

Extension, disruption, and translation of an orogenic wedge by exhumation of large ultrahigh-pressure terranes: Examples from the Norwegian Caledonides

Hannes K. Brueckner^{1,2} and Simon J. Cuthbert³

¹LAMONT-DOHERTY EARTH OBSERVATORY OF COLUMBIA UNIVERSITY, PALISADES, NEW YORK 10964, USA

²(EMERITUS) SCHOOL OF EARTH AND ENVIRONMENTAL SCIENCES, QUEENS COLLEGE, AND THE GRADUATE CENTER OF THE CITY UNIVERSITY OF NEW YORK, FLUSHING, NEW YORK 11367, USA

³SCHOOL OF SCIENCE, UNIVERSITY OF THE WEST OF SCOTLAND, PAISLEY CAMPUS, PAISLEY PA1 2BE, UK

ABSTRACT

Far-traveled allochthons (>100 km) within collisional orogenic wedges may have undergone significant lateral movement by passive transport (in addition to thrusting) where they lie tectonically above large, exhumed, high-pressure/ultrahigh-pressure (HP/UHP) metamorphic terranes. Continental collision results in the subduction of one craton beneath another into the mantle. The subducted craton undergoes HP/UHP metamorphism, while an accretionary orogenic wedge develops simultaneously at its junction with the overlying craton. The subsequent exhumation of a large HP/UHP terrane by either far-field extension or buoyancy-driven extrusion, or both, reverses the shear traction along its upper boundary from foreland-directed thrust motion to hinterland-directed normal displacement. This normal-sense shear can stretch, thin, and fragment the overlying wedge and even carry a detached frontal fragment passively toward the foreland on top of the exhuming plate. The total “piggyback” displacement would be a function of the amount of exhumation of the HP/UHP terrane and the timing of its breakoff from the hinterland portion of the wedge. This model is applied to the Trondheim and Jotun nappe complexes of the Caledonides of southern Scandinavia, which were translated >300 km to the E and SE, respectively, during the 430–385 Ma Scandian orogeny. Their hinterland boundaries rest on top of the HP/UHP Western Gneiss Complex. Kinematic indicators along their basal décollements indicate a change in shear sense from top-E/SE to top-W/NW at the same time (ca. 405 Ma) that radiometric ages indicate the Western Gneiss Complex began to exhume from the mantle. Displacements of tens of kilometers along these décollements stretched and thinned the Trondheim nappe complex and fragmented the Jotun nappe complex. Ultimately, this basal traction led to the breakaway of the frontal segments of the allochthons, allowing them to be carried passively to the E/SE as the Western Gneiss Complex continued to exhume. Top-W/NW shear continued between the Western Gneiss Complex and the stranded rearward segments of the allochthons, resulting in the opening up of the Western Gneiss Region tectonic window between the E/SE-translating nappes and their relatively “fixed” equivalents in the W/NW. The total displacement of the traveled frontal allochthons could have been considerably farther than that accomplished by thrusting alone.

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INTRODUCTION

The orogenic wedge model (Davis et al., 1983) provides a satisfactory mechanism for the large-scale displacements of nappes or thrust sheets in most accretionary prisms and fold-and-thrust belts. We argue here that it is not the complete answer for some truly far-traveled allochthons such as in the Scandinavian Caledonides, where total translations have been estimated to exceed 300 km (Törnebohm, 1896; Gee, 1975; Hossack and Cooper, 1986; Gale et al., 1987). We suggest that this enormous horizontal translation was also the result of stretching, disruption, and passive “piggyback” (Rice, 2005) transport on top of a large, high-pressure/ultrahigh-pressure (HP/UHP) metamorphic terrane as it was exhumed from deep in the mantle. We begin by exploring some general tectonic arguments for this mechanism and then present two examples from the southern Norwegian

Caledonides. We believe that this model solves several riddles that have bedeviled workers in the Caledonides of southern Norway and may be applicable to other far-traveled allochthons in other mountain systems where they rest atop HP/UHP terranes.

GENERAL TECTONIC MODEL FOR WEDGE DISRUPTION BY EXHUMATION OF A LARGE HP/UHP TERRANE

HP/UHP metamorphic terranes are characterized by rocks (eclogites, garnet pyroxenites, and garnet peridotites) and minerals (omphacite, coesite, and microdiamonds) that form under pressures of 1.5–5 GPa and temperatures of 550–900 °C. Tectonic lenses of mantle rocks (orogenic peridotites) are common within these terranes. There is a growing consensus that continental HP/UHP terranes form when the leading edges of cratons subduct into and are

subsequently exhumed from deep levels of the upper mantle (Andersen et al., 1991; Chemenda et al., 1996; Maruyama, et al., 1996; Chopin, 2003; Warren et al., 2008; Duretz et al., 2012). The mantle wedge that lies above a slab of subducted continental crust then provides a source for the mantle-derived tectonic lenses (Brueckner et al., 2010). Some of these continental HP/UHP terranes are very large (e.g., the Western Gneiss Complex, Norwegian Caledonides; the Gföll Nappe, European Variscides; and the Dabieshan of east-central China). It is reasonable to expect that the return to normal crustal levels of such a large mass of buoyant crust may have a significant effect on the dynamics of the orogenic wedge.

We present two simplified models in Figure 1 that link the exhumation of large HP/UHP terranes with a significant proportion of the translations of the allochthons that lie above them, and in the process disrupt the orogenic

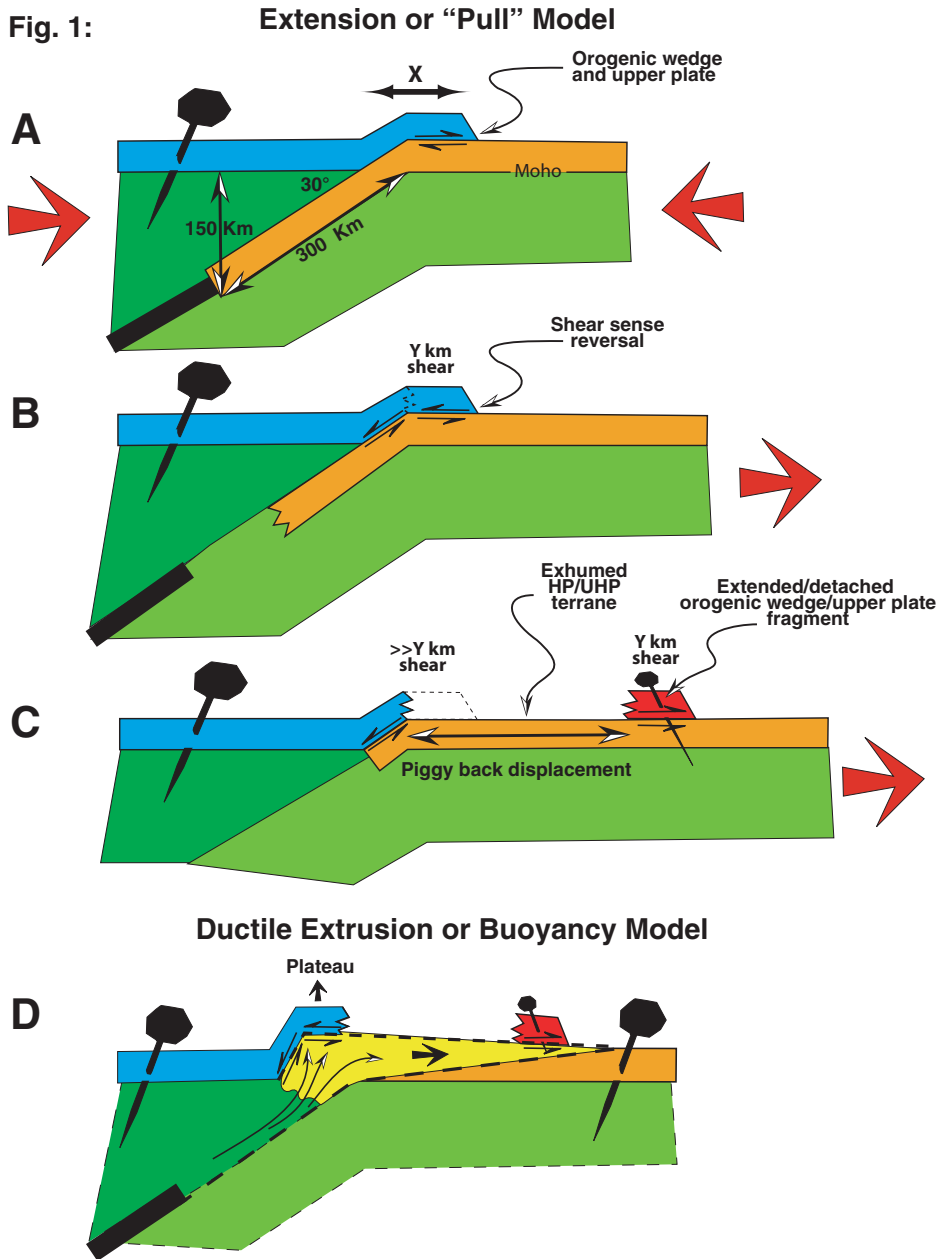


Figure 1. Schematic model for the translation of the leading edge of an upper plate during the exhumation of a subducted lower plate as a result of orogen-normal extension (A, B, and C) or buoyancy-induced extrusion (D). Blue and orange—continental crust; two shades of green—mantle lithospheres (asthenosphere not shown). (A) Construction of the orogenic wedge during plate convergence. (B) Exhumation of the lower plate during orogen-normal extension. Note reversal of shear sense from top right to top left. (C) Top-left (or bottom-right) shear ultimately breaks off the leading edge of the orogenic wedge and translates it passively to the right. (D) Shear sense reversal and passive translation also occur if the subducted crust delaminates from the mantle and extrudes buoyantly toward the surface bounded at top and bottom by a low-angle normal detachment and a thrust fault, respectively (yellow). HP/UHP—high-pressure/ultrahigh-pressure.

