1984) may reflect strain partitioning or temporal variations in the relative amounts of folding-related flattening strain and the shearing required for the sediments to be pinched in between unfolded basement blocks.

Secondary deformation structures (S2)

Cleavages secondary to the S1 foliation are pronounced in the phyllitic lithologies of the Vaktdal Formation, where it may be axial planar to open folds. A S2 cleavage is also observed in phyllitic matrix between pebbles in the conglomerates of the Skarfjell Formation. The secondary cleavages show a wide orientation in style and orientation in phyllitic lithologies, making correlation from outcrop to outcrop challenging. The picture is simplest on the northwest limb and in the northeastern fold closure near Myrketjørna (Fig. 5). Here the S2 cleavage overprinting the penetrative S1 foliation is consistently SE-dipping at ~60°. The S2 cleavage may be pervasive and locally stands out as the dominating cleavage in the phyllitic Vaktdal Formation. The S2 cleavage is again affected by open folds with gently

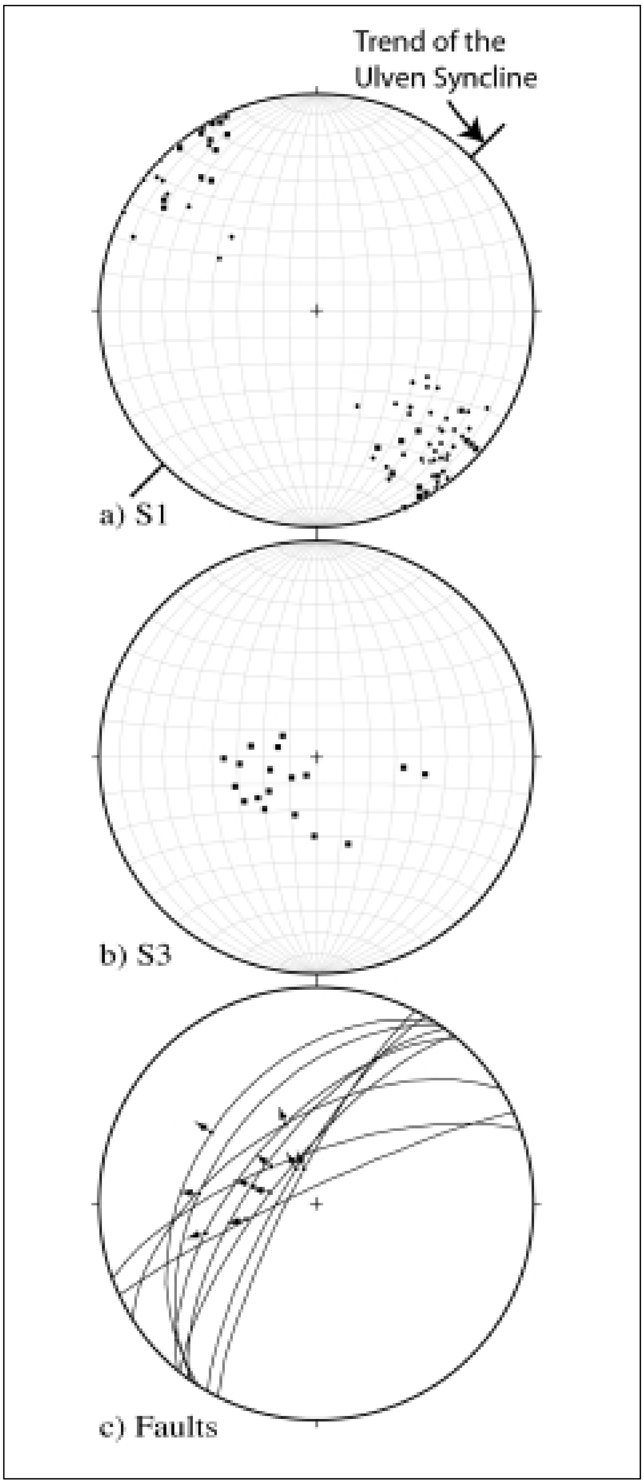


Fig. 4. Stereoplots of the main (S1) foliation recorded in phyllites of the Vaktdal Fm. (dots) and Skarfjell Fm. (squares), late (S3) cleavage in phyllites and fault slip data.

