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Structure and ^{40}Ar/^{39}Ar thermochronology of an ultrahigh-pressure transition in western Norway

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Abstract: The Nordfjord region of western Norway hosts an archetypal subducted crustal section, underpinned by ultrahigh-pressure (UHP) eclogite, overlain by Devonian sediments, and cored by a crustal-scale extensional shear zone. Structural mapping reveals two distinct displacement zones that played different roles during the formation and exhumation of this section: (1) the Sandane Shear Zone is a NW-dipping, amphibolite-facies, high-strain zone near the base of the eclogite-bearing crust that separates allochthonous units from underlying crystalline basement; it may have originated during early thrusting, but was overprinted by top-to-the-west extensional fabrics at lower crustal depths; (2) structurally above this, the Nordfjord–Sogn Detachment Zone is a top-to-the-west, amphibolite- to greenschist-facies detachment shear zone within allochthonous units that defines the upper boundary of the eclogitized crust and was responsible for exhumation through at least mid-crustal depths. Muscovite ^{40}Ar/^{39}Ar ages suggest that amphibolite-facies deformation below the Nordfjord–Sogn Detachment was mostly finished by *c.* 397 Ma, whereas muscovite ages from the deeper parts of the UHP domain indicate that it cooled after 390 Ma. During exhumation through the middle crust, west-directed stretching was accompanied by north–south folding. Late sinistral transpressional faulting in the middle to upper crust truncated the earlier folds and shear zones.

Supplementary material: Complete ^{40}Ar/^{39}Ar data and a summary geological map of the Nordfjord region are available at http://www.geolsoc.org.uk/SUP18460.

The exhumation of continental ultrahigh-pressure (UHP) rocks involves the largest known vertical motions of continental crust (>100 km), and occurs at plate-tectonic rates (>10 mm a^{-1}: Ernst *et al.* 2007). Major normal-sense shear zones define the upper boundary of many of these terranes, but it is unclear how much exhumation these features achieved. Additionally, if (U)HP crust is extruded as slivers in a subduction channel, a thrust must be present below any such sliver(s), and it must be active at the same time as extension on the upper side; such footwall thrusts, however, are enigmatic and multiply reactivated in all but a few examples. Geometric and chronological aspects of UHP terranes that remain in question, then, include the following: (1) Is exhumation completed by one set or multiple sets of extensional or contractional structures? (2) Does normal-sense shear produce solely intracrustal displacement or complete mantle-to-surface displacement? (3) To what extent do UHP terranes remain coherent or become dissected during exhumation? (4) How closely do extension and contraction overlap in time? Answers to these questions are important in understanding the mechanisms by which UHP terranes are exhumed, the late-stage evolution and termination of continental collisions, and the forces that drive syn- and post-orogenic collapse.

For decades the Nordfjord region of western Norway has been a classic locality for investigating the exhumation process because it preserves a regional metamorphic transition from amphibolite to coesite-eclogite facies (Smith 1984; Wain *et al.* 2000; Young *et al.* 2007) and hosts a large extensional shear system that is presumed to be responsible for exhumation of the high-pressure rocks (Andersen *et al.* 1991; Krabbendam & Dewey 1998; Labrousse *et al.* 2004; Johnston *et al.* 2007*a*). The absence of syn- to post-orogenic plutons, minor Carboniferous to Late Mesozoic reactivation (Torsvik *et al.* 1992*b*; Osmundsen & Andersen 2001), and excellent exposure permit detailed study of the deformation across the pressure–temperature gradient. Several detailed studies in the Nordfjord region have described eclogite-facies rocks overlain by detachment faults, but the regional relationships between major shear zones and the (U)HP rocks have not been completely established. Extensive new mapping reported here combined with petrology and ^{40}Ar/^{39}Ar thermochronology data redefine the geometry and timing of high-strain displacement zones, and prompt a re-evaluation of the role of extensional tectonics in exhuming the Nordfjord UHP domain.

Regional tectonic framework

The Scandinavian Caledonides resulted from closure of the Iapetus Ocean and collision of the Baltica and Laurentia continental plates over a *c.* 35 Ma period from the Late Silurian to the Early Devonian (Hossack & Cooper 1986; Torsvik *et al.* 1992*a*; Hacker & Gans 2005). Toward the end of the collision, referred to as the Scandian phase, the leading edge of the Baltica slab was subducted NW beneath Laurentia (present coordinates) (Krogh 1977; Griffin & Brueckner 1980; Andersen *et al.* 1991), and deeper parts attained UHP conditions in the coesite and diamond stability fields (Smith 1984; Wain 1997; Cuthbert *et al.* 2000; Terry *et al.* 2000*b*).

The resultant UHP terrane, exposed in central western Norway in a large basement culmination known as the Western Gneiss Region (Fig. 1), is one of two giant UHP terranes on Earth, the other being the Dabie–Sulu area of western China. The Western Gneiss Region is dominated by quartzofeldspathic gneiss typical of continental crust, referred to here as the Western Gneiss Complex, with a few per cent mafic rocks that range from amphibolite to UHP eclogite. It is overlain by the remnants of a stack of thin, areally extensive thrust allochthons that were delaminated from the outer Baltica margin (Lower and Middle Allochthons), the Iapetus Ocean (Upper Allochthon), and the Laurentian margin (Uppermost Allochthon) and emplaced hundreds of kilometres over Baltica during the collision (Roberts 2003; Tucker *et al.* 2004; Hacker & Gans 2005).

Geochronology of eclogites indicates that the edge of Baltica was at HP or UHP depths from 430 to 400 Ma (Terry *et al.* 2000*a*; Carswell *et al.* 2003; Krogh *et al.* 2003; Root *et al.* 2004; Kylander-Clark *et al.* 2007, 2009; Glodny *et al.* 2008). Late Scandian extension and unroofing, accompanied by widespread recrystallization at amphibolite-facies conditions, followed between 400 and 395 Ma (Labrousse *et al.* 2004; Walsh & Hacker 2004; Root *et al.* 2005; Kylander-Clark *et al.* 2008). Cooling through mica closure to Ar loss progressed from *c.* 400 Ma in the Scandian foreland (Fossen & Dunlap 1998) to 380 Ma in the UHP domains (Chauvet & Dallmeyer 1992; Berry *et al.* 1995; Hacker & Gans 2005; Walsh *et al.* 2007). Synextensional sedimentation in Devonian to early Carboniferous supradetachment basins along the coast of western Norway took place throughout the exhumation of the Western Gneiss Region (Steel *et al.* 1985; Osmundsen & Andersen 2001; Eide *et al.* 2005).

The Nordfjord–Sogn Detachment Zone and (U)HP rocks

The signature feature of late Scandian extension in western Norway is a system of shallowly west-dipping shear zones and detachment faults along the coast, collectively named the Nordfjord–Sogn Detachment Zone (Norton 1987). In its type section between Sognfjord and Sunnfjord (Fig. 1), the Nordfjord–Sogn Detachment Zone is a 2–4 km thick, normal-sense fault–shear-zone system that separates the quartz-eclogite-bearing Western Gneiss Complex from an upper plate of high-level allochthons and synextensional sedimentary basins (Dietler *et al.* 1985; Chauvet & Séranne 1989; Andersen & Jamtveit 1990; Wilks & Cuthbert 1994; Hacker *et al.* 2003; Johnston *et al.* 2007*a*). Structures within the Nordfjord–Sogn Detachment Zone show unroofing of the high-pressure domains from lower crustal depths, beginning with penetrative thinning and amphibolite-facies shearing, and ending with greenschist-facies shearing and late brittle faults.

