Exhuming Norwegian Ultrahigh-Pressure Rocks: Overprinting Extensional Structures and the Role of the Nordfjord-Sogn Detachment Zone

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[1] The Nordfjord-Sogn Detachment Zone(NSDZ) is widely cited as one of the primary structures responsible for the exhumation of Norwegian (ultra)high-pressure (UHP) rocks. Here we review data from the considerable volume of research describing this shear zone, and compile a strike-parallel cross section along the NSDZ from the Solund Basin in the south to the Sørøyane UHP domain in the north. This cross section highlights several previously unrecognized patterns, revealing a shear zone with top-to-the-west asymmetric fabrics that (1) initiated at amphibolite facies, (2) overprints metamorphic breaks and tectono stratigraphic contacts, and (3) has a gradational continuum of muscovite cooling ages. These patterns constrain the kinematic evolution of the NSDZ and suggest a new three-step model for the exhumation of Norwegian (U)HP rocks. The initial stages of exhumation were characterized by the rise of crustal rocks from (U)HP depths to the base of the crust by buoyancy-driven mechanisms not specified in this paper. Mantle exhumation was followed by top-to-the-west, normal-sense displacement within a broad noncoaxial ductile shear zone near the base of the crust that overprinted tectonostratigraphic contacts formed previously during mantle exhumation. In the final stages of crustal exhumation, top-W brittle-ductile detachments soled into and partially excised this ductile shear zone,dropping the Devonian basins into contact with rocks of varying tectonostratigraphic levels. This new interpretation of the NSDZ is significant as it accounts for the extreme crustal excision observed in western Norway using three sequentially overprinting structures active at different stages of UHP rock exhumation.

1. Introduction

[2] The discovery over the past two decades that ultra-high-pressure (UHP) rocks are distributed around the globe is changing fundamental concepts behind our understanding of the interaction between the crust and the mantle, and of the kinematics of continental collisions. In particular,the mechanisms responsible for exhuming rocks from depths greater than 100 km at rates exceeding 20 mm/yr requires high-strain, lithospheric-scale structures. Most models draw upon buoyancy-related rebound of low-density crustal rocks through the mantle and into the upper crust as the primary driving force behind UHP exhumation, but they vary widely with respect to the kinematics of the structures developed along the exhumation path. Whereas some models call for diapiric ascent of relatively weak UHP terranes through the mantle followed by a second stage of crustal-scale extension [e.g., Walsh and Hacker, 2004], other models argue that relatively strong UHP terranes are exhumed in the hanging walls of basal thrusts with passive, normal-sense roof faults [e.g., Chemenda et al., 2000] or by corner flow within the subduction

channel [e.g., Burov et al., 2001]. Still other models suggest exhumation of UHP terranes by combina-tions of vertical coaxial shortening and extension by rota-tional shearing in the footwalls of major normal-sense shear zones and faults [Andersen et al., 1994], reversal in plate motion [Fossen, 1992; Krabbendam and Dewey, 1998] or subhorizontal extrusion [Hacker et al., 2000]. These models have specific, but very different implications for plate tec-tonic processes as far-reaching as the growth and composi-tion of the continental crust, crustal recycling into the mantle, thedriving forces behind changes in plate motion, and the evolution of large mountain ranges. Evaluating each of these models and applying them to geologic settings where they may be valid is a vital step to understanding plate tectonics.

[3] The Norwegian Caledonides of western Norway present an excellent opportunity to assess the validity of the various models for the exhumation of UHP rocks (Figure 1). Because of a paucity of synorogenic magmatism and postorogenic tectonism, tens of thousands of square kilometers of Caledonian(U)HP and related lower-pressure terranes are preserved. The preservation of these rocks of drastically different metamorphic grade, in addition to the structural relationships that link them, provides the data

[4] necessary for temporal and kinematic reconstructions of the Norwegian Caledonides, reconstructions that are difficult or impossible in orogens that experienced subsequent defor-mation and/or thermal overprint. The goal of this paper is to consolidate theknown structural, petrologic, and geochro-nologic data from within and around the Nordfjord-Sogn Detachment Zone (NSDZ), a major normal-sense detach-ment zone thought to be the primary structure responsible for the exhumation of Norwegian (U)HP rocks, and to evaluate the different models for the exhumation of UHP rocks. The data support a three-stage exhumation model for western Norway: rapid exhumation of a (U)HP body through the mantle, followed by exhumation from the lower andmiddle crust along an initially broad ductile shear zone, and ultimately, more discrete brittle-ductile detachment faults. The fabrics and lithologic relationships developed within the NSDZ are the cumulative result of these three overprinting stages of exhumation. Because timing is critical in this study, all40 Ar/39Ar ages have beenrecalculated using fluence monitor ages recommended by Renne et al. [1998].

2. Regional Geology

[4] Subduction of Baltica beneath the leading edge of Laurentia during the Caledonian Orogeny has long been recognized as the primary event responsible for the forma-tion of Norwegian (U)HP rocks [Cuthbert et al., 1983]. Spanning the Early Ordovician through the Late Devonian, the Caledonian Orogeny was characterized by intraoceanic subduction within theÆgir and Iapetus oceans, early Caledonian events affecting distal parts of the Caledonian margin of Baltica during its northwarddrift and anticlock-wise rotation, and finally east directed stacking of allochth-onous and para-autochthonous thrust sheets onto the Baltica margin during the main Scandian continental collision [Brueckner and van Roermund, 2004; Torsvik and Cocks, 2004]. The final pulse of contraction was initiated after the Wenlockian [Andersen et al., 1998] and culminated in the burial of the Baltica autochthon and associated slivers from the accreted allochthons to(U)HP depths in western Norway

by 410–400 Ma [Hacker and Gans, 2005].

[5] The extent of this contraction and extreme crustal shortening is best seen in the individual,far-traveled thrust sheets of the foreland [Gee et al., 1985; Robinson, 1995]. The Baltica Autochthon, the structurally lowest unit, con-sists of Proterozoic crystalline basement gneisses with local sedimentary cover [Gee et al., 1985; Tucker et al., 2004]. The Lower and Middle Allochthons are composed of crystalline basement gneisses overlain by paragneisses and are thought to represent outboard regions of the Baltica Autochthon that were thrust eastward over the autochthon. Lower Allochthon crystalline gneisses are similar in com- position to the Baltica Autochthon, but Middle Allochthon orthogneisses include a more variable suite of distinctive K-rich granulites, gabbro-anorthosite and megacrystic augen gneisses that locally occur within the Western Gneiss Complex (WGC) and in the Fennoscandian base- ment of S. Norway [Krabbendam et al., 2000; Austrheim et al., 2003; Bingen et al., 2004]. The Upper Allochthon consists of a mixed group of crystalline continental and mostly ophiolitic rocks. The uppermost Allochthon has distinct lithologic and isotopic characteristics that suggest it represents a fragment of Laurentia [e.g., Roberts et al., 2002].