NE-dipping axial surfaces and a relatively weak crenulation cleavage (S3, see next section). This cleavage is well developed in rare phyllitic layers within the Skarfjell Formation (Fig. 3 b-c).

The S1 foliation is affected by secondary cleavages also

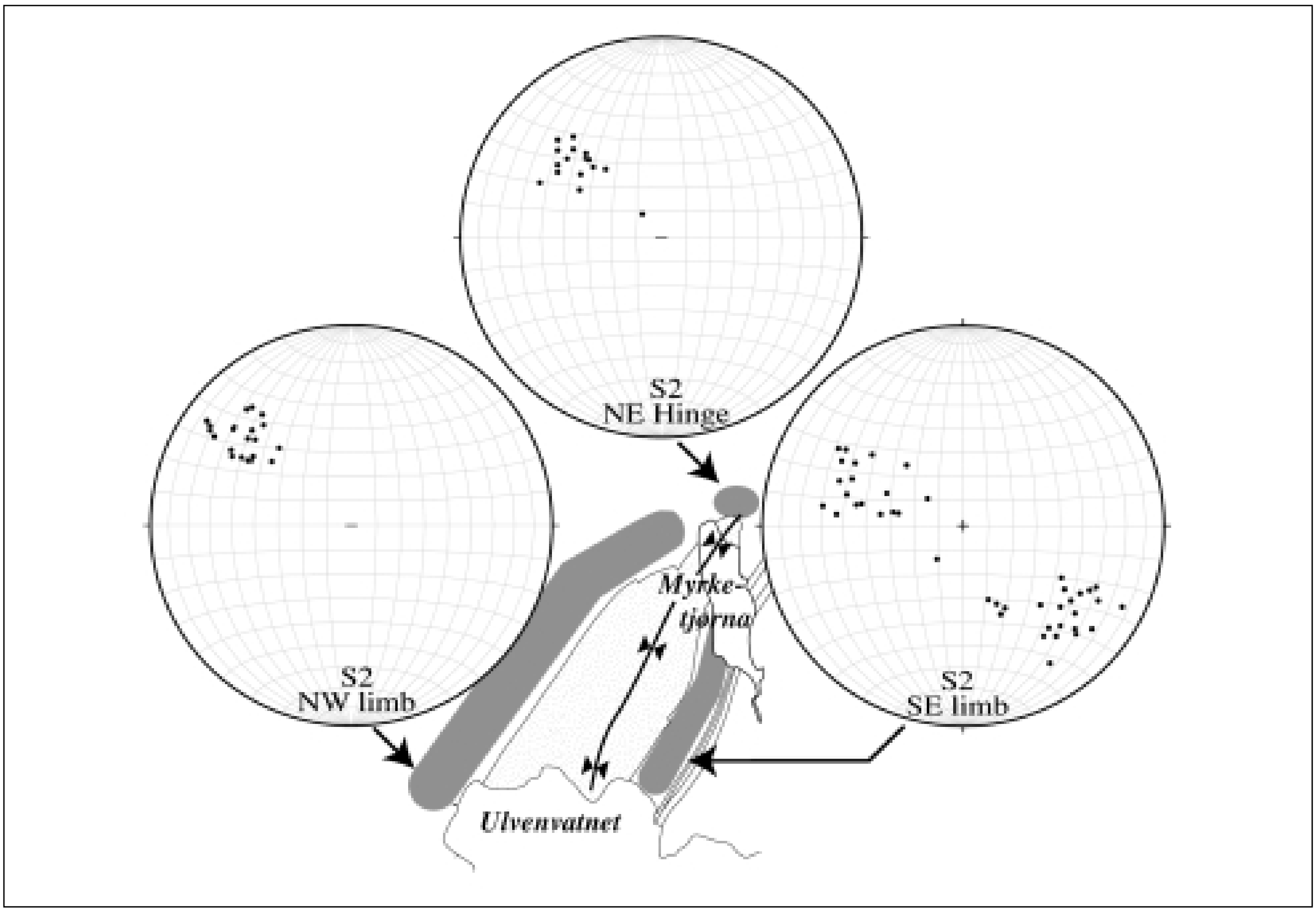


Fig. 5. Stereoplots of the second (S2) cleavage in phyllites of the Vaktdal Fm. around the northeastern closure of the Ulven Syncline. Note anomalous orientations on the SE limb.

along the southeast limb. A well-developed S2 cleavage is found to dip to the southeast in some outcrops and to the northwest in others. Both are deformed by a shallowly dipping S3 cleavage described in the next section. The age relations between the differently oriented S2 cleavages is not obvious, and clear overprinting relations have not been found. They obviously express differences in the strain field that may be temporal (D2 consisting of subordinate deformation phases) or spatial (local strain variations during the same deformation episode). They are both attributed to D2 in this account, as they are older than the more consistently oriented S3 cleavage and younger than S1.

A distinct cleavage is locally found along the contact between the Skarfjell Formation and the underlying Vaktdal Formation at the northwest side of Ulvenvatnet. As discussed in Ingdahl (1989), this cleavage affects S2 and is likely a result of shearing in a less than meter-wide zone along the contact.

The youngest cleavage (S3)

The latest crenulation cleavage in the area is developed as a sub-horizontal to NE-dipping (Fig. 4) planar structure on both limbs of the syncline and in the northeastern fold closure. Because of the consistent orientation of this late crenulation cleavage and because is consistently affects all earlier S1-S2 cleavages in the phyllites, it is considered to be formed during one deformation phase and is here named S3. This cleavage typically occurs in conjunction with localized open folding of the phyllites, but has not been identified in the more quartzitic rocks of the Skarfjell Formation.