North of the type section, in the outer Nordfjord area, the same high-level allochthons and synorogenic sedimentary basins are juxtaposed against coesite-bearing UHP eclogites (Andersen & Jamtveit 1990; Wilks & Cuthbert 1994). Early workers drew on structural relationships in the southern type section, and assigned to the Nordfjord–Sogn Detachment Zone all amphibolite-facies mylonites between the eclogite-bearing Western Gneiss Region and high-level allochthons and sediments. Subsequent studies in the Nordfjord area classified rocks according to this paradigm, placing all eclogite within the Western Gneiss Complex and all mylonitic rocks within the Nordfjord–Sogn Detachment Zone, and defining the boundaries of the eclogite-facies domains as the

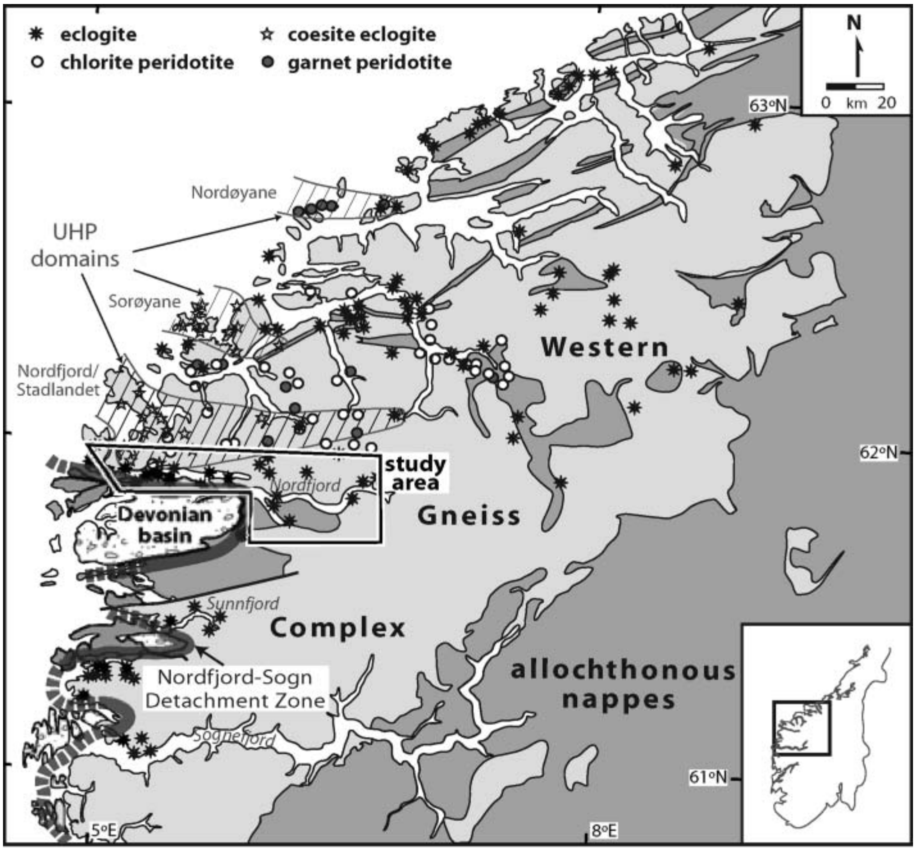


Fig. 1. Distribution of structural features, eclogite and high-pressure peridotite along the seaboard of the Western Gneiss Complex, Norway.

Nordfjord–Sogn Detachment Zone (Hartz *et al.* 1994; Krabbendam & Wain 1997; Labrousse *et al.* 2004; Johnston *et al.* 2007*a*).

More recent datasets have led to a revision of this model. The boundaries between eclogite-free, eclogite-bearing, and UHP domains are primarily metamorphic, rather than structural, features (Young *et al.* 2007). Furthermore, eclogites have been found within what was defined as the Nordfjord–Sogn Detachment Zone (Young *et al.* 2007), as well as within allochthonous rocks, revealing that the eclogite-bearing basement and ostensibly eclogite-free allochthons are not separated by a single, simple shear zone. This paper presents new data that bear upon the large-scale structural relationships of the eclogite-bearing domains, basement–allochthon tectonostratigraphy, and major zones of deformation in the Nordfjord area. Our findings reveal that the Nordfjord area contains two major shear zones: at higher structural levels the greenschist- to amphibolite-facies Nordfjord–Sogn Detachment Zone occurs mostly within the allochthons and broadly overlies the eclogite-facies domains. A lower shear zone follows the structurally deeper contact between the middle plate allochthons and the Western Gneiss Complex, and dips beneath the eclogite-bearing domains.

Tectonostratigraphy and petrology of Greater Nordfjord

A relatively clear tectonostratigraphy is present south of Nordfjord: the parautochthonous Western Gneiss Complex is overlain by shallowly dipping sheets of the Lower and Middle Allochthons, and capped by Devonian sediments of the Hornelen Basin (Fig. 2). In the study area the Western Gneiss Complex comprises fairly homogeneous, banded, granodioritic and granitic orthogneiss with trondhjemitic and syenitic layers, plus multi-kilometre-scale bodies of augen gneiss. The mineralogy is almost exclusively amphibolite facies: potassium feldspar + plagioclase + quartz + biotite. Epidote, garnet, hornblende and muscovite are less common, except toward the contact with the Lower Allochthon, and rare metre-scale eclogite pods are also present.

Above the Western Gneiss Complex, the Lower Allochthon consists of strongly deformed micaceous, quartzofeldspathic or calcic protomylonitic schists, with interlayered, discontinuous 10–50 m thick quartzite bands, slivers of megacrystic augen gneiss or anorthosite, scattered garnet amphibolites and rare eclogite. This complex thins from c. 1 km below the Hornelen Basin to zero in eastern Nordfjord, bringing the Western Gneiss Complex and overlying Middle Allochthon into contact.