wedge. Both start with the same geometry, where two plates converge and one overrides the other (Fig. 1A). The plates are composed of thin (10–30 km) continental crust on top of thick (~100–150 km) mantle lithosphere. The

lower plate subducts into the mantle, following the oceanic lithosphere that preceded and pulled it into the mantle. The continental crust at the leading edge of the overriding plate is thrust over the crust of the lower plate, result-

ing in the formation of an orogenic wedge (Fig. 1A). The amount of crust-on-crust overlap in continental subduction is relatively small (X in Fig. 1) because the lower craton bends downward to descend into the mantle rather than continuing to slide beneath the upper craton, i.e., geometrically similar to oceanic subduction, but involving continental rather than oceanic crust.

The subduction of continental crust is limited by its lower density relative to the enclosing mantle. This positive buoyancy, possibly associated with the breakoff of the oceanic slab, terminates continental subduction and, ultimately, causes the crust to exhume. Two exhumation scenarios are considered, reflecting current uncertainty about exact mechanisms. The “eduction” model (Figs. 1B and 1C), based on the models of Andersen et al. (1991) and Fossen (1992) for the Western Gneiss Complex of south Norway, assumes that exhumation is caused by net extension of the orogen perpendicular to its length (Fig. 1B). If large enough, divergence pulls the previously subducted continental crust and underlying mantle lithosphere out of the mantle, in effect reversing earlier subduction. The crust and underlying lithosphere are exhumed together, and therefore there is no thrusting along the base of the HP/UHP terrane during exhumation. The model shown in Figure 1C assumes that all of the subducted craton is exhumed to illustrate maximum possible lateral transport.

The “extrusion” model (Fig. 1D) assumes that the continental crust delaminates from its underlying lithosphere, moves out of the mantle due to buoyancy, and extrudes into the overlying crust as a large nappe bounded at the top by a low-angle detachment with normal displacement and at the bottom by a thrust fault with reverse displacement (Chemenda et al., 1996; Maruyama et al., 1996; the “delamination/eduction” model of Duretz, et al., 2012). The extrusion model is modified in Figure 1D by allowing the deepest and hence hottest portion of the craton to undergo ductile thickening to provide a plateau, a critical taper, and the necessary volume of low-density material in the mantle to push the exhumed portion of the slab through the crust. Large-scale thrusting occurs at the base of the exhumed HP/UHP terrane, but it is driven by buoyancy rather than externally applied compression.

Both mechanisms have essentially the same effect on the leading edge of the upper plate. The foreland-directed exhumation of the lower plate reverses the shear sense at its boundary with the upper plate from top-foreland to top-hinterland (Fig. 1B). The large normal-sense traction against the base of the previously

accreted wedge causes it to stretch, disrupt, and, potentially, detach a portion of its thinner frontal zone. This traction may be particularly strong during the exhumation of very large, and therefore very buoyant, HP/UHP terranes, which would be expected to subduct and exhume at relatively shallow angles (Kylander-Clark et al., 2012). The detached frontal fragment will travel passively on top of the exhuming HP-UHP terrane (Figs. 1C and 1D), resulting in what looks like a far-traveled klippe, while a tectonic window composed of the HP/UHP rocks opens up behind it. Figure 1C shows an extreme end member, where continental crust exhumed at 30° from a depth of 150 km (enough to generate microdiamonds) results in a lateral translation of ~300 km, not including original shortening within the wedge.

Note that the passively transported klippe can share an initial period of hinterland slip (Y km in Fig. 1B) with the rest of the wedge before breaking off, but once it breaks away, slip along its base will cease. However, top-hinterland slip will continue along the base of the stranded back-wedge until exhumation of the HP/UHP terrane ends (Fig. 1C). The model therefore predicts that the total top-to-hinterland relative motion between the base of the back-wedge and HP/UHP terrane will be significantly greater (>>Y km) than that below the frontal klippe (Y).

THE SOUTHERN NORWEGIAN CALEDONIDES

The key tectonic elements of the southern Scandinavian Caledonides are illustrated in Figure 2. The orogenic wedge is dominated by four major allochthons that were thrust E/SE (present coordinates) over the autochthonous Baltic Shield when Iapetus closed and Baltica subducted beneath Laurentia during the 430–385 Ma Scandian orogeny (Andersen et al., 1991). The wedge consists mainly of, from bottom to top, pre-Scandian arenaceous sediments (Lower Allochthon), crystalline slices derived from the Baltica margin (Lower and Middle Allochthon), oceanic terranes derived from Iapetus and its margins (Upper Allochthon), and the stranded Laurentian upper plate (Uppermost Allochthon; missing over all of Fig. 2). Historically, these units were thought to have accreted by progressive emplacement during the Scandian orogeny. However, some nappe and subnappe units were emplaced over Baltica during previous orogenies or just prior to final Scandian collision (Stephens and Gee, 1989; Stephens et al., 1993; Roberts 2003; Robinson and Roberts, 2008; Brueckner and Van Roermund, 2004; Hacker and Gans, 2005; Andersen et al., 2012) and were remobilized during Scandian collision.

Southern Norwegian Allochthons

The nappe pile south of the Trondheimsfjord (~64°N) is preserved in a major, open, regional downwarp (the Trondheim synform). The synform is occupied by nappes of oceanic origin originating from outboard of Baltica (the Köli Nappes of the Upper Allochthon; see Gee, 1975). Underneath and outcropping on either side, nappes of the Middle Allochthon are derived from the Baltic continental margin (the Seve and “Crystalline Nappes” in Fig. 2). We adopt the collective name Trondheim nappe complex (Wolff, 1979) for this tectonostratigraphic assemblage. The Trondheim nappe complex overlies crystalline and quartzofeldspathic thrust sheets of the Lower Allochthon, which rest in turn on a décollement horizon of regionally extensive Tremadoc-age shales. The foreland basin to these nappes is probably very extensive, but it appears to have been relatively thin (Cederbom et al., 2000; Huigen and Andriessen, 2004), possibly due to the low strength of the shales, which caused a low taper in the wedge tip region (Greiling et al., 1998).

The southern continuation of the Trondheim synform is the “Faltungsgaben” (Goldschmidt, 1912), which is a fault-bounded, downdropped block (Milnes and Koestler, 1985). The Faltungsgaben is dominated by the Jotun nappe complex of the Middle Allochthon, an extensive sheet of Proterozoic crystalline rocks and its Neoproterozoic sedimentary cover. The crystalline rocks include granulite-facies gneisses and igneous rocks that formed during the middle Proterozoic Gothian and middle/late Proterozoic Sveconorwegian orogenies (Bingen et al., 2008). Jotun nappe complex igneous rocks include the diagnostic anorthosite-mangerite-charnockite suite, which also occurs within the Sveconorwegian basement rocks of southern Norway (i.e., the Rogaland complex; Auwera et al., 2011). The rock types and age patterns show a very strong affinity to the Baltic Shield, and, importantly, not to the Laurentian Shield of eastern Greenland, which contains Archean elements (Thrane, 2002) that are lacking in the Jotun nappe complex, and which also lacks Proterozoic anorthosites (Dymek and Owens, 2001). The age patterns and lithologies suggest that the Jotun Nappe was part of the western Baltic craton (Emmett, 1996), possibly a fragment that rifted away from the edge of Baltica during a pre-Scandian episode of hyperextension (Cuthbert et al., 1983; Andersen et al., 2012). It was transported E/SE during the Scandian orogeny, and its root zone lies somewhere off the Norwegian coast, suggesting lateral displacement of >300 km (Hossack and Cooper, 1986; Rice, 2005; Milnes and Corfu, 2008). The base of the

Jotun nappe complex is an extensive phyllite-dominated mylonite zone containing sheared elements of the Lower Allochthon (Milnes and Corfu, 2008), as well as a mélange of crystalline and oceanic elements. The mélange may have originated from small ocean basins within the hyperextended margin (Andersen et al., 2012). The phyllite-dominated shear zone extends continuously beneath the Jotun Nappe and is variously called the “Main Caledonian thrust zone” and the “Jotunheimen detachment zone.” It rests in turn on fold-and-thrust duplexes of the Lower Allochthon.