[6] This tectonostratigraphy recognized in the foreland can be traced westward into the high-grade metamorphic rocks of western Norway (Figure 1) [Bryhni and Andre´asson, 1985; Robinson, 1995; Root et al., 2005]. In western Norway, the WGC is correlated with the Baltica Autochthon, and is exposed in a gently arching tectonic window through the structurally higher allochthons. The felsic host gneisses of the WGC contain extensive provinces where older meta- morphic or magmatic textures are preserved [Krabbendam et al., 2000], as well as meter- to kilometer-scale lenses of Caledonian eclogites that increase in metamorphic grade to the north and west [Krogh, 1977].

[7] There are important differences between the northern WGC (i.e., north of Nordfjord) and the southern WGC. The northern WGC is overlain by widespread folded slivers of exotic gneisses that have been correlated with the alloch- thons [Robinson, 1995; Walsh and Hacker, 2004], whereas the southern WGC is overlain by a thin veneer of variably attenuated gneisses and schists that lie depositionally beneath low greenschist-facies Devonian-Carboniferous sedimentary basins. In the northern WGC, the gneiss and allochthons contain eclogites that record HP and UHP conditions up to 3.4 GPa and 800~C [Terry et al., 2000]; eclogites in the southern WGC are found chiefly within the basement and reached only HP metamorphic conditions of 2.1–2.5 GPa and 700~C [Krogh, 1982; Chauvet and Dallmeyer, 1992; Labrousse et al., 2002].

[8] Caledonian contraction during the Early Devonian was immediately followed by, or synchronous with, exten- sion and the rapid exhumation of the WGC from (U)HP depths to the middle and upper crust. Most of this exhumation is thought to have occurred through a combination of coaxial vertical thinning and noncoaxial shearing along reactivated contractional detachments, the result of buoyancy-driven collapse of an overthickened continental crust [Wilks and Cuthbert, 1994; Andersen, 1998; Fossen and Dunlap, 1998; Young et al., 2007]. The most impressive of these structures is the Nordfjord-Sogn Detachment Zone (NSDZ), which extends along strike for several hundred km (Figure 1) [Andersen et al., 1994]. The NSDZ consists of a 2–6 km thick shear zone that

juxtaposes greenschist-grade Upper Allochthon and Devonian-Carboniferous sedimentary rocks in its hanging wall with the eclogite-bearing southern WGC in its footwall [Wilks and Cuthbert, 1994]. In the final stages of extension, semiductile to brittle normal-sense detachments soled into the NSDZ, opening the Devonian-Carboniferous basins [Andersen et al., 1998; Eide et al., 2005]. Although the greenschist-facies allochthons, Devonian-Carboniferous sediments, and extensional structures related to the NSDZ disappear north of Nordfjord, they reappear along Trond- heimsleden and in the Fosen Peninsula north of Figure 1, and it is thought that similar extensional structures were at least partially responsible for the exhumation of the northern WGC and the Central Norway Basement Window even farther north [Braathen et al., 2000; Eide et al., 2005; Osmundsen et al., 2006].

3. Recent Exhumation Models

[9] A wide variety of models for the exhumation of Norwegian (U)HP rocks and the evolution of the NSDZ have been proposed. While all of these models recognize the NSDZ as a major exhumational structure, they differ on the depth at which the NSDZ formed and on its role with respect to exhumation of rocks through the mantle and crust. Single-stage exhumation models [e.g., Hacker et al., 2003; Hacker, 2007] suggest that the NSDZ was the primary structure responsible for the rapid exhumation of (U)HP crustal rocks from mantle depths to the upper crust. These models imply that the NSDZ formed at (U)HP depths (60–135 km) by reactivation of the original subduction thrust geometry as a lithospheric-scale normal-sense detach- ment zone. Two-stage exhumation models call upon sepa- rate mantle and crustal exhumation structures, with mantle exhumation occurring via pure shear thinning during grav- itational collapse and orogenic extension [e.g., Andersen et al., 1994; Milnes et al., 1997], or imbricate thrusting and subduction channel flow [e.g., Terry and Robinson, 2003]. Mantle exhumation was then followed by displacement along the NSDZ through crustal depths only.

[10] The various models also differ on precisely what structure(s) define the NSDZ, and the extent to which localized deformation and excision occurred during mylo- nitization and top-to-the-west (top-W) transport. Local large metamorphic breaks between the WGC and overlying allochthons have led many researchers to define the alloch- thon-WGC contact as the primary detachment surface [Andersen and Jamtveit, 1990; Krabbendam and Dewey, 1998]. Models developed from this interpretation place the allochthons in the upper or middle plate of the NSDZ, and imply that significant crustal excision occurred across discrete high-strain shear zones within the NSDZ that are responsible for the juxtaposition of the different tectonos- tratigraphic units. In contrast, other researchers cite the uniformity of amphibolite-grade mylonites that cross tecto- nostratigraphic contacts, and suggest that the NSDZ repre- sents a near-homogeneous, top-W, ~6 km thick detachment zone between a brittle upper plate and a ductile lower plate [Swensson and Andersen, 1991; Fossen and Rykkelid, 1992; Wilks and Cuthbert, 1994; Milnes et al., 1997]. This interpretation places mylonitic allochthons in the lower plate and supports models that call for the juxtaposition of the allochthons and the WGC in the lower crust prior to the onset of noncoaxial shear along the NSDZ. In these distributed-shear models, crustal excision did not take place between tectonostratigraphic

units, but instead, across a broad shear zone that brought lower crustal allochthons and WGC into contact with upper crustal allochthons and Devonian sedimentary rocks.

[11] The spectrum of end-member models used to de-scribe the exhumation of Norwegian (U)HP rocks attests to the variety of exhumation structures observed in western Norway. The purpose of this paper is to review the simi-larities and differences among the various models and build a unifying model that can account for the multiple structural styles of Caledonian exhumation.

4. Cross Section: Detailed Study Areas

[12] Inaneffort to characterize the kinematic evolution of Caledonian exhumation, detailed studies have been com-pleted from field areas that span the length of the NSDZ. In aggregate, these studies document the entire range of extensional styles and place limits on the mechanisms responsible for the exhumation of Norwegian (U)HP rocks. In the following paragraphs, we brieflydiscuss the key field areas along the NSDZ in a cross section from the Solund Basin in the south to the Sørøyane UHP domain in the north; the section parallels the strike of the NSDZ and is perpendicular to the elongation direction of the primary exhumation-related structures in western Norway(Figure 1).