Brittle faulting

A number of minor faults crosscut all of the structures described above. These faults are kinematically consistent with NW-SE stretching (Fig. 4). Hence, they conform to a large number of observations of early post-Caledonian faults in the Bergen area (Fossen 1998).

Sampling for $^{40}Ar/^{39}Ar$ analyses

Our primary goal was to date the youngest rocks in the area involved in the Caledonian orogeny, i.e. the lamprophyric rocks. Hence, a sample (97-6), and later a second sample (0203) of the lamprophyres were collected from the quarry (UTM 014-777) in 1997 and 2003, respectively, where fresh samples unaffected by weathering are easily available. The lamprophyric dikes are foliated, notably by parallel oriented biotite grains. The foliation is interpreted as an S1 foliation, subvertical and subparallel to the bedding in the quarry. The intensity of the foliation varies in the quarry, and the dated samples were collected where the foliation was weak or abscent. The samples show a preferred orientation of the biotite crystals which could represent a gently modified flow texture. Original igneous textures are well preserved, and there is indication of very minor recrystallization only.

In an attempt to date the metamorphic growth of mica during the D1 deformation, white mica was extracted from a sample of the Middle Llandovery Vaktdal Formation. The phyllite sample (0103, UTM 033-796) contains a strong S1 foliation with an additional S2 crenulation cleavage.

Results

The micas were dated by the $^{40}Ar/^{39}Ar$ method. They were step-heated in a double-vacuum resistance furnace and the evolved gas was analyzed on a VG3600 mass spectrometer. The samples were irradiated for 576 hr at the HIFAR reactor, thanks to the Australian Institute of Nuclear Science and Engineering, and the Australian Nuclear Science and Technology Organization. Gas handling, cleaning and data reduction were the same as that discussed in Dunlap et al. (1995) except as noted here. The data are displayed in Fig. 6.