“Jotun”-like crystalline units such as the Dalsfjord Nappe (Fig. 2), as well as low-metamorphic-grade units equivalent to the Middle and/or Upper Allochthon, occur intermittently along the coast (henceforth, the “coastal” or “western” allochthons) in a series of synforms between Bergen and Trondheim. The Dalsfjord Nappe is a direct correlative of the Jotun Nappe (Corfu and Andersen, 2002; Lundmark et al., 2007), separated from it by the Western Gneiss Complex. Middle Devonian intramontane basins core these synforms and rest unconformably on the coastal allochthons (Wilks and Cuthbert, 1994; Osmundsen and Andersen, 2001). Another “Jotun”-like unit, the Lindås Nappe, occurs on the coast near Bergen (Fig. 2) and at a similar structural level as the Jotun nappe complex, but unlike the unmetamorphosed to very weakly metamorphosed Jotun and Dalsfjord Nappes, it underwent Scandian metamorphism, including partial eclogitization (Austrheim, 1987; Bingen et al., 2004; Glodny et al., 2008).

High-Pressure/Ultrahigh-Pressure Western Gneiss Complex

The Western Gneiss Region occurs between the western allochthons and the Trondheim nappe complex and Jotun nappe complex (Fig. 2) and exposes the exhumed HP/UHP rocks of the Western Gneiss Complex in a major tectonic window. The Main Caledonian thrust zone separates it from the structurally overlying nappe complexes in the east and southeast, and the Nordfjord-Sogn detachment zone (the Nordfjord-Sogn detachment of Norton, 1986) separates it from the coastal allochthons in the west.

Most of the crystalline rocks of the Western Gneiss Complex formed during Proterozoic orogenies, identical in age and character to the rocks of the Baltic Shield beneath the foreland. However, unlike the undisturbed shield rocks, those of the Western Gneiss Complex underwent recrystallization and deformation during the Scandian orogeny, with the degree of “Caledonization” increasing systematically from minimal in the southeast to diamond-

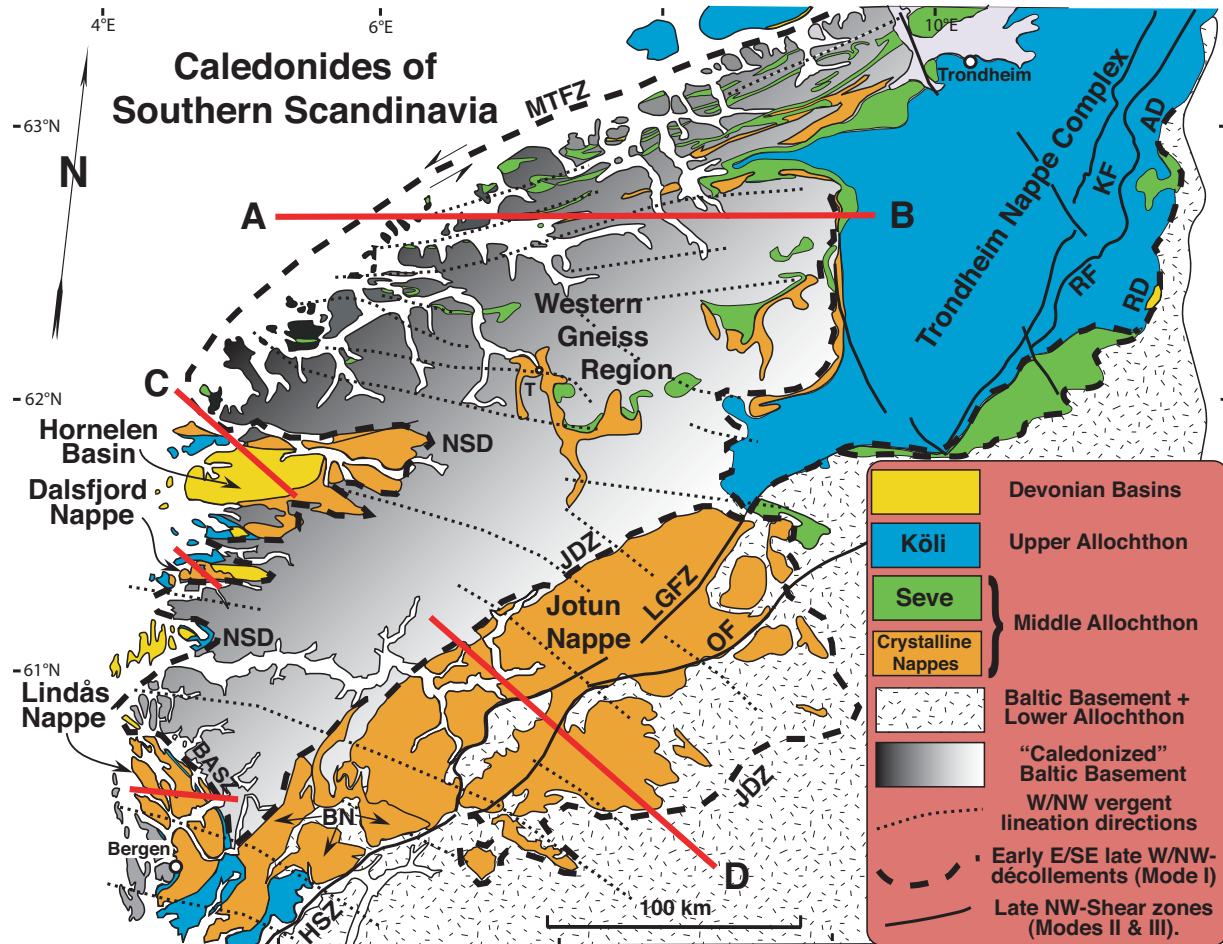


Figure 2. Simplified tectonic map (modified from Gee et al., 1985; Solli et al., 1997) of the Western Gneiss Region, Trondheim Basin, and the Jotun, Lindås, Dalsfjord, and Bergesdalen (BN) Nappes. The SE to NW change in grayscale color in the Western Gneiss Region illustrates increasing depth of subduction during the Scandian orogeny. T—Taffjord enclave. Major detachment zones and faults are generalized (see text for references). Thick dashed lines are approximate positions of and possible relationships between major, top-W mode I detachments developed during the exhumation of the Western Gneiss Region (AD—Åre detachment; BASZ—Bergen Arcs shear zone; JDZ—Jotunheimen detachment zone [aka basal Jotun thrust]; MTFZ—Møre Trondelag fracture zone; NSD—Nordfjord-Sogn detachment zone [includes the Sandane shear zone]; RD—Rørdanger detachment). Thin NE- and NW-trending continuous lines are approximate positions of selected later, high-angle, ductile/brittle extensional faults (HSZ—Hardangerfjord shear zone; LGFZ—Laerdal-Gjende fault zone; OF—Olestål fault; KF—Kopperå fault; RF—Rørdanger fault). Thin dotted ENE- to SW-trending lines represent shear sense trajectories during the exhumation of the Western Gneiss Complex (generalized from Séranne, 1992; Fossen, 1992, 1993, 2000; Hacker et al., 2010). Most shear senses are top-W/SW imprinted on an earlier top-E/SE thrust fabric. Lines A–B and C–D show approximate cross sections illustrated schematically in Figures 3 and 4, respectively.

grade eclogite facies in the northwest (Griffin et al., 1985; Hacker et al., 2010). This increase in metamorphic grade, shown schematically by progressively darker shading in Figure 2, was accompanied by increasing intensity of Caledonian deformation (Milnes and Corfu, 2008; Robinson and Roberts, 2008; Hacker et al., 2010), indicating that the northwest margin was plunged most deeply into the mantle (Krogh, 1977; Cuthbert et al., 2000). The Western Gneiss Complex also contains hundreds of (locally garnetiferous) peridotite bodies of sub-Laurentian lithosphere affinity (Brueckner

et al., 2010; Beyer et al., 2012), consistent with the existence of a Laurentian, rather than Baltic, mantle wedge above the Western Gneiss Complex during its subduction.

The Western Gneiss Complex also contains “internal” synclinal keels of the Upper and/or Middle Allochthon, which can be traced more or less continuously southwest along the Moldefjord syncline from the Trondheim synform to the coast (Tucker et al., 2004; Robinson and Roberts, 2008). Unlike the low-grade coastal allochthons, they show a progressive northeast to southwest increase in degree of “Caledonization,” with ele-

ments of the Middle Allochthon metamorphosed up to eclogite-facies conditions (Terry et al., 2000), and locally sheared to a thickness of less than 10 m (Robinson, 1995). Finally, the Upper and/or Middle Allochthons also occur as large isolated enclaves within the Western Gneiss Complex (Fig. 2; Bryhni and Grimstad, 1970; Brueckner, 1977; Young et al., 2007). These enclaves were also “Caledonized,” up to the eclogite facies in some areas; the Taffjord-Grotli enclave (T in Fig. 2) is well known for its swarm of orogenic peridotite masses, one of which is garnet bearing (Brueckner, 1977).