4.1. Solund Basin Region

[13] The Solund Basin, the southernmost of the major Lower Devonian to Lower Carboniferous basins along the cross section, formed in the hanging wall of the southern segment of the NSDZ [Osmundsen and Andersen, 2001], and is exposed within a broad E-W trending syncline that preserves much of the Caledonian nappe stack(Figure 2). The southern WGC is the structurally lowest unit and contains eclogites that equilibrated at~ 2.3 GPa and ~700°C [Hacker et al., 2003]. It is overlain by mafic schists, pelites, and metapsammites of the Hyllestad Com-plex that have been correlated with the Lower [Chauvet and Dallmeyer, 1992] or Middle[Tillung, 1999] Allochthon. Aluminous schists within the Hyllestad Complex indicate peak metamorphic conditions of 1.4–1.6 GPa and 575– 600°C [Hacker et al., 2003]. Although the contact between the southern WGC and the Hyllestad Complex represents an abrupt, >0.6 GPa break in peak metamorphic pressure, retrograde metamorphic conditions in the two units are similar, 0.6–1.0 GPa and 450–600°C [Hacker et al., 2003]. The structurally higher Lifjorden Complex includes metagraywacke, greenschist, metagabbro and serpentinite inferred to be part of the Upper Allochthon. Lower levels of the Lifjorden Complex are intruded by the~ 434 Ma Sogneskollen Granodiorite [Hacker et al., 2003]. Above the Sogneskollen Granodiorite, the Lifjorden Complex is exclusively greenschist facies, but below, all rocks show a late amphibolite-facies metamorphism at~ 0.8 GPa and 580°C [Hacker et al., 2003]. The Lifjorden Complex is truncated upward by the brittle-ductile Solund Fault that dropped the lowgreenschist-grade Solund Basin conglom-erates down on top of the Lifjorden Complex.

[14]The structure of the Solund Basin region is strongly affectedbythe extensional fabrics and detachments that brought the HP rocks of the southern WGC into close proximity with the Devonian sedimentary rocks. East of the area, the southern WGC is characterized by gently west dipping foliations, E-W stretching lineations, and generally symmetric fabrics [Milnes et al., 1988, 1997].

Structurally up section within the WGC these fabrics become progres-sively more asymmetric; the upper~ 1.5 km of the WGC contains a penetrative top-W fabric characterized by S-C mylonitic gneisses with abundant asymmetric boudins, s and S clasts, and shear bands [Hacker et al., 2003]. These amphibolite-facies asymmetric fabrics are also strongly developed in the overlying Hyllestad Complex and reach their peak in the base of the Lifjorden Complex, whereas structurally above the Sogneskollen Granodiorite, the extensional fabrics are only locally developed at greenschist facies. This >2 km thick zone of mylonitic rocks with penetratively developed top-W structures represents the NSDZ in the Solund Basin region. Although the contacts between the different tectonostratigraphic units are signifi-cant breaks in peak metamorphic grade, muscovite cooling ages from the WGC and the Hyllestad Complex fall in a relatively narrow range from 403 to 394 Ma [Chauvet et al., 1992]. No discrete zones of higher strain within the NSDZ have been identified along tectonostratigraphic contacts, and the lack of a discontinuity in muscovite ages across the NSDZ indicates that the WGC and Hyllestad Complex were juxtaposed at temperatures above muscovite closure. Structurally above the base of the Sogneskollen Granodio-rite, the Lifjorden Complex preserves Caledonian contrac-tional fabrics and is affected by penetrative extension only in outcrops immediately beneath the Solund Fault. There, mylonites with NW-SE stretching lineations grade into a discrete detachment zone with cataclasites, ultramylonites and pseudotachylites in the footwall [Norton, 1987] and flattened and rotated clasts in the hanging wall conglom-erates of the Solund Basin [Se´ranne and Se´guret, 1987]. The brittle-ductile Solund Fault cuts the Devonian basin, has a significantly different transport direction than the NSDZ, was active at much higher crustal levels than the NSDZ, and represents a later stage of Caledonian to entirely post-Caledonian exhumation [Hacker et al., 2003].

4.2. Kvamshesten Region

[15] The Kvamshesten Basin and associated extensional structures are located in the next broad syncline north of the Solund region(Figure 3). The tectonostratigraphyof this region is divided into an upper and lower plate by the Dalsfjord Fault, a top-W, reactivated, low-angle extensional fault [Torsvik et al., 1992; Andersen et al., 1994; Braathen et al., 2004]. The southern WGC is the lowermost unit within the lower plate of the Dalsfjord Fault and includes eclogites that record peak metamorphic conditions of 2.1 GPa and 580oC [Cuthbert et al., 2000] overprinted by an amphibolite-facies retrograde fabric [Andersen et al., 1994]. It is overlain byamphibolite- togreenschist-facies schists and phyllonites informally referred to as the “Ask-voll group” that formed from interlayered paragneisses and orthogneisses of the Lower Allochthon, Middle Allochthon, or WGC [Swensson and Andersen, 1991].

[16]Consistent E-W stretching lineations are observed throughout the Kvamshesten area. Amphibolite-facies, and locally eclogitic-facies, symmetric shear fabrics dominate lower structural levels within the southern WGC [Engvik and Andersen, 2000; Foreman et al., 2005], whereas amphibolite-facies asymmetric top-W shear fabrics, includ-ing S-C foliations and shear bands, increase in intensity up section. Within the uppermost levels of the WGC and throughout the Askvoll mylonites, these asymmetric shear fabrics are pervasively developed in a broad detachment zone,

and represent the Kvamshesten segment of the NSDZ [Swensson and Andersen, 1991]. These extensional fabrics developed at amphibolite-facies conditions within both the WGC and the Askvoll mylonites, indicating that at the initiation of mylonitization, there was no significant break in metamorphic grade between these two tectonostrati-graphic units [Swensson and Andersen, 1991]. Muscovite cooling ages from the detachment mylonites and the foot-wall range from 399 to 395 Ma [Andersen, 1998]. The top of the lower plate is defined by the brittle Dalsfjord Fault, which soles into and truncates the underlying mylonites of the NSDZ, placing the upper plate down against the Askvoll mylonites along the southern margin of the basin, and against the southern WGC along the northern margin of the basin.

[17] The Dalsfjord Fault is a discrete brittle-ductile fault characterized by pseudotachylites, ultramylonites, catacla-sites and breccias [Braathen et al., 2004] that formed in the Late Devonian and was reactivated in the Permian and Jurassic[Torsviket al., 1992; Eide et al., 1997]. From bottom to top, the allochthons in the upper plate of the Dalsfjord Fault consist of the Dalsfjord Suite orthogneisses and the Høyvik Group paragneisses (correlated with the Middle Allochthon [Corfuet al., 2003]), unconformably overlain by the Silurian Herland Group, the Solund-Stavfjord Ophiolite, and the Kalva˚gme´lange (all correlated with the Upper Allochthon [Osmundsen and Andersen, 1994]). These upper plate rocks preserve both Scandian and early Caledonian contractional structures, as well as primary depositional contacts; muscovite ages of -450 Ma from theHøyvik Group indicate that temperatures in the Kvam-shesten segment of the upper plate never exceeded greens-chist-facies conditions during the late Caledonian [Andersen etal., 1998;Eideet al., 1999]. There, allochthonous rocks are unconformably overlain by the Middle Devonian sedi-mentary rocks of the Kvamshesten Basin. Extensional structures in the upper plate are limited to normal-sense reactivation of earlier Caledonian low-angle thrust faults (with associated folding of preexisting planar and linear structures) and high-angle brittle normal faults that are truncated by the Dalsfjord Fault [Osmundsen and Andersen, 1994]. This upper plate extensional deformation was con-trolled by considerable top-W displacement along the Kvamshesten segment of the NSDZ, which opened the Kvamshesten Basin [Osmundsen etal., 1998, 2000]. Devo-nian through Carboniferous formation and younger reacti-vation of the Dalsfjord Fault ultimately juxtaposed the ductile Caledonian extensional fabrics in the lower plate with brittlely deformed upper plate rocks and the Devonian basin sediments during late Caledonian extension [Torsvik etal., 1986, 1992;Eideet al., 1997].