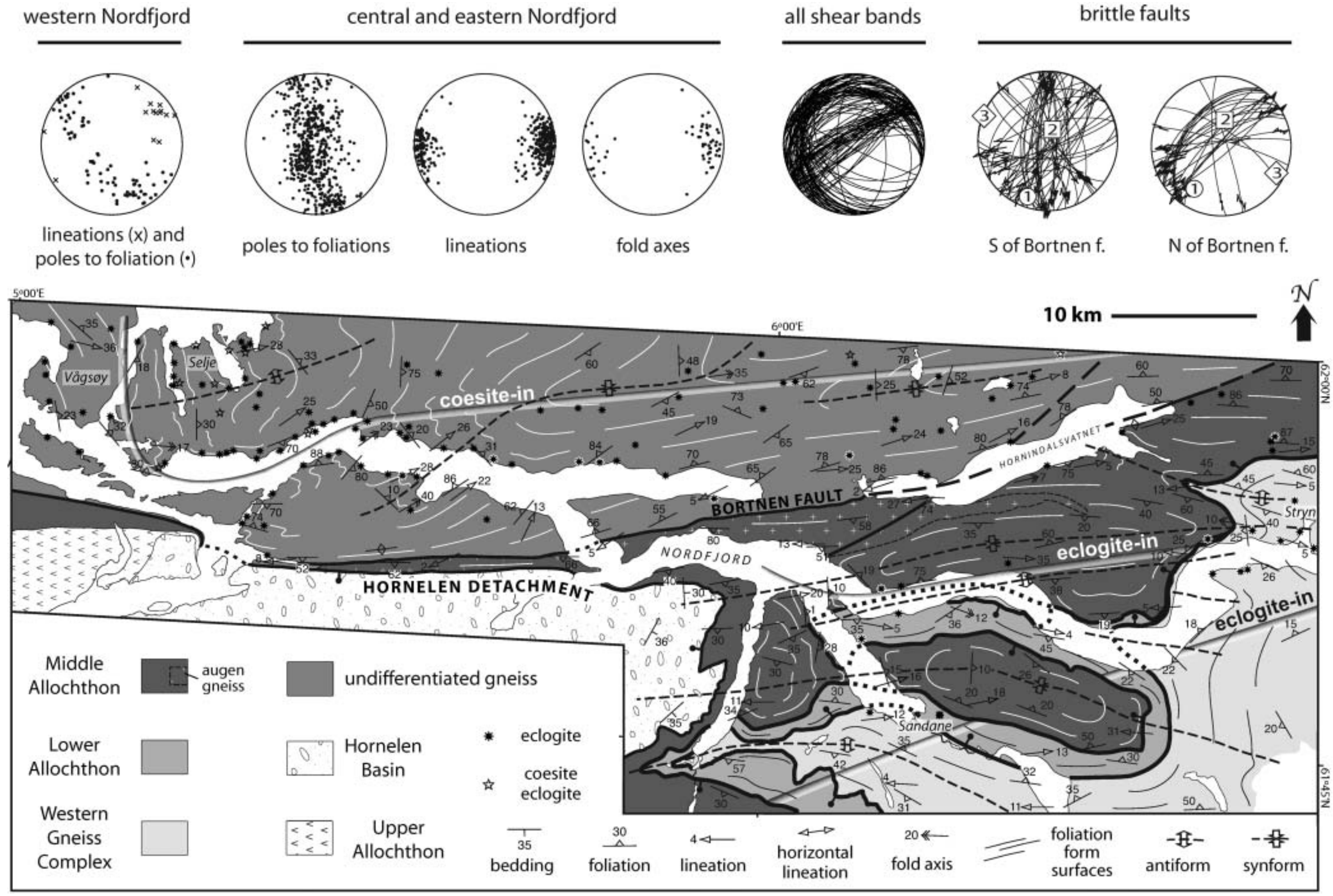


Fig. 2. Geological map of the Nordfjord area, compiled with data from the present study, Krabbendam & Wain (1997), Bryhni (2000*a*,*b*) and Bryhni & Lutro (2000). Isograds in the Middle Allochthon and north of the Bortnen Fault are labelled in white; eclogite-in isograd in the Western Gneiss Complex and Lower Allochthon is labelled in black. Eclogite symbols with white rims are those examined by Young *et al.* (2007). All structural data are plotted on lower hemisphere stereograms; brittle fault data are plotted with fault planes as great circles, striations representing fault slip as arrows, and principal stress axes determined from stress inversion as numbers 1–3.

The Middle Allochthon is an areally extensive unit of epidote amphibolite-facies, banded granodioritic and granitic gneiss that is outwardly similar to the Western Gneiss Complex (Fig. 2). Distinctive rock types include a structurally low, 200–500 m thick 'anorthosite–gabbro' unit, containing decametre-scale anorthosite horizons, metagabbro, and megacrystic augen gneiss, interspersed within mylonitic biotite + plagioclase ± hornblende ± epidote ± garnet gneiss. In the southern part of the study area the Middle Allochthon is entirely amphibolite facies, but north of Nordfjord the anorthosite–gabbro unit contains rare metre-sized eclogite pods (Young *et al.* 2007).

Rocks in the northern half of the study area (undifferentiated gneiss in Fig. 2) are fairly monotonous, banded or augen, locally migmatitic, two-mica granodioritic and granitic gneiss (feldspar + quartz + biotite + muscovite ± hornblende, garnet, clinozoisite–epidote). They are conventionally assigned to the Western Gneiss Complex (Andersen & Jamtveit 1990), but could belong to the Middle Allochthon or an imbricated slice of Western Gneiss Complex (see below). Scattered mafic eclogite bodies become larger (up to 100 m scale) and more recrystallized to the north and west; coesite relicts and small to kilometre-scale garnet peridotite bodies also appear in this direction (Fig. 2).

Structural geometry

Our regional dataset was compiled from detailed study of road exposures and fewer mountain traverses, supplemented by 1:50 000 geological maps of the Norwegian Geological Survey (see Fig. 2). The kilometre-scale structural geometry within the study area is outlined by the form surface of compositional layering, which is largely coplanar with the mylonitic foliation and mineral lineation. Mesoscopic shear-sense indicators comprise porphyroclasts (sigma and delta), S/C and C' shear bands, oblique foliations, asymmetric boudins, stretched veins and outcrop-scale brittle faults.

Macroscopic shear zones and detachments

Sandane Shear Zone. Across the eastern and southern half of the study area, the Middle and Lower Allochthons dip shallowly NNW, and are overprinted by penetrative mylonitization that fades downward, disappearing *c.* 2–3 km down into the uppermost Western Gneiss Complex. Along well-exposed sections near Sandane and Stryn (Figs 2 and 3a, b), the Western Gneiss Complex below the shear zone is coarser and granoblastic (Fig. 4a), with symmetric fabrics, sharp, planar, centimetre-scale compositional banding, and crosscutting dykes plus large, nearly massive bodies of augen orthogneiss. Rare eclogite at these structural levels is unfoliated. Within the uppermost 2 km of the Western Gneiss Complex, ductile strain increases upwards as shown by the development of a new penetrative foliation and lineation of finer-grained mica, elongate quartz and feldspar, plus thin, discontinuous shear bands. Layer-parallel thinning is indicated by progressive attenuation of gneissic banding, and transposition of dykes. With increasing strain, all rocks are transformed into thinly or weakly banded to augen-textured, medium- to fine-grained, strongly foliated S–L mylonites (Fig. 4b); L > S fabrics are mainly restricted to coarse augen gneiss. A strong east–west-trending lineation is defined by stretched feldspar, quartz and mica, and is subparallel to minor fold axes (Fig. 2 stereograms). Numerous west-dipping shear bands (C and C' shears: Berthé *et al.* 1979; Platt & Vissers 1980) cut the layering and foliation at low angles (8–30°); spectacular kinematic indicators demonstrate pervasive top-to-the-west normal-sense shear (Fig. 4b). Fine-grained eclogite within the mylonitic zone typically preserves an earlier, variably rotated foliation defined by oriented omphacite and amphibole.

The Lower Allochthon progressively thins northwestward, and is truncated by the Middle Allochthon along inner Nordfjord (Figs 2 and 3a, b). The schistose rocks that characterize the Lower Allochthon generally lack compositional layering and are dominated by a fine-grained mylonitic foliation and lineation defined by elongate matrix minerals (quartz, feldspar, biotite, epidote and white mica), and albite or garnet porphyroclasts belonging to a high-*P* assemblage that developed largely before penetrative mylonitization. Abundant west-dipping C and C′ shear bands cut the foliation at low angles (Fig. 4f); these features plus asymmetric boudins and porphyroclasts indicate pervasive top-to-the-west transport. Quartzites contain a strong foliation parallel to discrete C shear surfaces, and eclogites contain a high-pressure foliation defined by oriented white mica, omphacite and garnet.

The contact between the Lower and Middle Allochthons is typically a sub-metre-scale late brittle–ductile fault, with local pseudotachylite, breccia or chloritic gouge. Amphibolite-facies shear fabrics on both sides of the contact indicate that late low-temperature displacement was limited. The structurally lower parts of the Middle Allochthon are composed of finely laminated mylonite (Fig. 4d) interspersed with lower-strain lenses of coarser augen orthogneiss or anorthositic gabbro. This level is dominated by millimetre-spaced, top-to-the-west shear bands and strong thinning and transposition of pre-existing layering and dykes; feldspar augen in megacrystic gneiss vary from prolate to oblate (Fig. 4e). Like other eclogite in the Western Gneiss Complex and Lower Allochthon, rare eclogite in the lower part of the Middle Allochthon is foliated. Higher structural levels of the Middle Allochthon are more heterogeneously deformed, coarsely banded and protomylonitic; mesoscopic structures indicating asymmetric shear are less abundant, but transposition of gneissic layering, foliation and crosscutting dykes still indicate pervasive symmetric strain.

Therefore, in the east and south, amphibolite-facies mylonites with top-to-the-west kinematic indicators define a folded but on average shallowly NNW-dipping, normal-sense shear zone (Figs 2 and 3d). In the northeastern part of the study area, the shear zone is folded over a major antiformal structure and dips steeply north (Fig. 3); mylonitization and asymmetric shear indicators also fade northwestward. This shear zone continues across the study area: it is disrupted by faults through the centre of the area and overprinted by later mylonitization adjacent to the Hornelen Basin (see below), but may reappear on Vågsøy in far outer Nordfjord (Figs 2 and 3d). There, tectonostratigraphy and mylonitic foliation dip east to NE, and strongly sheared heterogeneous rocks on the eastern half of the island, which include large anorthosite and megacrystic augen gneiss bodies, overlie homogeneous mylonitic granite gneiss on the western half of the island; abundant kinematic indicators demonstrate a top-to-the-west shear sense (see also Hacker *et al.* 2010). Therefore, this mylonitic fabric may underlie (U)HP eclogites in the north–central part of the study area. This geometry is repeated along the length of the shear zone in the study area: eclogite is more abundant and coarser within the hanging wall of this feature.