Scandian Décollements

Figure 2 shows the approximate positions (heavy dashed lines) of the many, kinematically linked, low-angle ductile detachment zones that have been mapped in the southern Caledonides. These structures occur between the allochthons and the Baltic Shield to the east and south, and the Western Gneiss Complex to the north and west. They were originally considered top-E/SE thrust faults that led to the development of the orogenic wedge, which in fact they are. However, ductile shear sense indicators show that most or all of these detachments also underwent a later top-W/NW (i.e., top-toward-hinterland) motion that in many cases overprints the earlier top-E/SE motion (Hossack, 1984; Norton, 1986, 1987; Norton et al., 1987; Wilks and Cuthbert, 1994; Wennberg, 1996; Andersen, 1998; Fossen, 1992, 2000, 2010; Tucker et al., 2004; Fossen and Hurich, 2005; Rice, 2005; Johnston et al., 2007a, 2007b; Andersen and Austrheim, 2008; Milnes and Corfu, 2008; Young et al., 2007, 2011). These hinterland-directed structures were generally explained by either extensional collapse of an overthickened orogen (e.g., Norton, 1986; Sjöström and Bergman, 1989; Séranne, et al., 1989; Andersen and Jamtveit, 1990; Andersen et al., 1999) or orogen-normal extension (Fossen 2000, 2010) or a combination of the two.

The detachments along the western boundary of the Western Gneiss Complex, referred to generally as the Nordfjord-Sogn detachment zone (Fig. 2), juxtapose the upper-plate, relatively low-grade coastal allochthons and their Middle Devonian basins, against the lower-plate, HP/UHP gneisses of the Western Gneiss Complex (Chauvet et al., 1992; Wilks and Cuthbert, 1994; Hacker et al., 2003; Johnston et al., 2007a, 2007b; Young et al., 2007, 2011). This slip boundary is considerably more complicated, as discussed later herein, but overall, the juxtaposition of low-grade rocks over HP/UHP rocks indicates that the top-W/NW motion documented along these detachments was of a normal shear sense. The enormous gap in metamorphic grade between the HP/UHP Western Gneiss Complex and the overlying allochthons implies very large vertical flattening and excision along the detachment system (Marques et al., 2007).

Shearing beneath the Coastal Allochthons: Geometry and Timing

Top-W/NW shearing beneath the Caledonian allochthons was divided into two overlapping modes by Fossen (1992, 2000; Milnes et al., 1997): mode I, where the nappe pile slipped along the Main Caledonian thrust zone, Jotunheimen detachment zone, and related low-angle

ductile detachments beneath the allochthons, and modes II and III, where the nappe pile and, in some cases, the underlying Baltic craton were cut by steeper, ductile shear zones (mode II) that evolved into still-later high-angle brittle faults (mode III). A critical question is whether the ductile detachments below the coastal allochthons and their Devonian basins (i.e., the Nordfjord-Sogn detachment zone) were mode I, mode II, both, or one but not the other. A second and related question is whether the late, steep ductile shear zones in the coastal areas cut through the earlier, shallower shear zones, which would have effectively stopped or hindered further significant top-W/NW motion, or soled into the shear zones, which would have allowed “piggyback” transportation to continue.

The most dramatic crosscutting mode II shear zone in southern Norway is the NW-dipping, top-NW Hardangerfjord shear zone and its brittle extension, the mode III Laerdal-Gjende fault zone, which occurs south of the Western Gneiss Complex and within the Jotun nappe complex (Fig. 2). This composite structure (Fossen, 2000; Fossen and Hurich, 2005) clearly transects the Main Caledonian thrust zone (locally labeled the Jotunheimen detachment zone) and continues down into the lower crust of the Baltic craton and thus could not have created a large tectonic window similar to the Western Gneiss Complex. It initiated in the crystalline craton below the Main Caledonian thrust zone and propagated upward through the Main Caledonian thrust zone detachment and, ultimately, into the overlying allochthons (fig. 3 in Fossen and Rykkelid, 1992), thus ending further top-W/NW shear along the Main Caledonian thrust zone. Back rotation of the allochthons in the hanging wall of the Hardangerfjord shear zone resulted in the formation of the “Faltungsgaben” and also the late up-“doming” of the Western Gneiss Complex (Fossen, 2000), but did not result in the exhumation of the Western Gneiss Complex, which occurred further to the north. Fossen (2010) suggested that the Bergan Arcs shear zone (BASZ) and even the Nordfjord-Sogn detachment zone evolved as similar mode II faults caused by orogen-normal extension that affected much of the North Atlantic Caledonides.

We suggest, however, that the Nordfjord-Sogn detachment zone evolved differently than the Hardangerfjord shear zone, particularly along its central and northern extent. The Nordfjord-Sogn detachment zone around the Hornelen Devonian Basin (Fig. 2), for example, once considered a single 4–6-km-thick mylonitic shear zone separating the relatively low-metamorphic-grade western or coastal allochthons from the HP/UHP gneisses of the Western Gneiss Complex (Wilks and Cuthbert,

1994), is considerably more complicated (Johnston et al., 2007a, 2007b; Young et al., 2007, 2011). The shear zone overprints the lower portions of the overlying Middle and Upper Allochthons at relatively low metamorphic grade, but Middle and Upper Allochthon units also occur at deeper levels within the shear zone, where they contain eclogites and peridotites (Young et al., 2007). A single-stage exhumation history for the Nordfjord-Sogn detachment zone is clearly inadequate. Therefore, Johnston et al. (2007b) proposed a model for the evolution of the Nordfjord-Sogn detachment zone in three steps: an initial stage that exhumed the Western Gneiss Complex and subducted allochthons from the mantle, a subsequent top-W/NW stage that exhumed these tectonic elements further, from the base of the crust, within a broad ductile shear zone under amphibolite- to greenschist-facies conditions, and, finally, a brittle/ductile top-W/NW stage, which formed detachments that both soled into and partially excised the earlier shear zone. Evidence for the first stage was largely obliterated by the subsequent steps, but it almost certainly happened because the Western Gneiss Complex and the deeper-level Upper and Middle Allochthons are in the eclogite facies (Young et al., 2007) and, importantly, include orogenic peridotites that were probably derived from the overlying Laurentian mantle wedge (Brueckner, 1998).

Young et al. (2011) also subdivided the detachment around the Hornelen Basin into an earlier, deeper, allochthon-parallel shear zone (the Sandane shear zone) to the east and a later, shallower, discordant shear zone in the west (now the Nordfjord-Sogn detachment zone *sensu stricto*). The Nordfjord-Sogn detachment zone *sensu stricto* merges with the Sandane shear zone to the west, and so soles listrically down into it rather than cutting across it. The Sandane shear zone, therefore, could have continued to accommodate the exhumation of the Western Gneiss Complex out of the mantle and through the crust.

We equate slip along the earlier Sandane shear zone to stages 1 and 2 of Johnston et al.’s (2007b) model and suggest it is also equivalent to the mode I shearing of Fossen (2000), coeval with the top-W/NW shearing along the Main Caledonian thrust zone. We further equate movement along the Nordfjord-Sogn detachment zone *sensu stricto* with stage 3 of Johnston et al.’s (2007b) model, but, importantly, we do not correlate the steep stage 3 structures with the mode II structures of Fossen (2000), at least as exemplified by the Hardangerfjord shear zone. We suggest instead that the stage 3 structures developed initially within the allochthons above the mode I detachment rather than beginning in the Western Gneiss Complex beneath the

detachment. They developed in the allochthons as a result of tractions exerted along the base of the allochthons by stage 1 and 2 (or mode I) movement along the Sandane shear zone and equivalent low-angle detachments.

All of the coastal allochthons are bounded to the east by these W/NW-dipping, discordant detachment faults, which emplaced them down against the mylonite zone of the Western Gneiss Complex. These bounding faults separated the coastal allochthons from the Trondheim nappe complex and Jotun nappe complex, as originally proposed by Hossack (1984), making them the breakaway faults that allowed tectonic separation of the orogenic wedge as slip continued along the mode I detachment. Ultimately, later brittle faults (mode III) sliced through the detachment and cut up into the coastal allochthons of the hanging wall, marking the end of slip along the basal detachment while simultaneously creating accommodation space for the Early to Middle Devonian molasse basins (Wilks and Cuthbert, 1994; Johnston et al., 2007a).