The micas yield Paleozoic plateau-like ages, whereas some amphiboles that we have also measured (data not shown here) gave erratic spectra of Proterozoic age. Although no clear indication of excess argon is exhibited by the amphibole data or by isochron analysis, the apparent ages exceed the ages of the rocks, and we have discarded the amphibole data. Low chlorine content in the amphiboles precludes any analysis that might detect chlorine-correlated excess argon.

Biotite 97-6 from the lamprophyre dike yields a plateau-like age of 417.0 ± 0.6 Ma (1σ) over 100% of gas release. Inverse isochron analysis of the 97-6 biotite further attests to the homogeneity of this sample, giving an age of 418.1 ± 0.4 Ma (1σ) and an air-like intercept of 293.3 ± 2.1 (1σ) with no data points deleted. This age could represent the age of crystallization of the lamprophyre, the age of the greenschist facies metamorphism, or the age of cooling after the metamorphic event. Similarly, biotite 0203 yields a plateau-like age of 416.8 ± 2.0 Ma (1σ) over 80% of gas release, i.e. very consistent with the result of biotite 97-6.

Muscovite 0103 from the phyllite of the Vaktdal Formation yields a plateau-like age of 410.4 ± 0.6 Ma (1s) over 75% of gas release. Given the fact that the muscovite grains are metamorphic, the age must represent a deformation age or cooling age. This is discussed further in the discussion section below.