4.3. Hornelen Region

[18] The Hornelen Region(Figure 4) includes the largest and smallest of the Devonian-Carboniferous basins, the Hornelen and Ha˚steinen, respectively, and the thickest continuous exposures of the Lower and Middle Allochthons and the NSDZ between Sognefjord and Nordfjord. Like the Kvamshesten Region, the brittle-ductile Hornelen Fault beneath the Hornelen Basin (and the Standal and Sunnarvik faults beneath the Ha˚steinen Basin) divide the Hornelen Region into a lower plate with ductile extensional fabrics and an upper plate with ductile-to-brittle extensional fabrics. The base of the lower plate is composed of WGC amphibolite-facies granitic gneisses with inclusions

of eclogite. Across this region, the WGC transitions smoothly from HP metamorphic conditions of 2.1–2.3 GPa and 600oC [Cuthbert et al., 2000; Labrousse et al., 2004; Johnston, 2006] in the southern WGC, to UHP metamorphic conditions up to 2.9 GPa and 750oC [Cuthbert et al., 2000; Labrousse et al., 2004; Young et al., 2007] in the northern WGC north of Nordfjord. Whereas (U)HP ages from the northern WGC range from 415 to 400 M [Carswell et al., 2003;Krogh et al., 2003; Root et al.,2004], eclogites from the southern WGC complex have not been dated. The basement cover sequences of the Lower/Middle Allochthon structurally above the WGC display chiefly upper amphibolite facies peak metamorphic conditions [Wilksand Cuthbert, 1994; Johnston, 2006]. However,rareeclogite boudins within the Lower/Middle Allochthon near Sandane have pressures similar to those in the WGC [Young et al., 2007] and indicate a gradual northward increase in metamorphic grade like that observed in the WGC. If these eclogites within the Lower/Middle Allochthon are the same age as those in the WGC, as suggested by~ 410 Ma peak metamorphic ages in Lower/ Middle Allochthon amphibolite-facies pelites [Johnston, 2006], these two units must have been juxtaposed prior to or during subduction [Young et al., 2007]. Alternatively, these eclogites may be older,for example, similar to the eclogites in the Bergen Arc region just south of Figure 1 (~423±4 Ma[Bingen et al., 2004]).

[19] Above the brittle-ductile detachments, the base of the upper plate tectonostratigraphy is composed of greenschistfacies, and local amphibolite-facies, metasandstones and ophiolitic rocks correlated with the Upper Allochthon (Figure 4). Top-W extensional structures within these rocks are limited to relatively minor brittle faults; penetrative ductile extensional fabrics are not present. The Devonian sedimentary rocks of the Ha˚steinen and Hornelen basins unconformably overlie Middle and Upper Allochthon rocks. Provenance work from these basins suggests an Upper and Lower/Middle Allochthon source, and the conspicuous lack of (U)HP clasts implies that the WGC had not been exhumed to the surface at the time of deposition [Steel et al., 1985; Cuthbert, 1991]. The Hornelen Basin's asymmet-ric scoop shape, and stratigraphy defined by coarsening to fining upward sequences, suggests that these basins were opened and tectonically controlled by strike-slip faulting [Steel and Gloppen, 1980; Steel et al., 1985] or a combi-nation of an oblique- to strike-slip faulting on the north margin with low-angle detachment faulting to the south and east [Norton, 1987; Osmundsen and Andersen, 2001].

[20] Whereas deformation of the upper plate is limited to brittle extensional structures, consistent E-W stretching lineations associated with late Caledonian extension char-acterize the ductile lower plate. In the several hundred meters below the WGC–Lower/Middle Allochthon contact, symmetric stretching fabrics dominant within the bulkof the WGC are gradually replaced upward by phyllonitic, amphibolite-facies mylonites associated with top-W noncoaxial shear along the NSDZ [Young, 2005]. These asym-metric mylonites characteristic of the NSDZ, including asymmetric boudins, s and S clasts, S-C fabrics and shear bands, deformamphibolite-facies phase assemblages associated with prograde garnet growth from~ 425 to 410 Ma [Johnston, 2006], cut the WGC–Lower/Middle Allochthon contact, and are pervasively developed throughout the Lower/Middle Allochthon [Wilksand Cuthbert,1994;Johnston, 2006]. Muscovite ages ranging from 402 to 396 Ma increase gradually

upward through the WGC into the Lower/Middle

Allochthon [Chauvet and Dallmeyer,1992; Berry et al., 1995]; older 419–417 Ma ages from the structurally highest part of the Lower/Middle Allochthon[Berry et al., 1995] suggest either early motion along the NSDZ or incomplete resetting of muscovite during late Caledonian extension. The Lower/Middle Allochthon mylonites are cut by a series of brittle-ductile detachments characterized by greenschist-facies shear fabrics and pseudotachylites. The Hornelen–Sunnarvik–Standal Fault system comprises the uppermost of these brittle-ductile detachment structures and displays the largest offsets, placing the lower plate extensional mylonites in direct contact with brittlely deformed upper plate rocks. These discrete detachment horizons cut Devonian sedimentary rocks, and merge downward into discontinuous higher strain zones within the ductile lower plate; they are thought to represent reactivation of the NSDZ through the Early Carboniferous and younger [Eide et al., 1997]. Younger E-W striking, brittle normal faults and strike-slip faults cut the mylonitic fabrics as well as the brittle-ductile detach-ments [Braathen, 1999]. Whereas the brittle-ductile detach-ments and younger brittle faults locally juxtapose tectonostratigraphic units along discrete high-strain zones, these structures represent the final stages of exhumation and are temporally and kinematically different from earlier ductile structures.