We propose that this tectonic picture can be extended southward to encompass the Nordfjord-Sogn detachment zone beneath the Kvamshesten (Andersen and Jamtveit, 1990; Swenson and Andersen, 1991; Hacker et al., 2003; Osmundsen and Andersen, 2001; Johnston et al., 2007a, 2007b) and Solund (Hacker et al., 2003; Johnston et al., 2007b) Basins. Johnston et al. (2007b), for example, mapped two major top-W/NW ductile slip surfaces beneath the Solund Basin that appear to merge, consistent with later shear zones soling into an earlier (mode I?) shear zone. Even maps and cross sections that show steep, later faults cutting into uppermost sheared Western Gneiss Complex do not generally show them cutting through the mylonite zone into unshaped Western Gneiss Complex gneisses (e.g., figs. 2 and 3 in Vetti and Fossen, 2012), allowing for the possibility that slip could have continued along the shear zone.

Milnes et al. (1997) interpreted the Nordfjord-Sogn detachment zone below the Solund Basin as a mode II rather than mode I structure. This structural reconstruction involves very large footwall uplift (>50 km; see fig. 3 in Milnes and Corfu, 2008), which would have exposed a very large portion of the Western Gneiss Complex in the footwall. If so, the Solund Basin fill should be dominated by Western Gneiss Complex debris. No such debris has been found in the alluvium of the Hornelen Basin (Cuthbert, 1991), so if a similar lack of Western Gneiss Complex clasts is true of the Solund Basin (as suggested by Hartz et al., 2002), the >50 km amount of footwall uplift becomes unlikely. The Sognfjord structural section can be equally well

interpreted as bounded below by a relatively shallow mode I shear zone with the later listric Solund detachment rooting into it.

Wilks and Cuthbert (1994) correlated the units of the eclogite-bearing coastal allochthons beneath the Nordfjord-Sogn detachment zone eastward across the Western Gneiss Complex culmination to the internal, in-folded enclave of Lower and Middle Allochthons that occurs in the Tafjord-Grotli area (Brueckner, 1977). The Tafjord allochthons also contain eclogites and numerous mantle-derived peridotite bodies, suggesting they lay close to the stage 1 mantle exhumation slip horizon of Johnston et al. (2007b) and the Sandane shear zone of Young et al. (2011). If so, a mode I shear zone could have extended beyond the Tafjord allochthons to form a broad antiformal window that stretched from beneath the coastal allochthons to beneath the Jotun nappe complex prior to post-Caledonian erosion.

TECTONIC TIMING

Critical evidence for our model includes timing constraints that indicate the Scandian décollements reversed their shear senses from top-E/SE to top-W/NW at the same time as the Western Gneiss Complex switched from subduction to exhumation. Sm-Nd and Lu-Hf mineral dates for garnet formation under eclogite-facies conditions in the Western Gneiss Complex are as old as 415–435 Ma (Griffin and Brueckner, 1980; Kylander-Clark et al., 2007; Spengler et al., 2009), and zircons within eclogites have been U-Pb dated as old as 415 ± 1 Ma (Krogh et al., 2011). These older ages mark prograde eclogite-facies metamorphism during subduction. Garnets in gneisses continued to form between 404 and 398 Ma (Peterman et al., 2009), and trace-element profiles across these garnets indicate that many of them formed during retrograde amphibolites-facies metamorphism, presumably dating exhumation. U-Pb rutile and titanite ages of 393–385 Ma (Tucker et al., 2004; Kylander Clark et al., 2008) and $^{40}\text{Ar}/^{39}\text{Ar}$ white mica ages of 397–380 Ma (Root et al., 2005; Walsh et al., 2007) indicate exhumation continued to at least 385 Ma, and that the southeastern and eastern Western Gneiss Complex was exhumed before the northwestern and western Western Gneiss Complex, and the nappes of the Trondheim synform were exhumed even earlier (Hacker and Gans, 2005). Taken together, the geochronology suggests that the Western Gneiss Complex underwent the transition from subduction to exhumation at ca. 405 Ma.

Stratigraphic relationships indicate the early top-SE (thrust) movement of the orogenic wedge

along the Main Caledonian thrust zone began around 425 Ma and ended in a less well-constrained time interval between 415 and 390 Ma (Fossen, 2000). Geochronological and kinematic relationships suggest a tighter interval for the end of thrusting and the beginning of reverse motion. $^{40}\text{Ar}/^{39}\text{Ar}$ ages from muscovites and biotites in rocks with top-SE fabrics indicate thrusting continued between 415 and 408 Ma (Fossen and Dunlap, 1998). These ages overlap the older Western Gneiss Complex eclogite ages, suggesting that thrusting and the construction of an orogenic wedge coincided with the subduction of Baltica. Muscovites and biotites in rocks with the later top-NW fabrics (Fossen, 1992, 2000; Milnes and Corfu, 2008) are consistently younger than those with top-SE fabrics, at 402–394 Ma (Fossen and Dunlap, 1998). Thus, the switch in shear direction in the Jotun nappe complex was coincident with the beginning of Western Gneiss Complex exhumation at ca. 405 Ma. This timing could hardly be a coincidence.

CONSTRUCTION OF THE OROGENIC WEDGE

Shear sense reversal has also been demonstrated for units beneath the Trondheim nappe complex (Séranne, 1992; Robinson and Roberts, 2008), though the timing is less well constrained. The Trondheim nappe complex does, however, offer precise timing constraints on the construction of the orogenic wedge. Elements of the Middle Allochthon (the Seve Nappe) were emplaced onto the Baltic Shield during an earlier, mid-Ordovician orogeny (informally, the Jämtlandian orogeny of Brueckner and Van Roermund, 2007). Igneous activity within Iapetus (i.e., the Upper Allochthon) ranged between 470 and 432 Ma (Andersen et al., 2012; Tucker et al., 2004; Hacker and Gans, 2005), setting a maximum age of 432 Ma for the collision of Baltica and Laurentia. Stratigraphic evidence indicates that Scandian thrusting started ca. 425–415 Ma (Fossen, 2000). The interval between 432 and 425 Ma therefore marks when this Iapetan assemblage was obducted onto the Middle Allochthon. This age is consistent with Wenlockian (430–423 Ma) fossils from the Herland Group in the coastal allochthons on Atløy, which record the arrival of the Upper Allochthon (Andersen et al., 1990). The Trondheim nappe complex and equivalent coastal nappe complexes give Silurian–Devonian recrystallization ages (435–415 Ma; Hacker and Gans, 2005; Wilks and Cuthbert, 1994), reflecting the metamorphism that accompanied the construction of the orogenic wedge. Thus, the translation of the Upper Allochthon (the Köli Nappe) over the already emplaced Middle Allochthon (the

Seve Nappe) was followed by emplacement of the Uppermost Allochthon (Laurentia), resulting in the production of a thick nappe stack at ca. 420 Ma (Nilsen et al., 2007; Hacker and Gans, 2005). The wedge therefore existed 10–20 m.y. before the thermal maximum of UHP metamorphism in the Western Gneiss Complex. It follows that inboard elements of this orogenic wedge would have been subducted along with the crystalline basement rocks of the Western Gneiss Complex (Hacker and Gans, 2005).

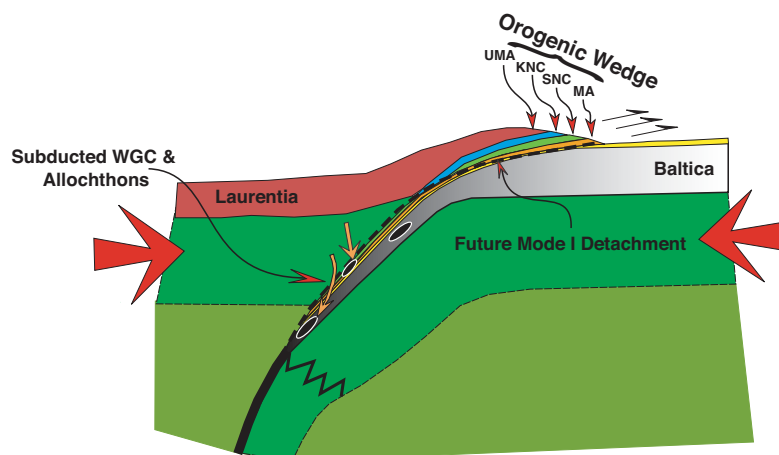
Indeed, units of the Trondheim nappe complex can be traced westward into the Western Gneiss Complex all the way to the coast, where they are in-folded with UHP Baltica basement (Robinson, 1995; Tucker et al., 2004; Krogh et al., 2011). Western elements of the Upper Allochthon are of low metamorphic grade, but a Middle Allochthon unit (the Blahø Nappe) contains eclogite and, in the far west, diamond-grade pelitic gneiss, eclogite, and garnet peridotite (Dobrzhinetskaya et al., 1995; Terry et al., 2000; Spengler et al., 2009). Orthogneisses in the subjacent Western Gneiss Complex basement underwent similar UHP metamorphism (Carswell et al., 2006). The common UHP metamorphic evolution of nappe and basement requires that the western portions of the previously emplaced nappes were subducted, along with the underlying Western Gneiss Complex, into the mantle to depths exceeding 150 km (Hacker and Gans, 2005; Carswell et al., 2006). The eastern parts of the Trondheim nappe complex experienced Scandian metamorphism at relatively lower metamorphic grades (greenschist and lower), and thus were not subducted into the mantle, but instead remained part of a crustal orogenic wedge.