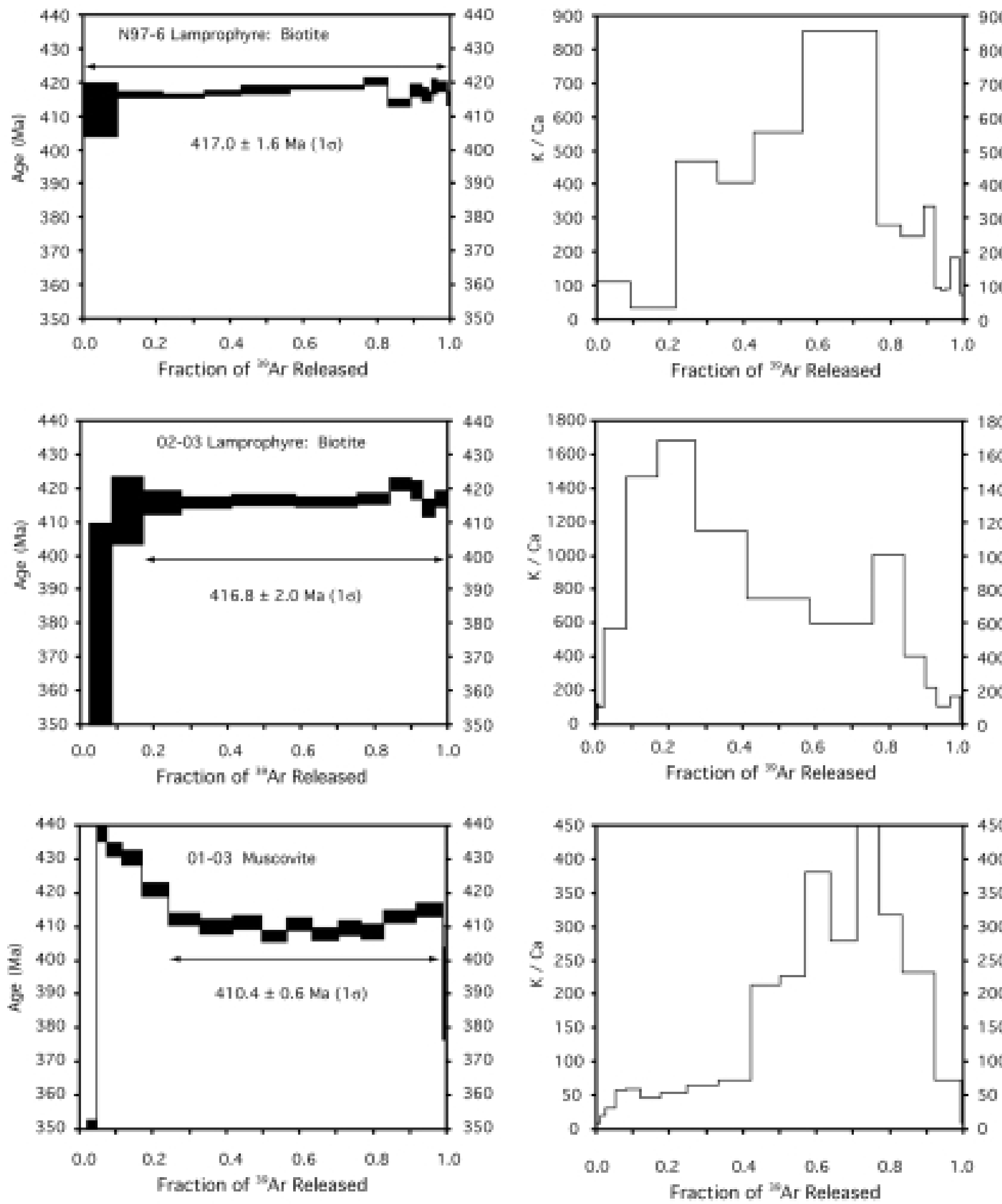
Discussion

There is little doubt that the entire downfolded and sheared sequence of rocks within the Ulven Syncline was deformed during the main Caledonian (Scandian) orogeny.

This conclusion is further supported by the well-defined ~417 Ma $^{40}Ar/^{39}Ar$ age of biotite in the lamprophyre and the ~410 Ma age of white mica in the phyllitic Vaktdal Formation. These ages fall within the time period of the Scandian phase, i.e. the final build-up of the Caledonian orogenic wedge at the time of continent-continent collision between Laurentia and Baltica (e.g. Milnes et al. 1987). Kinematic studies coupled with $^{40}Ar/^{39}Ar$ data indicate that the Scandian phase lasted until around 404 Ma in this part of the Caledonides, while post-contractional, extension-related ages tend to fall around 400 Ma (Chauvet & Dallmeyer 1992; Boundy et al. 1996; Fossen & Dallmeyer 1998; Fossen & Dunlap 1998).

What do the ages mean?

While the new ages from the Ulven Syncline clearly indicate a Late Silurian-Early Devonian age for the main deformation of the Ulven Group and similar strained zones in the Bergen Arc System, the precise meaning of the ages is not immediately clear. White micas are generally thought to have a closure temperature of about 350-400°C for medium pressure terranes and with a cooling rate of a few tens of degrees per million years. Although not very well constrained, the closure temperature for biotite is considered to be slightly lower, possibly 300-350°C (Harrison et al. 1985). If micas grow at temperatures well above the temperature of argon retention, the measured age likely reflects the time since cooling through the closure temperature. However, if deformation and recrystallization of mica take place at lower temperatures, the age of deformation may be recorded (cf., Dunlap 1997). Under the greenschist facies conditions that accompanied the D1 deformation of the Ulven Group, temperature was probably close to the closing temperature of muscovite, thus opening the possibility that the muscovite age in the phyllite may be a deformation age.