[21] North of Nordfjord, asymmetric mylonites associated with the NSDZ follow outcrops of the Lower/Middle Allochthon to the northeast where the asymmetric fabrics and exposures of the Lower/Middle Allochthon merge into the Nordfjord Mylonitic Shear Zone [Labrousse et al., 2004; Young et al., 2007]. The Nordfjord Mylonitic Shear Zone, exposed along Nordfjord and the northern margin of the Hornelen Basin, consists of dextral shear fabrics that are interpreted to represent a south dipping segment of the NSDZ that was folded into an anticline up and over the northern WGC[Krabbendam and Dewey, 1998; Labrousse et al., 2004]. North of the Nordfjord Mylonitic Shear Zone, increasingly younger muscovite ages ranging from 400 to 385 Ma in HP domains and <385 Ma in UHP domains reflect the deeper levels of exhumation achieved in the northern WGC created through Late Devonian and younger E-W striking regional folds[Root et al., 2005;Hacker, 2007; Walsh et al., 2007]. Although the NSDZ of the southern WGC is not exposed in the northern WGC, we assume that similar structures existed but have since been eroded.

5. Summary of Key Patterns

[22] In spite of the significant along-strike variation in extensional structures and geologic interpretations, the cross section of Figure 1 reveals several unifying patterns:

[23] 1. The NSDZ is a 2–6 km thick ductile shear zone characterizedbyrelatively evenly distributed, pervasively developed, top-W, asymmetric extensional shear fabrics within rocks of all tectonostratigraphic levels. This shear zone is not localized along tectonostratigraphic contacts, but is instead broadly centered within the Lower and Middle Allochthons. It fades out down section over several hundred meters to kilometers into the ductile, symmetric extensional fabrics of the WGC, and up section into the allochthonous rocks and Devonian-Carboniferous sedimentary rocks.

[24]2. Although some tectonostratigraphic contacts with- in the NSDZ correspond to significant breaks in peak metamorphic grade, all tectonostratigraphic units affected by the NSDZ share an amphibolite-facies extensional fabric developed at 0.6–1.0 GPa. Asymmetric shear fabrics within the NSDZ developed after peak metamorphic conditions, during progressive cooling from amphibolite- through greenschist-facies conditions; although these fabrics locally overprint older eclogite-facies tectonites, asymmetric eclo-gite-facies fabrics are not observed at any structural level.

[25] 3. Muscovite cooling ages across the Lower/Middle Allochthon–southern WGC contact define a continuum, indicating that juxtaposition of the tectonostratigraphic units occurred at temperatures above muscovite closure. Abrupt jumps in muscovite cooling ages (identifying a shear zone that originally straddled muscovite closure temperatures or signaling upper crustal excision) are found only within the upper levels of the asymmetric ductile mylonites of the NSDZ, or are associated with discrete brittle-ductile, top-W detachments. These upper crustal detachments cut Devonian sedimentary rocks and drop brittlely deformed upper plate rocks of varying tectonostratigraphic level down onto top-W ductile fabrics, and represent only relativelyminor, final stages of (U)HP exhumation and motion along the NSDZ.

6. Discussion

6.1. Problems With Existing Models

[26]This compilation of structural, thermobarometric and geochronologic data along the 200-km strike of the NSDZ reveals previously unrecognized patterns and new structural relationships that force a reinterpretation of the exhumation of Norwegian(U)HP rocks and the role of the NSDZ therein. In particular,the regional patterns recognized here highlight problems with single-stage exhumation models [Hacker et al., 2003; Labrousse et al., 2004; Hacker, 2007] that suggest continuous normal-sense shear from mantle through crustal levels along reactivated subduction-related thrusts. Although asymmetric eclogite-facies fabrics are present locally [Engvik and Andersen, 2000; Foreman et al., 2005] and may have been more widespread prior to overprinting by amphibolite-facies fabrics, the lack of eclogite-facies top-W fabrics suggests that the NSDZ was not involved in exhumation of the (U)HP rocks through the mantle but instead was initiated at amphibolite-facies con-ditions near the base of the crust. Further,the single-stage models do not provide a mechanism for the regionally consistent 0.6–1.0 GPa metamorphic overprint that affected rocks of different tectonostratigraphic levels and temporally different exhumation paths. Models that require abrupt breaks in metamorphic grade along tectonostratigraphic contacts as detachment horizons within the NSDZ [Andersen and Jamtveit, 1990; Krabbendam andDewey, 1998] are also problematic. Amphibolite- through greenschist-facies asymmetric shear fabrics, which define the bulkof the NSDZ, are not localized along tectonostratigraphic contacts, but occur primarily structurally above the largest metamor-phic break,the contact between the WGC and the Lower/ Middle Allochthon. In addition, the presence of similar amphibolite-facies mylonites that cut across tectonostrati-graphic contacts within the NSDZ, indicates that these different units were juxtaposed prior to the onset of dis-placement along the NSDZ. Finally, models that place the NSDZ

along brittle-ductile detachments that separate lower plate mylonites from upper plate brittle structures [Norton, 1987; Se´ranne and Se´guret, 1987; Fossen and Rykkelid, 1992;Milnes et al., 1997] are oversimplified. Although discrete detachment horizons throughout the area juxtapose brittle upper crustal rocks against mylonites and high-grade metamorphic rocks, these detachments are late, brittle-ductile structures that account for relatively minor upper crustal excision, and need to be differentiated from earlier, broad ductile shear zones developed under amphibolite-facies conditions.

6.2. A New Model for the Nordfjord-Sogn Detachment Zone

[27] We propose that the structures that have previously been grouped together as a single top-W mylonitic shear zone must be subdivided into multiple, distinct structures active at different depths and times(Figure 5). Juxtaposition of the (U)HP rocks with upper crustal metamorphic rocks and Devonian-Carboniferous sedimentary rocks across the NSDZ in the southern Western Gneiss Region is the result of sequential deformation along these structures. In the first stages of exhumation (possibly triggered by break-off of the subducting mantle lithosphere and the end of Caledonian contraction) the (U)HP Baltica Autochthon was exhumed through the mantle and juxtaposed with the Lower/Middle Allochthon against the Upper Allochthon at the base of the crust by 405–400 Ma (Figures 5a and 5b). Other than the sharp tectonostratigraphic contacts and the abrupt metamor-phic breaks observed within the NSDZ, the structures responsible for this mantle exhumation are subtle and were significantly overprinted during subsequent exhumation through the crust. Possible mechanisms for this mantle exhumation include diapiric rise, orogen-wide pure shear extension, slab roll-up, or wedge extrusion, buoyancy-driven processes that may have exhumed (U)HP continental material through the mantle but that became inactive upon arrival of the deeply subducted continental crust at the Moho. Here we follow Walsh and Hacker [2004] and suggest that mantle exhumation began when relatively weak subducted continental crust delaminated from the down-going Baltican mantle lithosphere, and rapidly ascended along the subduction interface before stalling at the upper plate Moho(Figure 5b). This model is compatible with analogue models that show that failure in subducted conti-nental crust is likely near the base of the crust [Chemendaet al., 1996, 2000] and with metamorphic petrology from the WGC that indicates that large volumes of subducted Baltica margin remained intact during exhumation [Hacker, 2007; Young et al., 2007]. However, the structures associated with this first stage of exhumation remain elusive, and the mechanisms responsible for mantle exhumation demand further work. It is also probable that some of the breaks in metamorphism are the result of early Scandian thrust juxtaposition of different tectonostratigraphic units, and disequilibrium during subsequent Caledonian subduction.