Petrographic observations indicate that shearing within the Sandane Shear Zone took place at mid- to lower amphibolite-facies conditions: small (*c.* 50 μm) biotite, muscovite or hornblende neoblasts line C and C′ shear planes, hornblende + intermediate-composition plagioclase + epidote–zoisite were stable during ductile deformation, and garnet was either stable or

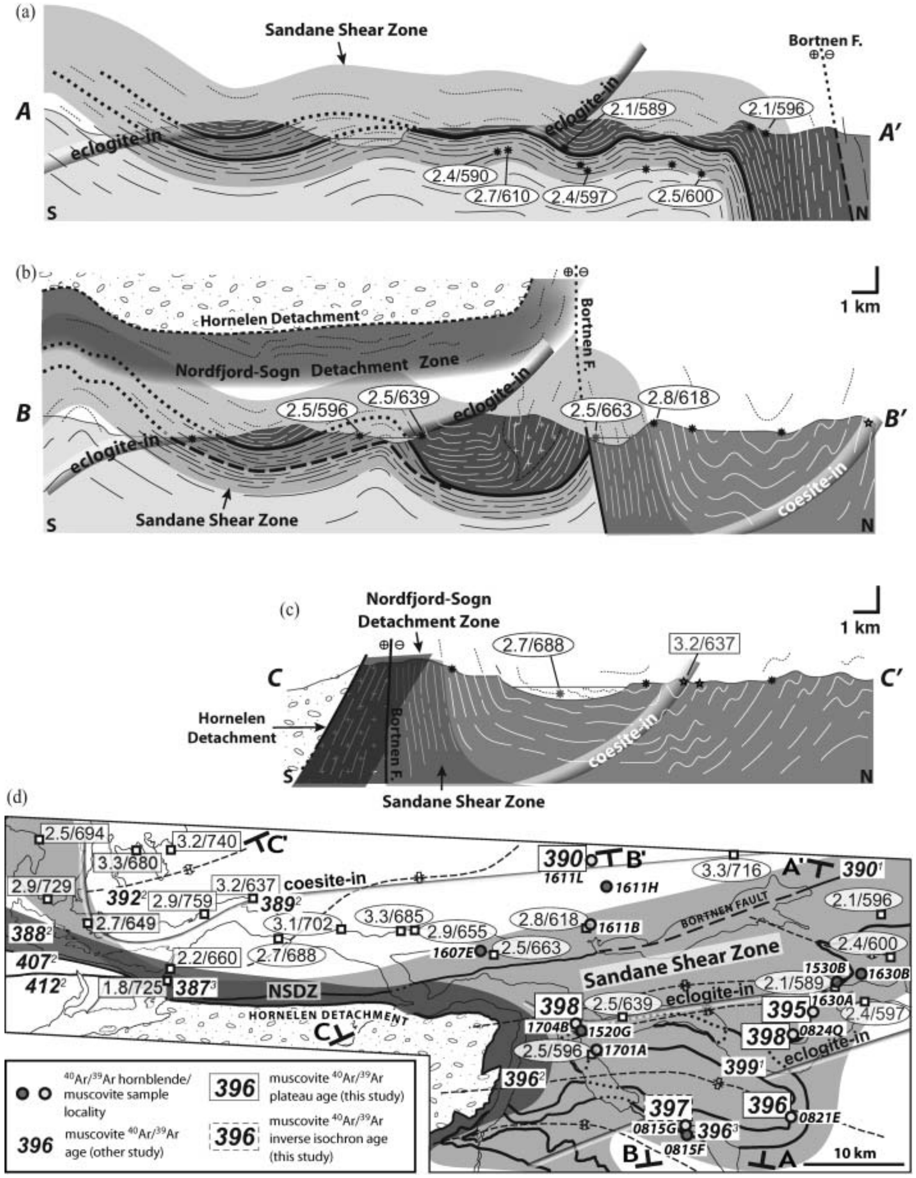


Fig. 3. Structural cross-sections looking west demonstrate folded allochthons overlying Western Gneiss Complex basement: (**a**) A–A′ eastern section; (**b**) B–B’ central section; form surfaces beneath the Hornelen Basin are adapted from Krabbendam & Dewey (1998); (**c**) C–C′ western section; (**d**) summary map showing regional extent of the Sandane Shear Zone and Nordfjord–Sogn Detachment Zone (NSDZ) deformation envelopes and locations of hornblende and muscovite ^{40}Ar/^{39}Ar samples. Eclogite pressure (GPa) and temperature (°C) determinations in ovals are from Young *et al.* (2007), and those in boxes are from other studies (Cuthbert *et al.* 2000; Labrousse *et al.* 2004). Other ^{40}Ar/^{39}Ar studies are [1]Walsh *et al.* (2007); [2]Andersen (1998); [3]Chauvet & Dallmeyer (1992); ages in the latter two studies have been adjusted upward to account for revised MMhb-1 fluence monitor age (i.e. Renne *et al.* 1998).

locally retrogressed to biotite and/or chlorite. Northward, the average matrix grain size increases from *c.* 100 μm to >300 μm, foliations weaken, matrix grains become more equant, and asymmetric microstructures fade (see Fig. 4f and g).

In summary, the allochthons–Western Gneiss Complex contact in the eastern half of the study area is enveloped by a *c.* 5 km thick, shallowly NNW-dipping, amphibolite-facies shear zone. Eclogite is present above and below the shear zone. Because such relationships are inconsistent with the accepted definition of the Nordfjord–Sogn Detachment Zone (that it overlies the eclogite-bearing crust of western Norway) we informally name this newly discerned structure the Sandane Shear Zone. A zone of similar features on Vågsøy in the northwestern corner of the study area may be part of the same structure.

Nordfjord–Sogn Detachment Zone. Previous workers in the study area typically placed the Nordfjord–Sogn Detachment Zone along the margins of the Devonian Hornelen Basin, following the regional limit of eclogite (Andersen & Jamtveit 1990; Hartz *et al.* 1994; Krabbendam & Wain 1997; Johnston *et al.* 2007*b*). We find support for this interpretation in the northern and eastern footwall of the basin, where a detachment fault is defined by several hundred metres of very fine-grained, intensely foliated and lineated, platy amphibolite- to greenschist-facies mylonites derived from Middle Allochthon protoliths; pre-existing fabrics are completely overprinted. These mylonites dip steeply south to subvertical on the north side of the basin (Fig. 3c), and shallowly west on the eastern side; stretching lineations are subhorizontal or plunge shallowly (≤10°) west. Mesoscopic kinematic indicators yield pervasive dextral or top-to-the-west normal-sense shear; porphyroclasts are rarer and finer grained in these rocks than within the Sandane Shear Zone. Deformation microstructures are characterized by a fine-grained (<50–100 μm) shape-preferred orientation (Fig. 4h), significant undulatory extinction in quartz and mica, small porphyroclasts of feldspar showing brittle deformation, and abundant chlorite. These assemblages indicate that the Nordfjord–Sogn Detachment Zone was active at chlorite- and biotite-stable conditions of the greenschist or lower-amphibolite facies.