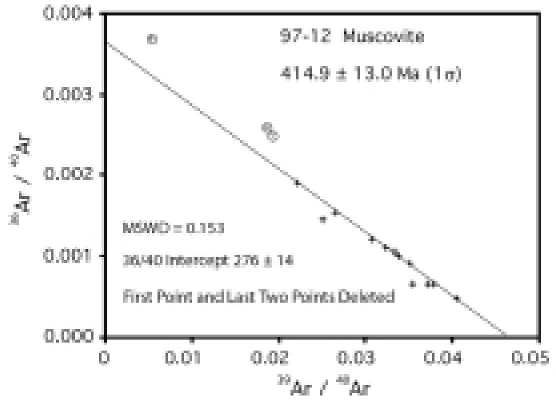


Fig. 6. $^{40}Ar/^{39}Ar$ ages (release spectra) of micas from the study area. Experimental temperatures increase from left to right; samples melted at end of procedure. Height of bars reflects a one sigma uncertainty. K/Ca plots (right) show that calcium contamination, by adhering fragments of feldspar, is insignificant Inverse isochron diagram, at lower right, for sample 97-12 muscovite. For locations of samples see Figure 2.

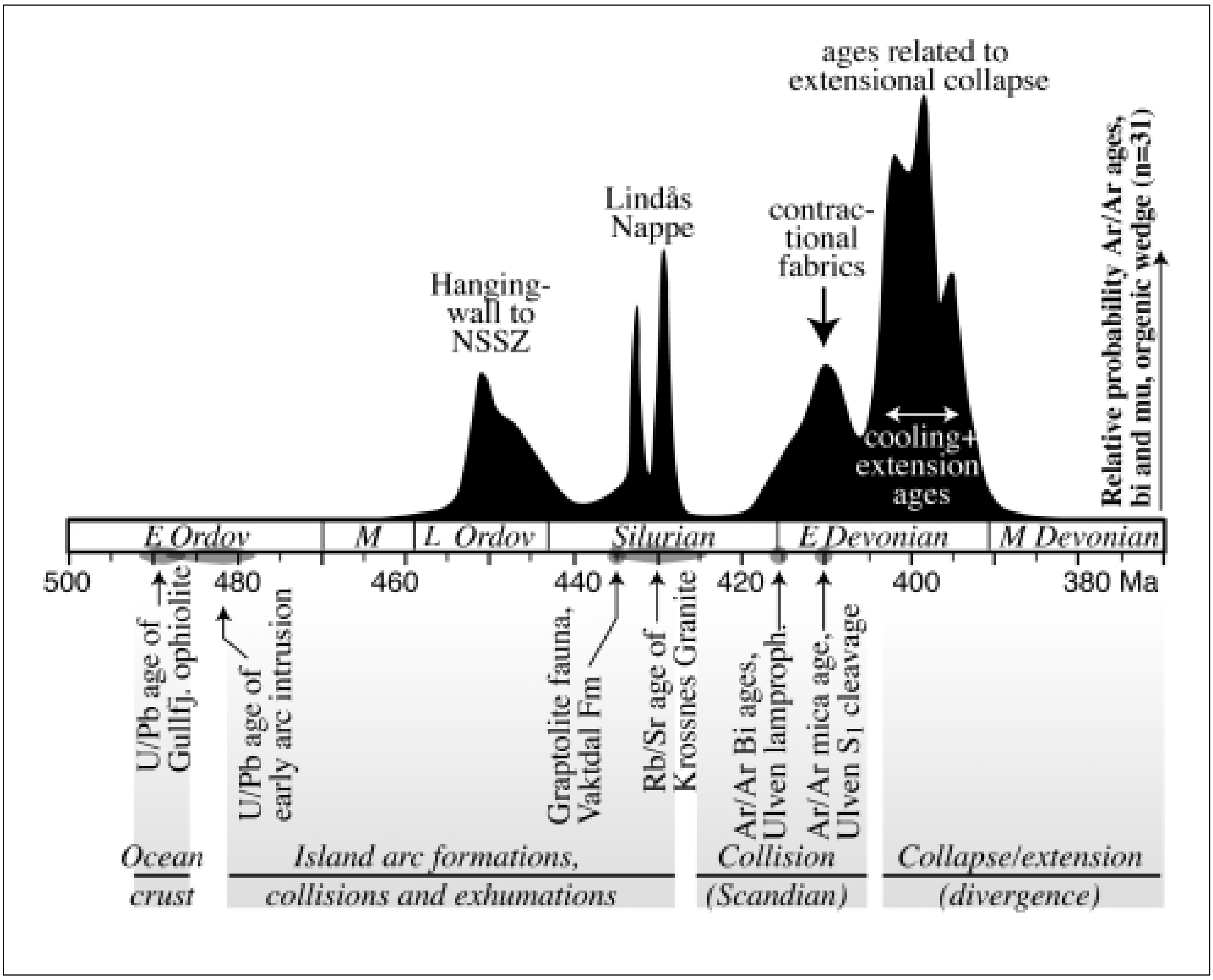


Fig. 7. Relative probability of 40Ar/39Ar ages reported from the orogenic wedge in the Bergen Arcs and Sunnfjord area. Age constraints are added and orogenic events and phases stated at the bottom.

In the present case we have biotite ages that are ~6-7 my older than the white mica age. From the discussion above, biotite ages would be expected to be younger than white mica ages if recording regional cooling through their respective cooling temperatures. In this perspective, it seems likely that the white mica age may represent the age of deformation and crystallization of white mica in the Vaktdal Formation, i.e. the time of S1 formation. In this perspective, the biotite ages are likely to reflect the time of intrusion of the lamprophyric dikes.

At the very least, we are certain that the lamprophyres intruded at 417 Ma or before. They do not reflect the time of D1 deformation because the sampled biotites are large magmatic crystals that did not recrystallize during D1. The best interpretation from the geological evidence, therefore, is that the biotite ages are likely to be slightly younger than the age of intrusion, due to the propensity of biotite to lose radiogenic argon at the temperatures indicative of the metamorphism that has affected the syncline. Given this cautionary statement, however, it is still possible that the biotite ages faithfully record a crystallization age; the fact that two separate samples give identical results is somewhat encouraging in this regard.