[28] Following mantle exhumation, temporary ponding of the Baltica Autochthon and the Lower/Middle Allochthon at the Moho permitted the development of the regional 0.6– 1.0 GPa metamorphic overprint [Walsh and Hacker, 2004]. This ponding significantly thickened the crustal column through the addition of the hot and radiogenic (U)HP crustal sequence to the base of the upper plate, and resulted in a large lateral gravitational potential energy gradient and a low-viscosity

crustal section that drove widespread Caledo-nian extension. Noncoaxial shear along the NSDZ was initiated during 0.6–1.0 GPaamphibolite-facies metamor- phism as a top-W shear zone broadly centered within the Lower/Middle Allochthon, perhaps because their quartzofeldspathic sedimentary rocks acted as a weak layer between the cold Upper Allochthon and the massive Baltica autochthon (Figures 5b and 5c). Ductile deformation that developed within this top-W shear zone completely over printed earlier deformation related to mantle exhumation of these rocks. During progressive extension, amphibolitefacies mylonites within the NSDZ were succeeded by greenschist-facies mylonites and rapidly exhumed through muscovite closure by 400–395 Ma. In the final stages of top-W shearing and crustal exhumation, after 395 Ma and into the Early Carboniferous, brittle-ductile detachments that soled into the mylonitic shear zone (the Solund Fault, Dalsfjord Fault and the Hornelen Detachment) were reactivated, cutting the Devonian basins and dropping them onto top-W mylonitic rocks of varying tectonostratigraphic levels (Figure 5d).

[29] Application of this model to UHP orogens world- wide highlights significant limitations and important differences between syncontractional and late to postcontractional exhumation of UHP rocks. In particular,the proposed model does not provide a viable mechanism for multiple UHP events[Brueckner and van Roermund, 2004] or syncontractional exhumation of relatively thin(<1km) UHP nappe sheets (e.g., Kokchetav[Maruyama and Parkinson, 2000]). During syncontractional UHP exhumation, uninterrupted subduction of the mantle lithosphere may conductively cool strong ascending UHP slabs, which could then be exhumed into the upper crust via a combina-tion of basal thrusting and passive normal-sense roof faults. Continued subduction of mantle lithosphere could also drive further shortening, which could ultimately lead to (U)HP subduction of progressively inboard continental crust. In contrast, near the end of contraction and after break-offof the mantle lithosphere, the driving force behind collision, subduction, and conductive cooling is eliminated, and a much hotter and weaker ascending UHP bodymay be trapped at the base of the lower crust. This underplating may initiate orogen-wide extension, ultimately exhuming an areally extensive and thick UHP bodyinto the upper crust. While the model presented here does not apply to syncontractional UHP exhumation, our model for the evolution of the NSDZ can be directly applied to large UHP provinces exhumed near the end of the orogenic cycle (e.g., Dabie-Sulu [Ratschbacher et al., 2006]).

7. Conclusion

[30] The NSDZ is one of the largest extensional detach-ments on Earth. In order to arrive at a coherent model of the evolution and effects of this structureon the exhumation of (U)HP rocks in western Norway, we have evaluated previ-ous descriptions and interpretations from all parts of the NSDZ. The patterns developed along strike beneath the Devonian basins of western Norway suggest that the NSDZ can be divided into three types of structures that sequen-tially overprinted and excised earlier stages of deformation: (1) early structures not specified in this paper that juxta-posed various tectonostratigraphic units near the base of the crust; (2)amphibolite- through greenschist-facies, top-W mylonitic fabrics of the NSDZ developed at crustal depths; and (3) late

brittle-ductile detachment faults that partially excised the higher temperature mylonites and led to the final juxtaposition of lower crustal rocks with the base of the Devonian-Carboniferous basins.

[31] It is probable that the NSDZ originally continued farther north above the UHP domains, and has since been removed through erosion. The model proposed here diverges significantly from earlier models that suggested continuous normal-sense displacement along the NSDZ from mantle through crustal levels, and others that sug-gested crustal-scale displacement along discrete detachment horizons within the NSDZ. Here, we infer that the (U)HP rocks were exhumed in three structurally unique, overprint-ing stages consistent with the marked differences in styles of deformation, cooling ages and metamorphic conditions observed along strike of the NSDZ.

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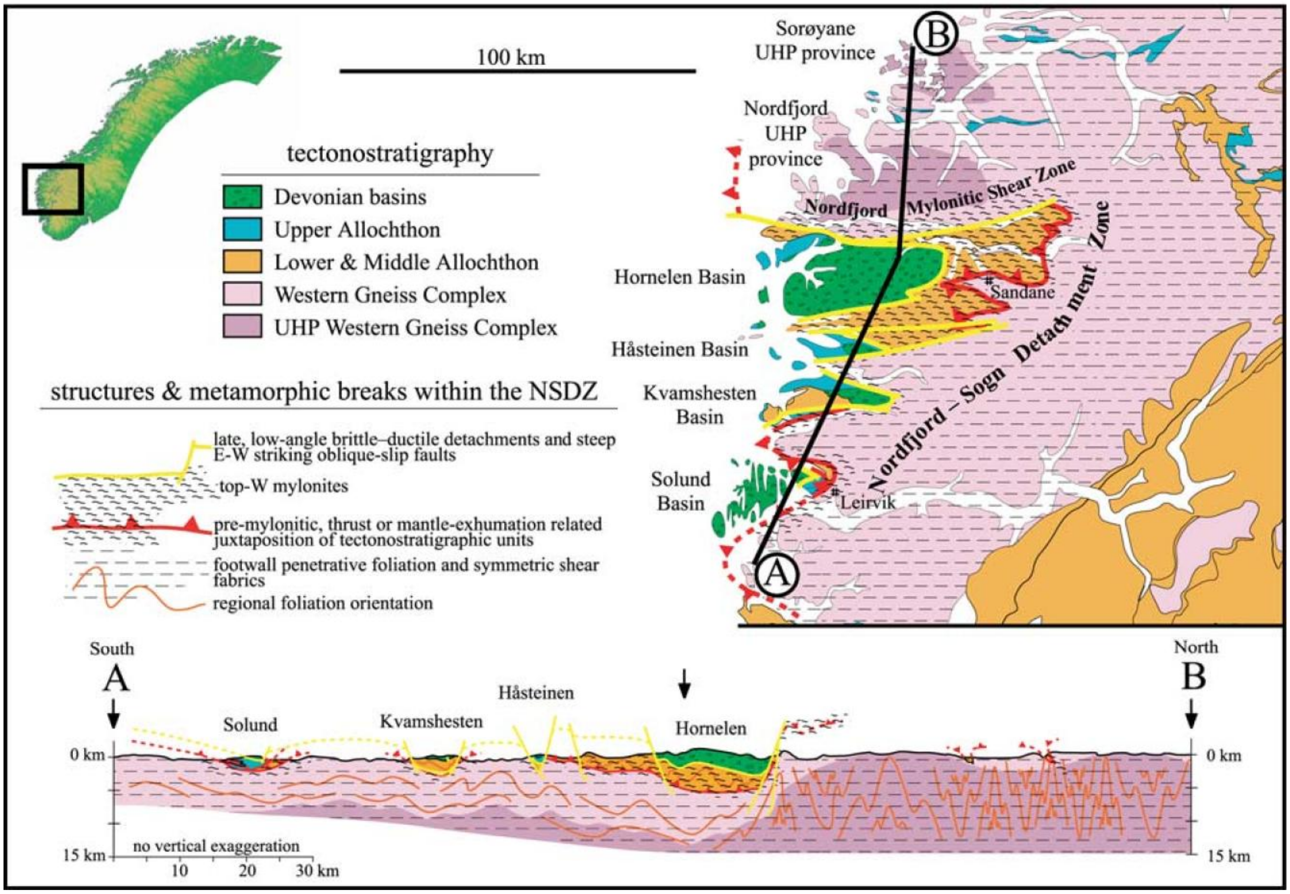
100 km
tectonostratigraphy
Devonian basins
Upper Allochthon
Lower & Middle Allochthon
Western Gneiss Complex
UHP Western Gneiss Complex
structures & metamorphic breaks within the NSDZ
late, low-angle brittle–ductile detachments and steep E-W striking oblique-slip faults
top-W mylonites
pre-mylonitic, thrust or mantle-exhumation related juxtaposition of tectonostratigraphic units
footwall penetrative foliation and symmetric shear fabrics
regional foliation orientation
Sorøyane UHP province
Nordfjord UHP province
Nordfjord Mylonitic Shear Zone
Hornelen Basin
Håsteinen Basin
Kvamshesten Basin
Solund Basin
Sandane
Leirvik
Nordfjord – Sogn Detachment Zone
A
B
South
North
Solund
Kvamshesten
Håsteinen
Hornelen
0 km
15 km
no vertical exaggeration
10
20
30 km