This high-strain zone grades downward into coarser protomy-

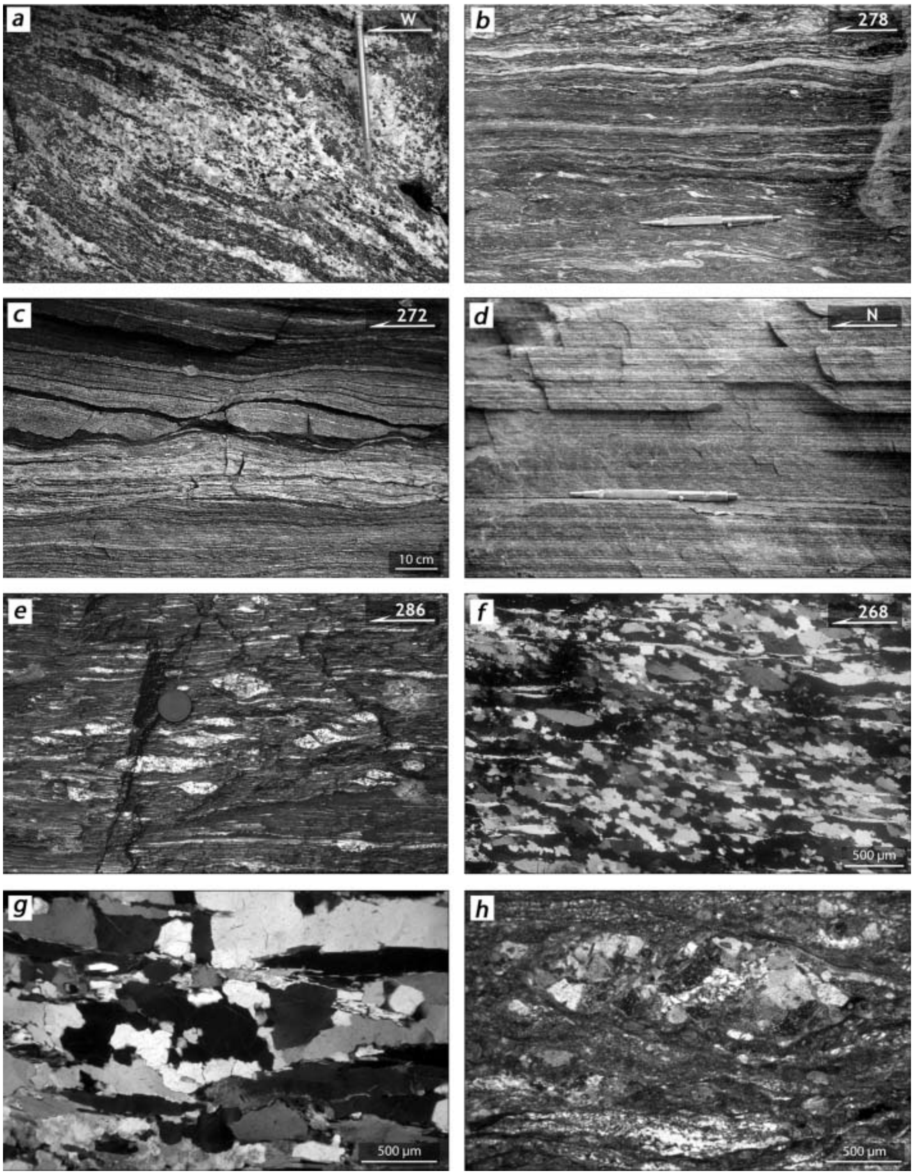


Fig. 4. Field photographs, with geographical coordinates in top right corner: (**a**) less deformed Western Gneiss Complex below the Sandane Shear Zone [0361073E, 6841735N]; (**b**) top-to-the-west mylonitic fabrics in the Western Gneiss Complex [0357244E, 6849370N]; (**c**) top-to-the-west asymmetric boudinage in the Western Gneiss Complex [0357244E, 6849370N]; (**d**) planar laminated mylonite in the base of the Middle Allochthon [0350423E, 6855141N]; (**e**) feldspar megacryst augen with top-to-the-west sense of shear in the Middle Allochthon north of Stryn [0376826E, 6870272N]; (**f**) top-to-the-west S/C fabrics and mica fish in Lower Allochthon quartzite mylonite from the Sandane Shear Zone [0369620E, 6860160N]; (**g**) weak foliation in coarse-grained muscovite granite gneiss located north of the Bortnen Fault [0329282E, 6869206N]; (**h**) greenschist-facies mylonite from higher structural levels of the Nordfjord–Sogn Detachment Zone [0328171E, 6863185N]. West is to left in all cases except (**d**), which looks east. Pens in (**a**), (**b**), (**d**) are 15 cm long; diameter of lens cap in (**e**) is 5 cm. UTM zone is 32VLP.

lonitic gneiss with abundant evidence of dextral or top-to-the-west non-coaxial shear at biotite-stable conditions, and variable preservation of earlier layering and foliation. Eclogite is found in the footwall of the Nordfjord–Sogn Detachment Zone, *c*. 2 km structurally below the northern basin contact (Wain 1997). Mylonitization and asymmetric shear structures persist for *c*. 2–3 km structurally below the basin, passing at deeper levels into more symmetrical deformation that fades into pre-existing amphibolite-facies fabrics of the Sandane Shear Zone. Therefore, approaching the basin, shear strain increases upward toward an overlying greenschist- to low-amphibolite-facies detachment shear zone. These observations are consistent with those of Johnston *et al.* (2007*b*) for the Nordfjord–Sogn Detachment Zone on the south side of the Hornelen Basin.

On the northern side of the basin, the Nordfjord–Sogn Detachment Zone deflects and transposes folds of the Sandane Shear Zone, demonstrating that the Nordfjord–Sogn Detachment Zone is younger: foliation and fold axial trends swing from ENE to almost parallel to the Hornelen contact (Fig. 2), consistent with dextral shear (top-to-the-west when the south-dipping orientations are restored to horizontal; see Labrousse *et al.* 2004).

Hornelen Detachment. The Hornelen Basin sedimentary succession rests unconformably on slivers of high-level allochthons that were not deeply subducted (Steel *et al.* 1985; Andersen & Jamtveit 1990; Johnston *et al.* 2007*b*); the contact between these units and the underlying gneissic basement is a brittle fault, known as the Hornelen Detachment (Wilks & Cuthbert 1994; Krabbendam & Wain 1997; Braathen 1999). This contact is difficult to access in the study area because of steep topography; it dips steeply south on the north side of the basin, and *c*. 8° to the west on the eastern side.

Regional folds

Folds related to the Caledonian thrusting are common within high-level allochthons above the Nordfjord–Sogn Detachment Zone on Bremanger (Hartz *et al.* 1994), but no macroscopic closures predating extension have been identified elsewhere in the study area. Smaller, metre- to decametre-scale, west-plunging and downward-verging, reclined to recumbent folds with hornblende and biotite oriented parallel to their axial surfaces are locally present in the lower levels of the Middle Allochthon.

These folds are cut by normal-sense shear bands and passively amplified by bulk stretching, indicating a pre-extension or early extension origin.

The structural map pattern is mostly controlled by a later generation of upright, open to tight, shallowly east- and west-plunging, lineation-parallel folds with semi-cylindrical or polyclinal shapes, 100 m to kilometre scale amplitudes, and lengths of many kilometres (Fig. 2). Kinked and unrecovered mica and quartz in the axial surfaces of these folds indicate crenulation at temperatures below amphibolite-facies mylonitization. The Nordfjord–Sogn Detachment Zone and the Hornelen Detachment are folded more openly than the Sandane Shear Zone (Fig. 3a and b), and the detachment truncates fold closures in the allochthons, Western Gneiss Complex and overlying Devonian sediments (Chauvet & Séranne 1994; Krabbendam & Dewey 1998). This late folding is mostly Devonian, but probably continued into the early Carboniferous (Torsvik *et al.* 1986; Eide *et al.* 1999).

Late brittle–ductile faults

Transecting the centre of the study area is the Bortnen Fault, a *c.* 100 m wide, steeply NNW-dipping, brittle–ductile fault array containing K-feldspar–epidote alteration, breccia and pseudotachylite, and surrounded by NNW-dipping sinistral tears and subsidiary faults. Slickenlines plunge <10° SW, indicating mostly strike-slip movement (Fig. 2 stereograms). Overall left-lateral displacement along the fault zone is probably less than 10 km based upon the length (*c.* 100 km) and width (<100–200 m) of the deformation zone (where displacement is *c.* 0.03 × length; Scholz 2002), limited deflection of regional structural trends, regional continuity of amphibolite-facies mylonitic shear fabrics, and minimal offset of eclogite-facies pressures (Young *et al.* 2007).