Regional context

Published Siurian-Devonian $^{40}Ar/^{39}Ar$ ages from the nappe stack of West Norway tend to fall into three groups at ~430, 415-405 and 404-395 Ma (Fig. 7). Ages belonging to the latter (~400 Ma) group are typically associated with extensional collapse structures and hinterland-directed transport, whereas the older ages are typically extracted from rocks with Caledonian (foreland-verging) structures. The new data from the Ulven Group clearly belong to the Caledonian (415-405 Ma) age group, suggesting that the deformation of the Ulven Group and its subsurface is related to the build-up of the Caledonian orogenic wedge. The only metasedimentary rock in the Bergen Arcs previously dated by the $^{40}Ar/^{39}Ar$ method is a quartz-mica schist of the Rundemanen Formation (Blåmanen Nappe; Fig. 1), yielding a plateau age of 411 ±1 Ma (Fossen & Dunlap 1998), which is within error of the white mica age from the Vaktdal Formation presented here.

Micas from both the northern and southern internal part of the nearby Lindås Nappe (Fig. 1) tend to yield ages around 430 Ma (Boundy et al. 1996; Fossen & Dunlap 1998). This suggests that the Lindås Nappe was not heated above the closure temperature of muscovite for any significant amount of time since the time of deposition of the Vaktdal Formation. It is likely that the last phase of strong deformation of the rocks of the Major Bergen Arc (D1 in the Ulven Group) is related to its juxtaposition with the Lindås Nappe. Hence, the 430 Ma cooling ages in the Lindås Nappe give some support to the model where the temperature did not exceed the closure temperature of white mica and the biotite and white mica $^{40}Ar/^{39}Ar$ ages from the Ulven area represent intrusion age and deformation age, respectively.