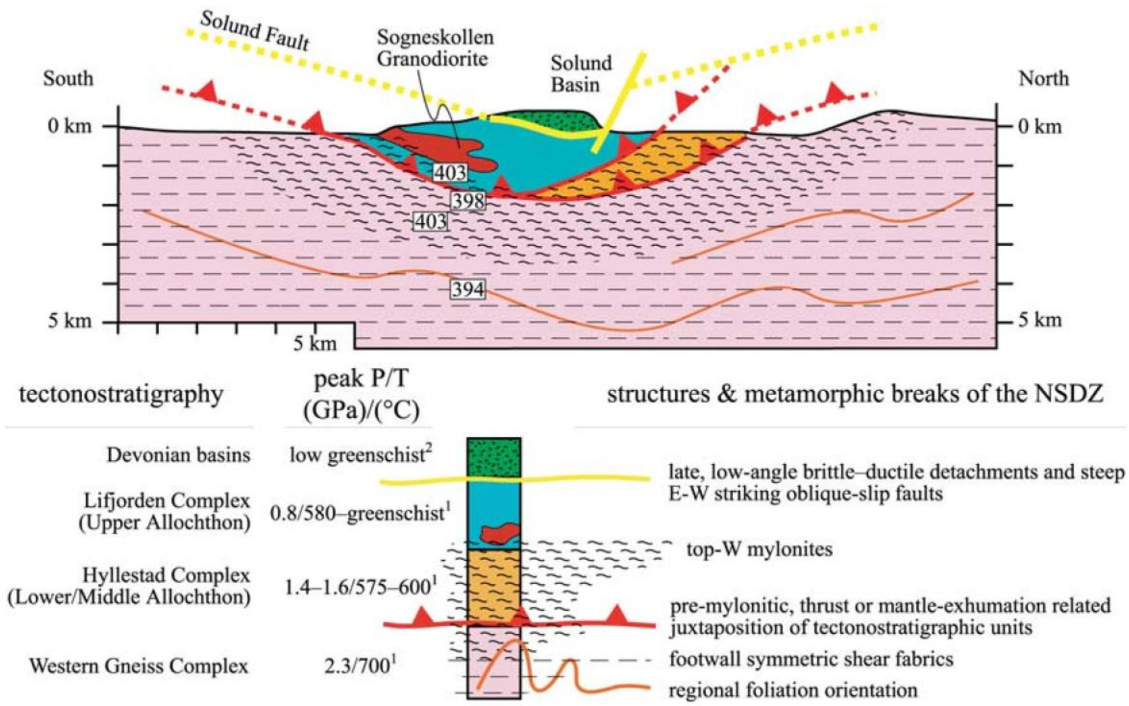

Figure 2. Detailed cross section (no vertical exaggeration) of the area adjacent to the Solund Basin. Muscovite cooling ages shown in white boxes, given in Ma, are from *Chauvet and Dallmeyer* [1992]; pressure-temperature estimates are from, as indicated by superscripts, 1, *Hacker et al.* [2003] and 2, *Séranne and Séguret* [1987].