Minor centimetre- to decimetre-scale, brittle–ductile faults are widespread across the study area. Slip direction was obtained from striations or slickenfibres, and sense of displacement inferred from such features as polished asperities, stylolites, and Riedel planes. In the northern half of the study area, the predominant fault population dips NW subparallel to the Bortnen Fault, with shallowly west- to SW-plunging slip lineations and sinistral offset. Faults east of the Hornelen Basin have a variety of orientations: steep north–south-striking normal faults, steep NE–SW-striking sinistral and NW–SE-striking dextral faults. Fault-slip analysis applied to fault planes, striations and displacement indicators (e.g. Ratschbacher *et al.* 1994) indicates a shallowly south- to SSW-plunging shortening direction, a subvertical intermediate axis, and shallow NW- or SE-plunging extension (Fig. 2 stereograms).

Summary

Synthesizing the field relations: (1) the amphibolite-facies Sandane Shear Zone is a penetrative zone of thinning and non-coaxial strain along the allochthon–Western Gneiss Complex contact, and broadly follows the lower extent of eclogite-facies rocks; (2) the Nordfjord–Sogn Detachment Zone is restricted to a 2–3 km zone beneath the Hornelen Basin and above eclogites; (3) the Sandane Shear Zone and Nordfjord–Sogn Detachment Zone are folded by upright, shallowly plunging, open to tight regional folds; the Nordfjord–Sogn Detachment Zone overprints folds of the Sandane Shear Zone but is itself only folded gently; (4) the Hornelen Detachment truncates the Sandane Shear Zone and Nordfjord–Sogn Detachment Zone; (5) the Bortnen Fault cuts the Sandane Shear Zone, regional folds and the Nordfjord–Sogn Detachment Zone; (6) late minor faults imply roughly north–south shortening and WNW–ESE extension.

Undifferentiated gneiss north of the Bortnen Fault is in the hanging wall of the Sandane Shear Zone, but the tectonostratigraphic affinity of these rocks remains uncertain because the allochthons–Western Gneiss Complex contact has not been recognized in this area. The conventional interpretation (favoured by two of the authors, T.B.A. and B.R.H.) is that rocks in the northern part of the study area belong to the Western Gneiss Complex; the map relations detailed above, however, permit that such rocks are structurally higher than the Western Gneiss Complex (interpretation proposed by D.Y.).

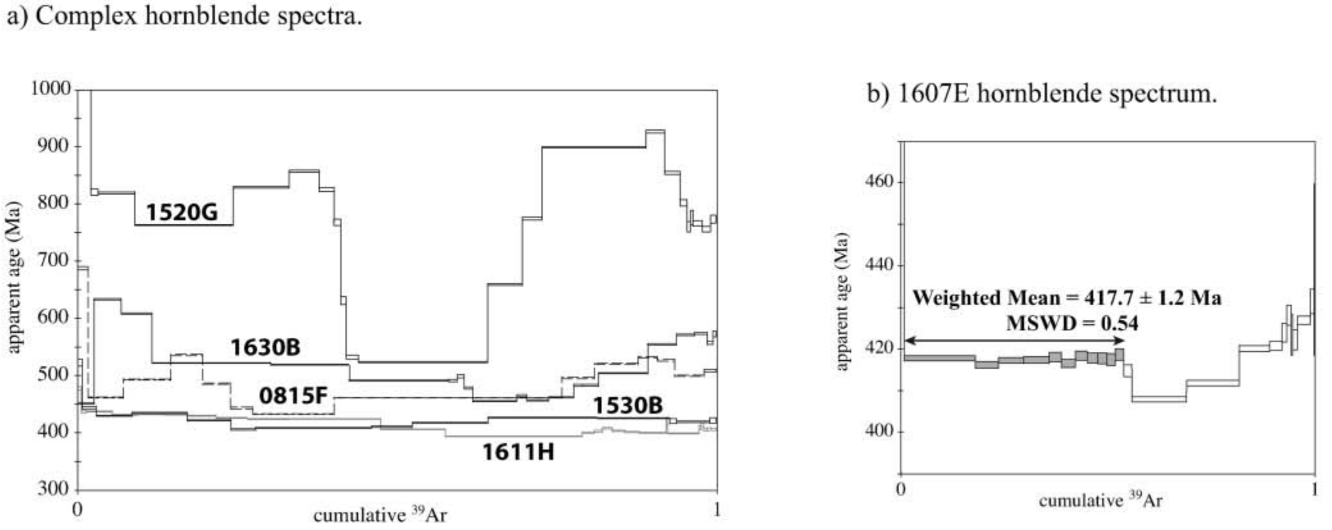
Muscovite and hornblende ^{40}Ar/^{39}Ar geochronology

^{40}Ar/^{39}Ar geochronology was used to place a lower age limit on amphibolite-facies shearing; all samples are located within the Sandane Shear Zone, largely below the Nordfjord–Sogn Detachment Zone (Fig. 3d). Six hornblende and eight muscovite multigrain separates were analysed. Mineral grains were separated by standard techniques, irradiated for 20 h at Oregon State University, and analysed by resistance-furnace step heating at the University of California, Santa Barbara, using techniques described by Calvert *et al.* (1999). Sanidine from the Taylor Creek Rhyolite was used as a fluence monitor, for which an age of 28.34 Ma was assumed (Renne *et al.* 1998). Isotopic data were analysed using EyeSoreCon (software written by B. R. Hacker) and Isoplot (Ludwig 2001). Age uncertainties are reported at the 95% confidence interval.

Hornblende grains were extracted from amphibolite layers or veins (1630B, 1611H) and hornblende-bearing gneiss (0815F, 1530B2, 1607E, 1520G) (Fig. 5a). They are part of the foliation, and are generally *c.* 200–1000 μm in size and free of inclusions. Some larger grains (>500 μm) are zoned from sodic cores to calcic rims; they are also generally inclusion free except for large (≤3 mm) poikiloblasts in 1630B that contain quartz, plagioclase, epidote and titanite. All yielded complex, crankshaft-shaped apparent-age spectra typical of amphiboles from high-pressure rocks (El-Shazly *et al.* 2001); spectra are less disturbed in more northerly samples. K/Ca ratios for each sample are consistent, precluding any influence from compositional heterogeneity or mineral or fluid inclusions on isotopic ratios. Instead, these spectra indicate the presence of excess ^{40}Ar or partial retention of an older trapped Ar component, which precludes determination of meaningful ages. Isochron plots typically do not add additional insight to the step-heating spectra, yielding dates that are at least 20 Ma younger or up to 600 Ma older than nearby white mica ages (see below). The only partial plateau (1607E) has a weighted mean age of 417 Ma (Fig. 5b) and an isochron age of 413 Ma.