Implications for the tectonometamorphic history of the Bergen Arcs

The structural investigations carried out in this work supports the tectonometamorphic model suggested by Ryan & Skevington (1975) and later advocated by Ingdahl (1989) that the Vaktdal and Ulven formations experienced the same tectonometamorphic history. The tectonic break between the Vaktdal and the Skarfjell formations, which was suggested by some previous investigators (Sturt 1983; Saltnes 1984), finds little support in the new isotope data. According to their model, the Vaktdal Formation and older rocks were strongly deformed, uplifted and exposed after deposition of the Middle Llandovery (~435 Ma) Vaktdal Formation and prior to the overlying Skarfjell Formation (postdated by the lamprophyric intrusion dated to 417 Ma in this work). The simpler model where the structural development in the two formations is coincident, albeit with somewhat different expressions in the two mechanically contrasting formations, is thus favored here.

Previous workers have found a fairly penetrative fabric that can be followed continuously throughout the Minor and Major Bergen Arcs and into the Lindås and Blåmanen Nappes and attributed this fabric to the final Caledonian (Scandian) orogenic phase (e.g. Fossen 1986). The new $^{40}Ar/^{39}Ar$ data from the Ulven Syncline combined with the age from the Blåmanen Nappe (Fig. 1) indicate that this deformation lasted until ~410 Ma, i.e. into the Lower Devonian. This was possibly the time when the rocks of the Lindås and Blåmanen Nappes were emplaced on top of the Lower Paleozoic rocks of the Minor and Major Bergen Arcs, i.e. where rocks of the Middle Allochthon in the scheme of Bryhni & Sturt (1985) were emplaced atop rocks belonging to the Upper Allochthon. In the Major Bergen Arc the Scandian deformation formed a series of pinched-out synclines (Thon 1985a; Ingdahl 1989), a pattern that is also found in the Blåmanen Nappe of the Bergen Arcs and in the Karmøy ophiolite and its cover (Thon 1980). As discussed by Thon (1980), the isoclinal folding of Lower Paleozoic cover sediments coupled with shear zones in their ophiolitic subsurface is a characteristic Scandian deformation style in West Norway. The ~410 Ma white mica age presented in this work may represent the first direct date of cleavage formation associated with this deformation.

Later deformation structures, such as the secondary cleavages in the Ulven Syncline, are seen many places in both arcs. It is currently unclear whether they are related to Caledonian contraction or to the later history of extensional collapse. In the Ulven Syncline it would be reasonable to relate at least the subhorizontal D3 fabric to gravitational instabilities of the Caledonian orogen, since such instabilities would produce a subvertical $\sigma 1$.

Conclusion

The new data from the Ulven Syncline in the Major Bergen Arc suggests that both the Vaktdal and Skarfjell Formations of the Ulven Group are of Silurian age, according to most current timescales. The Ulven Syncline and its axial plane cleavage probably formed around 410 Ma, and the Ulven Group and its substrate deformed together with other rock units in the Major Bergen Arc during the Scandian phase of the Caledonian orogeny.

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Appendix

In each experiment the temperature was raised in uneven increments up to ~1350-1450°C, aiming to evolve ~5-10% of the total sample gas in each step. The duration of each heating step was 15 min and essentially all the gas was released by 1350°C. The data was reduced in our usual manner, by regressing seven peak-heights for each mass and taking the zero-time intercept as representative of the unfractionated aliquot. Production ratios for interfering nuclear reactions were monitored with CaF_2 and a synthetic K-glass included in the irradiation package: (36/37)Ca = 0.00035, (39/37)Ca = 0.0008, with associated errors typically less than 5%. The $(40/39)_K$ varies from one sample to the next (next irradiation) and the range encountered was 0.047-0.0025. The samples were also irradiated with the GA1550 biotite standard. This standard was located in Al foil packets placed serially between samples ~ every 4 mm, in a single column formation rather than in the central position (Dunlap et al., 1995). Fluence for the unknowns was determined by cubic spline interpolation. The sensitivity of the mass spectrometer for argon was ~2.4E-17 mol/mV.