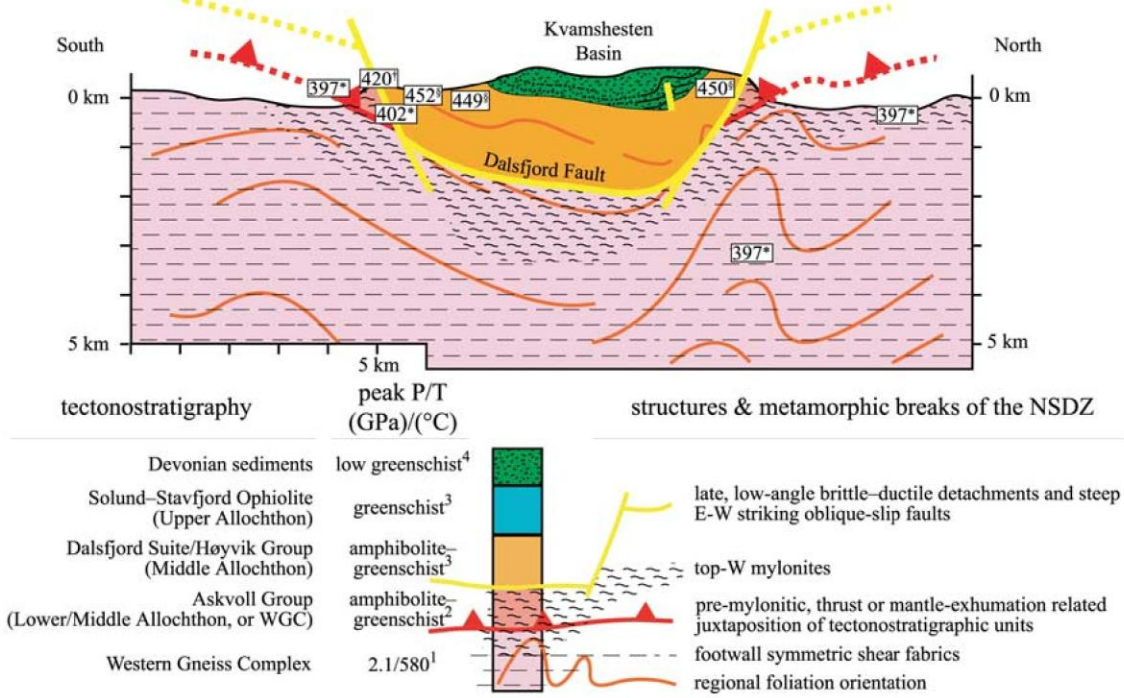

Figure 3. Detailed cross section (no vertical exaggeration) of the area adjacent to the Kvamshesten Basin. Muscovite cooling ages shown in white boxes, given in Ma, are from, as indicated by superscripts, asterisk, *Berry et al.* [1995]; section symbol, *Andersen et al.* [1998]; and dagger, *Eide et al.* [1999]; pressure-temperature estimates are from 1, *Cuthbert et al.* [2000]; 2, *Swensson and Andersen* [1991]; 3, *Osmundsen and Andersen* [1994]; and 4, *Séranne and Séguret* [1987].

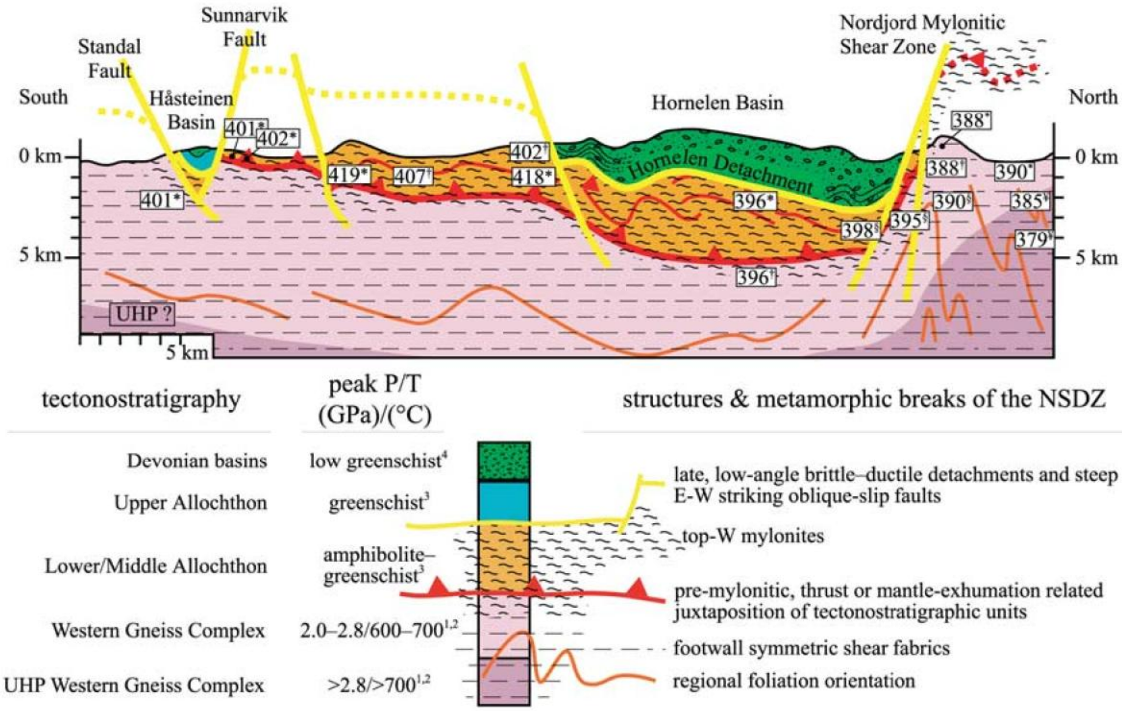

Figure 4. Detailed cross section (no vertical exaggeration) of the area adjacent to the Hornelen Basin. Muscovite cooling ages shown in white boxes, given in Ma, are from, as indicated by superscript asterisk, *Berry et al.* [1995], dagger, *Chauvet and Dallmeyer* [1992]; section symbol; *Young* [2005]; crossed y, *Root et al.* [2005]; pressure-temperature estimates are from 1,*Cuthbert et al.* [2000]; 2, *Labrousse et al.* [2004]; 3, *Wilks and Cuthbert* [1994]; and 4, *Séranne and Séguret* [1987].

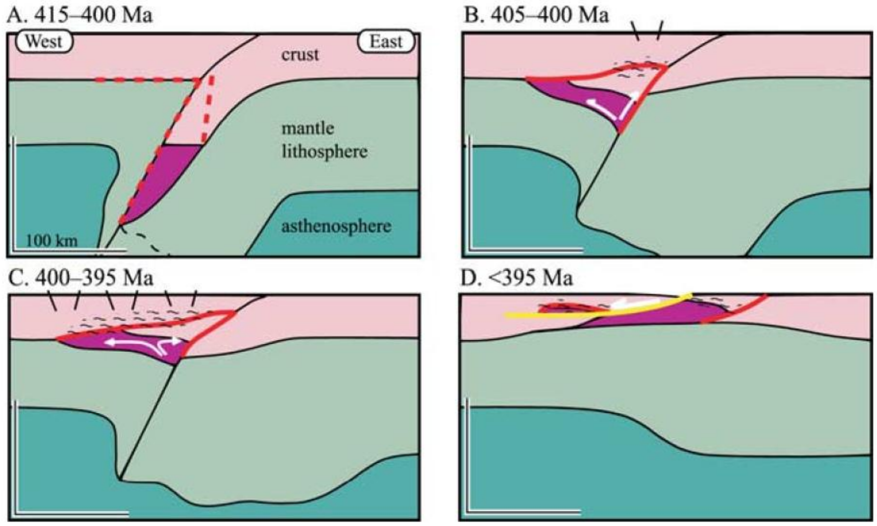

Figure 5. Schematic west-east cross sections illustrating three individual structural regimes active within the NSDZ that cumulatively exhumed the (U)HP provinces of western Norway. (a) Geometry at the height of collision. (b) Mantle exhumation, shown here as a weak (U)HP body delaminating from the mantle lithosphere near the base of the crust and underplating the overriding plate (contacts shown with heavy red lines). Early, ductile, top-W displacement along the NSDZ is initiated (shown with wavy fill pattern). (c) Orogen-wide extension: widespread lower crustal stretching and top-W ductile displacement within the NSDZ. (d) Brittle-ductile detachment faults (shown with heavy yellow lines) progressively exhume and excise earlier top-W fabrics developed within the NSDZ.