EXHUMATION OF THE WESTERN GNEISS COMPLEX AND LARGE-SCALE TRANSLATION OF THE TRONDHEIM BASIN NAPPE COMPLEX

The model (Fig. 3A) assumes that the uppermost allochthon (i.e., Laurentia) was the overriding plate during collision and was subsequently removed by erosion. The eastern parts of the allochthons were thrust over the Baltic foreland to produce the foreland orogenic wedge postulated by Hacker and Gans (2005). A basal shear zone cut structurally upward from east to west, so that the western portions of the allochthons were subducted, along with the underlying Baltic Shield, into the mantle beneath Laurentia (Fig. 3A). There, they underwent HP/UHP metamorphism and acquired peridotites from the overlying mantle wedge. The units above the shear zone were not deeply subducted and hence underwent lower-grade metamorphism.

Fig. 3: Trondheim Nappe Complex segment

A. Scandian Collision at ca. 435-405 Ma



B. Exhumation of The Western Gneiss Region, 405-390 Ma

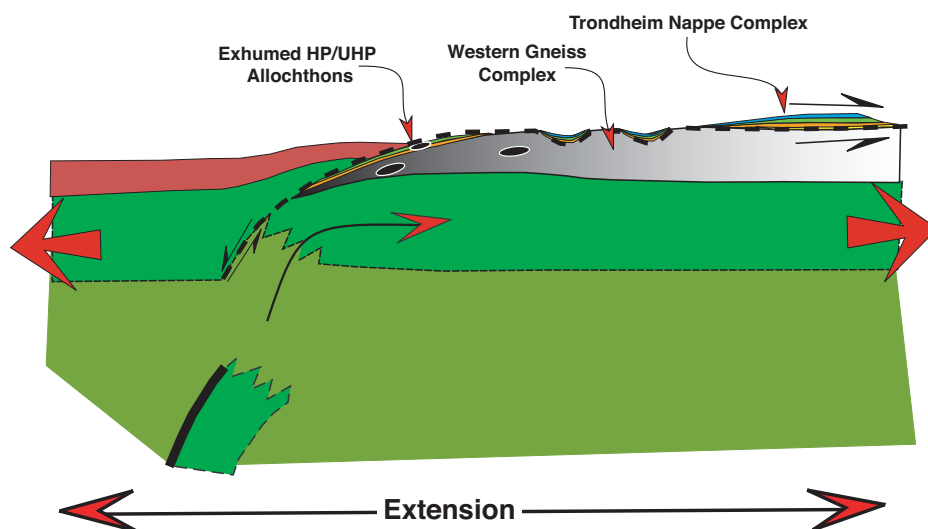


Figure 3. Conceptual exhumation and lateral translation model for the Trondheim Basin nappe complex more or less along transect A–B in Figure 2 (not to scale). (A) Initial collision, formation of a nappe stack, and early subduction of the Western Gneiss Complex (WGC) and westernmost overlying allochthons. (B) Exhumation of the Western Gneiss Complex, stretching of the coastal allochthons, and passive transport of the eastern allochthons. UMA—Uppermost Allochthon; KNC—Koli nappe complex (Upper Allochthon); SNC—Seve nappe complex (Middle Allochthon); MA—crystalline units of the Middle Allochthon. Grayscale gets darker as subduction gets deeper. Units are colored as in Figure 2. HP/UHP—high pressure/ultrahigh pressure.

Subsequent exhumation occurred along the same shear zone, but now as a top-W, thick ductile mode I detachment, allowing the Western Gneiss Complex and associated allochthon(s) to rise from the mantle. The deepest portion of the detachment occurred at the boundary between the top of the subducted Seve Nappe and the mantle wedge, but it cut structurally downward and eastward through the allochthons to their boundary with the underlying Baltic Shield.

Unlike the simplified model shown in Figure 1, a discrete brittle breakaway of the units above the detachment did not develop initially. Instead, the units within the detachment were very strongly sheared and thinned even as the units above the detachment were passively translated eastward. This distributed shearing left drastically thinned veneers of the higher allochthons (Robinson, 1995) along the top of the basement, preserved today in narrow NE-SW-trending synforms

(shown schematically in Fig. 3). The shear zone evolved, locally, to ductile and then brittle low-angle normal faults (mode II/III) as the rocks were exhumed and cooled, resulting in progressively older closure ages from west to east as predicted by the model (fig. 6 in Hacker, 2007). Faults and detachments near the eastern margin of the Trondheim nappe complex (Fig. 2) show the expected top-W motion (Gee et al., 1994; Sjøström and Bergman, 1989; Bergman and Sjøström, 1997; Mosar, 2000).

For simplicity, we illustrate exhumation as simple rollback due to orogen-normal extension effectively pulling (educting) the Western Gneiss Complex back out of the mantle still attached to its underlying lithosphere. However, the northern Western Gneiss Complex may be allochthonous (Cuthbert et al., 1983; Rice, 2005; Robinson and Roberts, 2008; Krogh et al., 2011), and, if so, it was buoyantly extruded back up as one or more giant flakes, overriding the main Baltic craton. Regardless, the transport of the Trondheim nappe complex remains the same—the nappes were sheared and stretched, and their eastern component was carried passively upward and eastward as the Western Gneiss Complex rose out of the mantle. The hot, ductile, and possibly partially molten western extremity of the Western Gneiss Complex could have thickened and created an orogenic plateau, which might have provided the gravitational potential drive for extrusion through the crust and late (403–399 Ma), top-E motion (Terry et al., 2000; Hacker et al., 2010).

EXHUMATION OF THE WESTERN GNEISS COMPLEX AND LARGE-SCALE TRANSLATION OF THE JOTUN NAPPE COMPLEX

The model for the Jotun nappe complex differs in that the Seve Nappe and the Upper Allochthon are largely absent in the Faltingsgraben (probably eroded away). Instead, there is the large, crystalline, Jotun Nappe and other large, previously autochthonous slices of Baltica (the Jotun nappe complex) that had to be emplaced over the main part of the Baltic craton. A further complication is the existence of the lithologically identical Lindås Nappe (Fig. 2), which, unlike the Jotun nappe complex, contains eclogite-facies shear zones that formed at ca. 424–429 Ma (Bingen et al., 2004; Glodny et al., 2008), well before peak metamorphism in the Western Gneiss Complex but at the same time the Jotun nappe complex was thrust over the Baltic craton. Hence, the western Baltic craton was thrust, subducted, and exhumed in at least two stages: the first stage thrust part of Baltica (the future Jotun nappe complex) on

top of the future Western Gneiss Complex at the same time the western portion of Baltica subducted into the deep mantle, and the second phase translated the Jotun nappe complex passively eastward as the Western Gneiss Complex was exhumed.

The western edge of Baltica was in the mantle by 424–429 Ma (dated by the eclogites within the Lindås Nappe), while the Jotun Nappe, farther to the east, escaped significant subduction, and instead was thrust E/SE over the Baltic foreland (Fig. 4A) at approximately the same time (ca. 425 Ma; Fossen, 2000). These simultaneous processes required the development of a detachment (heavy dashed line in Fig. 4A) that cut structurally downward from the boundary between the subducted slab and the mantle wedge in its westernmost and deepest portion through the allochthonous cover and into the crystalline rocks of the Baltic Shield upward and eastward. This geometry created a flake above the detachment that was undergoing subduction in the west and generating a fold-and-thrust belt in the east. The geometry of this detachment differs significantly from that of the northern Western Gneiss Region (Fig. 3A) by cutting deeply into the crystalline Proterozoic shield. This incision allowed slivers or flakes of that shield, represented presently by the Lindås Nappe and the Jotun/Dalsfjord Nappe, to delaminate from the main slab and be exhumed, while simultaneously the main slab below the detachment (now the Western Gneiss Complex and its cover of allochthons) continued to subduct into the mantle (along the deeper dashed black line in Fig. 4B), as suggested by eclogite ages as young as 400–405 Ma (Griffin and Brueckner, 1980; Kylander-Clark et al., 2007).