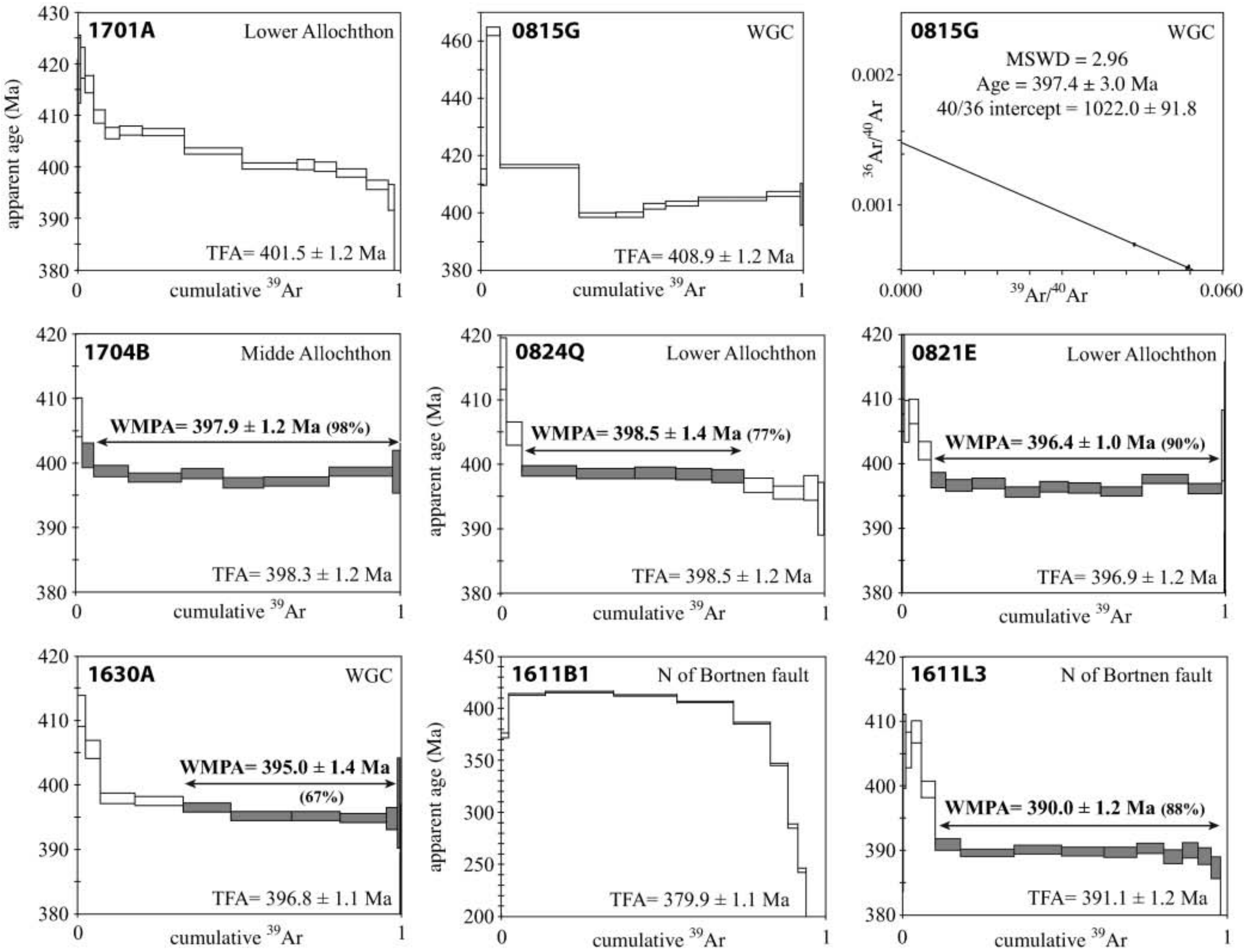
Potassium white mica (hereafter ‘muscovite’) was extracted from aluminous garnet-bearing pelite (0824Q, 1701A), micaceous quartzite and gneiss (0821E, 1630A, 1611B1, 1704B), and pegmatitic veins (0815G, 1611L3). In mylonitic rocks the muscovites are 0.5–3 mm porphyroclasts (‘mica fish’) with serrated boundaries and weak undulatory extinction; in 1701A and 0815G the grains are kinked. Muscovite in most samples is weakly altered to biotite along grain boundaries or cleavage planes. Because the main deformation occurred at amphibolite-facies conditions, the muscovite ages are interpreted as cooling rather than deformation ages.

The muscovite ^{40}Ar/^{39}Ar spectra are less complex than those of hornblende (Fig. 5c). Sample 1701A from the Lower Alloch-



a) Complex hornblende spectra.

b) 1607E hornblende spectrum.



c) white mica spectra.

Fig. 5. (**a**) & (**b**) Hornblende ^{40}Ar/^{39}Ar spectra. Step age uncertainties are 1σ, without error in irradiation parameter, *J*; age uncertainties are 2σ. (**c**) Muscovite ^{40}Ar/^{39}Ar spectra. Step ages have uncertainties of 1σ without error in irradiation parameter, *J*; age uncertainties are 2σ and include intralaboratory uncertainty as well as error in the decay constant and standard age. TFA, total fusion age; WMPA, weighted mean plateau age.

thon near Sandane yielded a reverse staircase spectrum with most of the step ages ranging from 410 to 400 Ma, and no well-fit isochron. Muscovite from 0815G, a pegmatitic vein from the southern Western Gneiss Complex in the same area, has a similar but more complex spectrum that spans the same 10 Ma range; an inverse isochron yields an age of 397 Ma. Gneiss 1704B from the Middle Allochthon near Sandane produced a 398 Ma plateau for 98% of the ^{39}Ar released. Samples 0824Q and 0821E from the Lower Allochthon gave plateau ages of 398 and 396 Ma and equivalent isochron ages. Muscovite 1630A, from the Western Gneiss Complex, yielded a plateau age of 395 Ma and an equivalent isochron age. In summary, plateau ages across the southern and eastern parts of the study area span a narrow range from 399 to 395 Ma (Fig. 3d). Few muscovite-bearing rocks were located adjacent to and north of the Bortnen Fault: gneiss 1611B1 produced an uninterpretable hump-shaped spectrum and no isochron, but a vein selvage of pure muscovite (1611L3) produced a 390 Ma plateau, a result consistent with muscovite ages from other studies north of Nordfjord. Overall, the muscovite ^{40}Ar/^{39}Ar data indicate two age clusters: 399–395 Ma within the Sandane Shear Zone south of Nordfjord, decreasing to 392–387 Ma north of Nordfjord.

Discussion

Our datasets compel revision of various paradigms for the exhumation of UHP rocks in the Nordfjord region; in particular, for the location and role of different macroscopic shear zones, the tectonostratigraphic position of eclogite-facies rocks, and the structural coherence of the HP–UHP transition. Data that bear on the questions raised in the introduction (namely, the relationship between shear zones and eclogite distribution; the identity and relative age of different structural features; and the role of top-to-the-west normal-sense shear in exhuming the UHP rocks of western Norway) are discussed below.

Relationships between tectonostratigraphy, eclogites and shear zones

Between Sognefjord and the Hornelen Basin (Fig. 1), the Nordfjord–Sogn Detachment Zone is an amphibolite- to greenschist-facies shear zone with three major characteristics: (1) it separates an eclogite-bearing footwall from a thin hanging wall of amphibolite- to greenschist-facies allochthons and supradetachment basins that escaped Scandian burial, implying significant displacement; (2) it borders the Devonian basins and is folded by the same folds that affect the basins; (3) ductile shearing is mainly concentrated in the Western Gneiss Complex. These characteristics underpin regional models that identify the Nordfjord–Sogn Detachment Zone as a first-order structure that juxtaposed an eclogite-facies footwall against high-level allochthons.

The Nordfjord area presents some important differences from this description, as follows. (1) A thick sequence of allochthons is present between the Western Gneiss Complex and the Hornelen Detachment. (2) Eclogite is found in all tectonostratigraphic units north of the fjord. (3) There are two distinct shear zones, one above the eclogite-facies domain and one at the lower edge of it. The Nordfjord–Sogn Detachment Zone is a greenschist- to low amphibolite-facies feature, developed mainly within the Middle Allochthon beneath the Hornelen Basin, which truncates and ultimately overlies the eclogite-facies rocks. The Sandane Shear Zone is a structurally lower, amphibolite-facies shear zone along the allochthons–Western Gneiss Complex contact, and parallels the eclogite-in isograd. These shear zones merge in the Nordfjord area, and to the west and south they are recognized only as a singular feature. The allochthons–Western Gneiss Complex contact zone probably originated as an early NNW-dipping thrust (e.g. Bryhni 1989), but any kinematic indicators that might verify thrust displacement have been erased. In the contact zone, a foliation defined by high-pressure amphibolite-facies minerals predates most extensional features, although this fabric has been strongly attenuated by normal-sense shear. The Sandane Shear Zone is characterized, then, as a cryptic early high-strain zone that may have placed the allochthons above the Western Gneiss Complex, but was subsequently overprinted by peak pressure metamorphism and late extensional fabrics.

The transition from HP to UHP metamorphism in the western half of the study area was originally inferred to be tectonic (Wain 1997), but subsequent workers (Labrousse *et al.* 2004; this study) failed to find discrete high-strain contacts within the transition. The size of the eclogitic domain, uniform intensity of the shear fabrics, the continuity of various rock types, the preservation of pre-Scandian gneissic banding (however disrupted by extensional deformation and amphibolite-facies recrystallization) and the relatively smooth pressure–temperature gradient implied by regional eclogite thermobarometry all indicate that the HP–UHP transition is probably the result of differential eclogite-facies recrystallization, rather than tectonic juxtaposition of various high-pressure slices (Carswell & Cuthbert 2003).