The difference in metamorphic grade between the HP Lindås Nappe and the unmetamorphosed Dalsfjord Nappe requires the development of a second, higher detachment that soles into the basal detachment toward the west, but cuts eastward and upward through the overlying flake (Fig. 4A) to create two smaller slivers. These detached slivers of the Baltic crust continued to thrust over the Baltic shield (i.e., top-SE) between 425 and 405 Ma, in agreement with the stratigraphic, geochronologic, and structural evidence reviewed earlier herein. The exhumed allochthons on top of the Jotun nappe complex sliver were of lower metamorphic grade as a result of shallower subduction and are represented today by the weakly Caledonized coastal allochthons. Retrogression of the Lindås Nappe, the most deeply subducted (and eclogitized) portion of this sliver, is dated by amphibolites-facies assemblages at ca. 415 Ma (Glodny et al., 2008), recording exhumation and subsequent emplacement over the

rearmost portion of the Jotun nappe complex sliver (Fig. 4B). Even as these slivers exhumed, the main portion of the Baltic slab continued to subduct into the mantle, where it was metamorphosed to HP/UHP assemblages and collected peridotites from the mantle wedge. The Middle and Upper Allochthon, now exposed as enclaves at Tafjord, Nordfjord (Fig. 2), and elsewhere, remained attached to this slab (Fig. 4B) during this journey into the mantle and so also underwent HP/UHP metamorphism.

The remaining history of the Western Gneiss Complex and the Jotun nappe complex then followed essentially the pattern shown in Figure 1. The subducted Western Gneiss Complex reached its deepest level at ca. 405 Ma (Peterman et al., 2009). Its subsequent exhumation introduced a top-NW shear between the top of the main slab and the bottom of the previously exhumed flakes between 405 and 390 Ma (Fossen and Dunlap, 1998; Fossen, 2000), consistent with the beginning of Western Gneiss Complex exhumation. Shear resulted in a minimum displacement of 20–30 km (Fossen and Holst, 1995; Fossen, 2000) before causing the breakoff of part of the unmetamorphosed eastern edge of the upper sliver (dotted line in Fig. 4B), while the more metamorphosed western or tail end became stranded as it accreted to the base of the orogenic wedge in the hanging wall of the subduction zone. The detached leading fragment, now the Jotun nappe complex and underlying allochthons, was translated southeast as a passive passenger, requiring that the shear zone along its base (the Jotunheimen detachment zone) became inactive. However, top-NW shear continued to the west of the breakaway, resulting in the further evolution of the mode I Nordfjord-Sogn detachment zone surface, with its much thicker shear zone and proportionally higher displacement of 60–100 km (Norton, 1986; Fossen, 2000). It is possible that the displacements were much larger, since some strain rate calculations result in high, perhaps “unrealistically high,” displacement estimates when integrated for the entire thickness of the Nordfjord-Sogn detachment zone over million-year time scales (Johnston et al., 2007a). This displacement ultimately brought the HP/UHP rocks of the Western Gneiss Complex and its allochthons into contact with the lower-grade rocks of the stranded overlying allochthons (e.g., Young et al., 2007, 2011; Johnston et al., 2007a, 2007b), including the weakly Caledonized Dalsfjord Nappe (Andersen et al., 1990).

We show, again, final exhumation of the Western Gneiss Complex as the result of orogen-perpendicular extension (Fig. 4C), but the buoyant forceful intrusion or delamination/eduction model (Duretz, et al., 2012) works

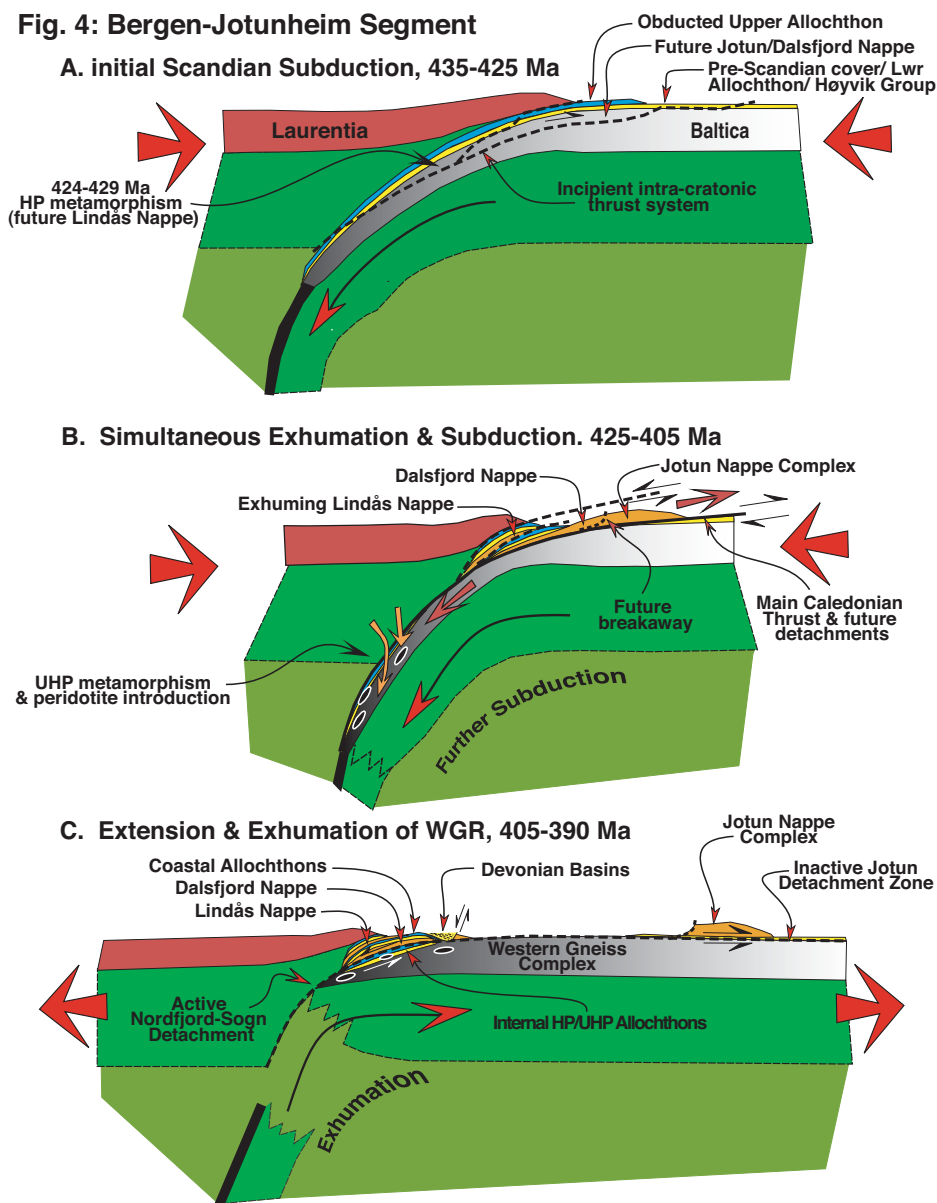
Fig. 4: Bergen-Jotunheim Segment


Figure 4. Conceptual exhumation and lateral translation model for the Jotun and Lindås Nappes roughly along C–D in Figure 2 (note offsets; not to scale). Units are colored as in Figures 2 and 3. The orogenic wedge is simplified so other aspects of the model can be illustrated (see Fig. 3A for details of the wedge). (A) Initial collision, subduction of Western Gneiss Complex and westernmost allochthons, and early eclogite-facies formation. Two detachment faults (dashed lines) cut down section into the basement from W to E to create two separate tectonic flakes; the more subducted flake will become the Lindås Nappe, and the weakly subducted flake will become the Jotun/Dalsfjord Nappe. (B) The Jotun/Dalsfjord Nappe and overlying easternmost allochthons extrude over the foreland, and the Lindås Nappe extrudes over the Dalsfjord/Jotun Nappe, while the underlying Western Gneiss Complex and westernmost allochthons continue subduction, high-pressure/ultrahigh-pressure (HP/UHP) metamorphism, and “downtrusion” of mantle fragments. (C) Exhumation of the Western Gneiss Complex and internal HP/UHP allochthons below the detachment, shearing and stretching of the coastal allochthons, including the Dalsfjord Nappe, above the detachment, and passive transport of the detached Jotun Nappe on the other side of the Western Gneiss Complex tectonic window (other Jotun nappe complex allochthons are not shown). WGR—Western Gneiss Region.

equally well and presumably must have operated during the simultaneous exhumation of the Lindås and Dalsfjord-Jotun slivers and the subduction of the Western Gneiss Complex (Fig. 4B). Overall, the exhumation of these tectonic units must have been a combination of extension and forceful intrusion. Certainly, extension was required later to develop mode II/II extensional shear zones (Fig. 2), which transect the whole crust in some cases (Fossen and Hurich, 2005), and which occur throughout much of the North Atlantic Caledonian system (Fossen, 2010).

DISCUSSION

We emphasize a reference frame where exhumation moved Baltica E/SE relative to the overlying orogenic wedge to create drag along the base of the overlying allochthons. Of course, this “bottom E/SE” motion is kinematically equivalent to the “top W/SW motion” discussed so frequently in the literature, but it is conceptually different in that it helps to visualize an upward and foreland-directed driving force to create the normal slip motions on the detachment zones, in contrast to frequently cited “orogenic collapse” and “backsliding” models,” which emphasize the W/SW movement of the wedge over Baltica. This traction set up the orogen-normal and roughly horizontal least principal stress axis (σ_3) in the wedge that ultimately caused it to rupture, so that a substantial portion of the wedge tip could be carried passively, “piggyback” style, by the continued foreland-directed underflow of the Baltic craton.

This reference frame makes it easier to conceptualize puzzling features of the Scandinavian Caledonides. One can visualize, for example, that the Devonian clastic basins (Hornelen, Håsteinen, Kvamshesten, and Solund) formed, initially, immediately adjacent to the Jotun nappe complex but remained in place within the hanging wall of the coastal allochthons and moved relatively southeastward on top of the exhuming Western Gneiss Complex footwall (Fig. 4C). This model is supported by the rutile clasts in the basins, which match nonmylonitic “coastal” Middle and Upper Allochthon sources, and not the Western Gneiss Complex (Cuthbert, 1991), and by the fact that Kvamshesten Basin rests positionally on the weakly Caledonized Dalsfjord Nappe, a direct correlative of the Jotun Nappe. Thus, the eastward movement of the exhuming Western Gneiss Complex carried the Jotun nappe complex from the basins rather than the westward movement of the basins from the nappe.

The breakaway resulted in the equivalent and initially continuous Jotun and Dalsfjord

Nappes ending up on opposite sides of the Western Gneiss Complex culmination, with the Dalsfjord Nappe resting on the eclogite-bearing western Western Gneiss Complex and the Jotun Nappe resting on the eastern Western Gneiss Complex with the weakest Scandian overprint. Both nappes were emplaced as a single unit over foreland basement rocks (Fig. 4A), and both segments either escaped subduction or were subducted to relatively shallow levels, particularly the western (Dalsfjord) segment (Fig. 4B). The subsequent exhumation of the Western Gneiss Complex broke off the Jotun Nappe from the Dalsfjord Nappe relatively early during exhumation, before it was brought into contact with Western Gneiss Complex footwall rocks with a strong Scandian HP/UHP overprint. Breaking away early would have resulted in no further slip between the nappe and the Western Gneiss Complex, explaining why the basal phyllites are only weakly metamorphosed and show only a relatively weak increase in metamorphic grade from SE to NW, and why the underlying Western Gneiss Complex and overlying nappe show little “Caledonization.” The Dalsfjord Nappe, in contrast, remained attached to the main body of the upper plate (the coastal allochthons), resulting in an enormous top-W slip between it and the Western Gneiss Complex and its juxtaposition with HP/UHP rocks.

The older age of eclogite-facies metamorphism of the Lindås Nappe relative to the Western Gneiss Complex is resolved if both terranes were initially subducted at the same time, but the detachment and exhumation of the Lindås Nappe from the rest of the Western Gneiss Complex occurred 10–15 m.y. earlier than the exhumation of the Western Gneiss Complex. Some Western Gneiss Complex eclogites and garnet pyroxenites give ages close to or even older than the ca. 425 Ma eclogites of the Lindås Nappe (Hacker et al., 2010; Spengler et al., 2009), suggesting eclogitization commenced in both complexes at roughly the same time and continued in the Western Gneiss Complex during further subduction, but ceased in the Lindås Nappe as it exhumed.

The Seve Nappe of the Trondheim nappe complex wedge was subducted to much deeper mantle levels than the Jotun nappe complex. Therefore, it and the underlying basement were strongly “Caledonized,” so that they became too hot and ductile to break off along discrete brittle structures during exhumation, but instead underwent distributed extension and thinning along mode I ductile shear zones. Ductile thinning during exhumation in turn provides an explanation for the hitherto puzzling geometry of Scandinavian nappes (particularly the Seve Nappe), which are thickest in the east and thin dramatically

toward the west (Andréasson, 1996; Rice, 1999). The most deeply subducted, and hence most ductile, portions of the nappes thinned the most during exhumation, whereas the cooler and less ductile eastern portions of the nappes underwent little or no thinning during transport on top of the exhuming Western Gneiss Complex.

It remains difficult to determine the relative contributions of lateral movement through thrusting during wedge construction versus passive transport during Western Gneiss Complex exhumation. A minimum estimate is provided by the difference in estimated shear displacements (reviewed in Fossen, 2000) between the eastern detachments below the Jotun nappe complex (~30 km) and the western detachments within and below the coastal allochthons (60–100 km). These differences, taken literally, indicate passive transport between 30 and 60 km, a significant percentage of the total 300 km inferred for the EWE translations of the Caledonian allochthons. A maximum estimate, based on palinspastic reconstructions (Rice, 2005) suggests that the Western Gneiss Complex moved laterally as much as 215–320 km. If so, passive transport of the overlying allochthons could have been even more substantial. However, these reconstructions assume that the allochthons maintained constant length during thrusting and that movement was contractural or extensional, but not both. The Scandinavian allochthons violate these assumptions, making most reconstructions maximum estimates, a problem that was acknowledged by Rice (2005).

CONCLUSION

Our premise is that far-traveled nappes are thrust tens to hundreds of kilometers over the foreland during the construction of an orogenic wedge, but that this wedge can also be stretched and disrupted, and the forward elements of the wedge can be carried passively even farther, perhaps much farther, by the exhumation of an underlying HP/UHP metamorphic-grade terrane of significant size. The critical evidence for this model will come from the detachments that occur beneath the coastal or western allochthons and from the Devonian basins that rest unconformably on them. Further structural studies should be carried out to determine whether later, steeper ductile shear zones sole into or crosscut the earlier, shallower ductile detachments. Provenance studies of the sediments in the basin should also help to resolve this issue, since uplift along steep, crosscutting structures would have exposed the Western Gneiss Complex in the footwall to erosion, in which case, clasts from the Western Gneiss Complex should be found within the sediments of these basins.

If, however, slip continued along the low-angle detachments, with the later, steeper detachments serving solely as breakaway structures, uplift of the Western Gneiss Complex is not required, and clasts from the Western Gneiss Complex would not be expected in the basins until very late in their evolution.

It is entirely possible that both geometries developed. Crosscutting mode II shear zones, as defined by Fossen (2000), do exist in the southernmost Caledonides, where the Hardangerfjord shear zone, the Bergen Arcs shear zone, and the Nordfjord-Sogn detachment zone south of the Solund Basin are mapped as penetrating undeformed basement (Fossen, 1992, 1993; Milnes et al., 1997; Wennberg et al., 1998; Fossen and Hurich, 2005). The question becomes one of how much exhumation-related top-W/NW slip occurred along mode I detachments before the mode II/III shear zones sliced up into the overlying allochthons and prevented further motion. Mode II/III displacement creates a growing NW-facing “step” in the surface of the lower plate, but it does not necessarily stop NW motion on the offset mode I detachment, at least initially, because the offset can be filled by ductile mobilization and folding of the mode I detachment, allowing slip to continue above (fig. 11 in Fossen and Hurich, 2005). So the existence of true mode II/III structures along the southern boundary between the Western Gneiss Complex and the coastal allochthons does not preclude the likelihood that significant exhumation of the Western Gneiss Complex occurred along the mode I detachment within the Nordfjord-Sogn detachment zone.

Nevertheless, it could be argued that the switch to mode II/III motion occurred significantly earlier in the south than it did along the Nordfjord-Sogn detachment zone to the north, which in turn suggests there was less exhumation of the Western Gneiss Complex in the south. This explanation could account for the narrowing of the Western Gneiss Complex window toward the south (Fig. 2), as well as the decrease in metamorphic grade of the Western Gneiss Complex from north to south. Locking slip in the south while exhumation continued in the north would also have resulted in a clockwise rotation of the Western Gneiss Complex as it exhumed out of the mantle, bounded to the north by the major left-lateral strike-slip Møre-Trøndelag shear zone (Fig. 2). This suggestion is similar in many respects to the transtensional models for the exhumation of the Western Gneiss Complex proposed by Krabbendam and Dewey (1998) and Osmundsen and Andersen (2001), which explain several features of the Western Gneiss Complex—among them the fanning of exhumation-related stretching lineations (Fig. 2), vertical

shortening of the Western Gneiss Complex, the N-S compression that led to the formation of very large-scale E-W-trending antiforms and synforms, and the development of Devonian Basins within the synforms along the west coast.

We conclude by emphasizing that the passive transport model is meant to augment the orogenic wedge model; it is not meant to supplant it. We think it may apply to other orogens as well. Many mountain belts develop ductile low-angle normal faults during orogeny, which are commonly attributed to the “collapse” of the overthickened orogen. The passive transport model offers another explanation for these structures and may be applicable to mountain systems where these detachments lie tectonically above large metamorphic terranes that exhumed from deep within the upper mantle.

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