These discoveries have important implications for the tectonostratigraphic and structural evolution of the Nordfjord UHP domain. The presence of eclogite in the allochthons demonstrates that at least part of the Western Gneiss Complex was subducted and exhumed with at least 6 km of overlying allochthonous rocks (Fig. 6). The absence of any profound breaks in the regional thermobarometric gradient, and limited displacement of the eclogite boundary by extension along the Sandane Shear Zone, suggests that the Nordfjord UHP terrane remained connected to lower pressure parts of the slab up-dip through peak metamorphism, and was exhumed from the mantle to the middle crust as a relatively intact section (Young *et al.* 2007).

Whether top-to-the-foreland displacement along the Sandane Shear Zone continued during early exhumation remains unclear. Early extension at garnet-amphibolite-facies conditions along the Sandane Shear Zone indicates that the UHP domain had reached lower crustal pressures prior to the extensional overprint. The structural position of the Sandane Shear Zone beneath the UHP rocks also implies that non-coaxial shear along this feature produced minimal exhumation of the UHP terrane. Therefore, structurally higher contemporaneous normal-sense detachments must have exhumed the UHP rocks from the lower crust (Fig. 6). Although differences in fold profiles suggest that the Nordfjord–Sogn Detachment Zone may be slightly younger than extension along the Sandane Shear Zone, we follow previous workers (e.g. Chauvet & Séranne 1994; Krabbendam & Dewey 1998; Johnston *et al.* 2007*a*,*b*) in concluding that extension was a progressive event: early, amphibolite-facies symmetrical stretching in the deep crust resulted in perhaps 50% thinning of the section (Dewey *et al.* 1993; Marques *et al.* 2007), and shear along weaker zones such as the Sandane Shear Zone, beneath large high-level extensional detachment faults such as the Nordfjord–Sogn Detachment Zone, was overprinted by these lower-temperature detachments as the footwall was exhumed through the mid- to upper crust. The strain history also includes shortening perpendicular to the stretching direction at this time, to explain lineation-parallel folding. At mid- to upper crustal depths, the Sandane

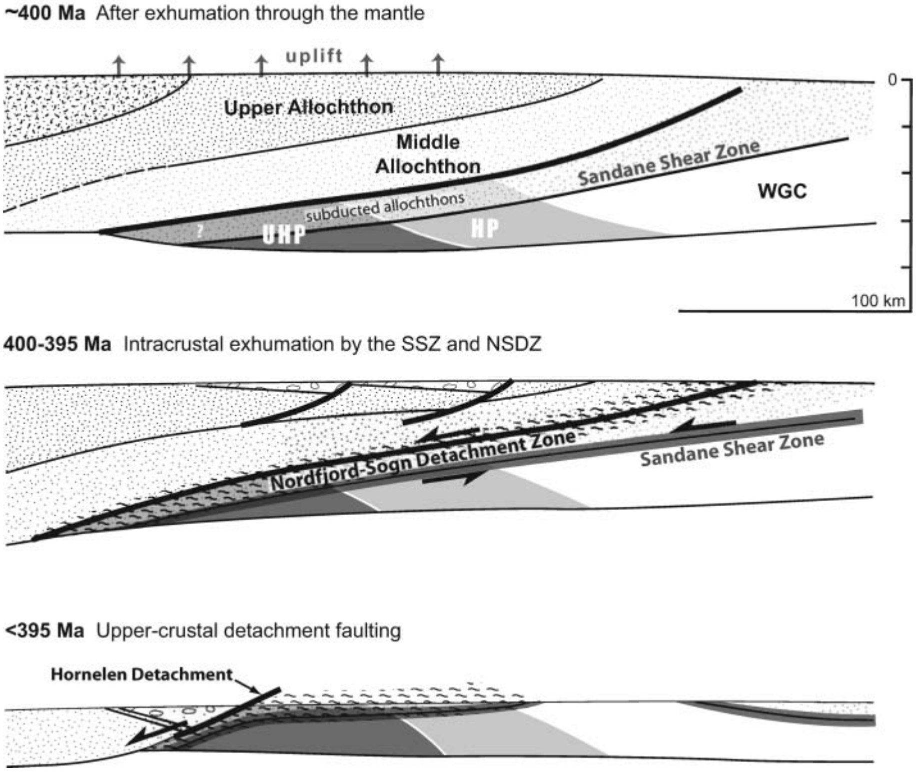


Fig. 6. Schematic, NE-looking, cross-sections through the Western Gneiss Region illustrating the role of late Scandian extension in exhuming the Nordfjord (U)HP province: (*c.* 400 Ma) after exhumation through the mantle the (U)HP slab flattens against the Moho of the overlying plate; (400–395 Ma) early top-to-the-west movement along the Sandane Shear Zone may be coeval with backsliding along the allochthons–Western Gneiss Complex (WGC) contact in the foreland; the Nordfjord–Sogn Detachment Zone forms a breakaway through the allochthonous carapace, and exhumes the (U)HP rocks through mid/upper crustal depths; (<395 Ma) after the Nordfjord–Sogn Detachment Zone becomes too shallow and folded for slip, the Hornelen Detachment cuts the Nordfjord–Sogn Detachment Zone and exhumes the Nordfjord area to within a few kilometres of the surface.

Shear Zone, Nordfjord–Sogn Detachment Zone and regional folds were deflected and truncated by sinistral transtension along the Bortnen Fault and related structures.

Timing and rate of exhumation

Current geochronology indicates that the Nordfjord–Sogn Detachment Zone and Sandane Shear Zone were active within the same time frame at the end of the Scandian orogeny. The youngest muscovite ^{40}Ar/^{39}Ar ages in the hanging wall of the Nordfjord–Sogn Detachment Zone are *c.* 411 Ma; Sm–Nd dating of garnet from gneiss in the Hornelen area in the Nordfjord–Sogn Detachment Zone footwall establishes a upper limit of 407 Ma for amphibolite-facies deformation (Johnston *et al.* 2007*b*), and U–Pb zircon ages of eclogite suggest that exhumation was active after 405 Ma in the outer Nordfjord area (Root *et al.* 2004). Our ^{40}Ar/^{39}Ar data through the Sandane Shear Zone east of the Hornelen Basin indicate that amphibolite-facies shear largely predated cooling through muscovite closure at 398–395 Ma, and that these ages mainly reflect exhumation and cooling in the footwall of the Nordfjord–Sogn Detachment Zone. Muscovite ages of 392–387 Ma north of the Bortnen fault and also within the Sandane Shear Zone are younger, however, than ages south of the fault. This discrepancy may be the result of late folding (Root *et al.* 2005; Hacker 2007) or higher peak temperatures and slower cooling in the northern half of the study area (Young *et al.* 2007). In aggregate, these constraints imply exhumation of the Nordfjord area from depths of *c.* 100 km to *c.* 30 km in 10 Ma, at a (composite) rate of 6–7 mm a^{-1}.

Conclusions

The Western Gneiss Region shows a regional pattern of westward increase in Caledonian structural and metamorphic reworking. New structural data reveal that this regional pattern is modified in the Nordfjord region by two major shear zones: the Sandane Shear Zone, a lower amphibolite-facies, top-to-the-west shear zone that separates a weakly deformed autochthon from strongly deformed allochthons, and the higher-level, amphibolite- to greenschist-facies Nordfjord–Sogn Detachment Zone that marks the top of the eclogite-bearing crust. The data indicate that a carapace of allochthons was emplaced over the Western Gneiss Complex by early thrusting, and the deepest part of the section was buried to depths >90 km. Following exhumation from the mantle, the (U)HP section was exhumed through the crust by extensional thinning and detachments that truncated the overlying allochthons. Vertical shortening and top-to-the-west shear overprinted the Sandane Shear Zone at lower crustal depths; muscovite ^{40}Ar/^{39}Ar ages indicate that this amphibolite-facies stretching was complete before *c.* 398 Ma. Subsequently, the area underwent north–south shortening and folding, and was exhumed to upper crustal depths in the footwall of the Nordfjord–Sogn Detachment Zone.

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