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Ascent of the ultrahigh-pressure Western Gneiss Region, Norway

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ABSTRACT

Ca. 415–400 Ma ultrahigh-pressure (UHP) eclogites in the Western Gneiss Region of Norway occur in three discrete ~2500 km^2 to >100 km^2 antiformal domains separated by high-pressure rocks. Disparate eclogite ages suggest that the northern UHP domain and the two southern UHP domains are separate crustal blocks that experienced and were exhumed from UHP conditions at different times. The UHP rocks underwent isothermal decompression to <20 km depth in ~5 m.y., suggesting adiabatic exhumation of a >20–30 km thick UHP body. The UHP slab rose coherently from mantle to crustal depths and was exhumed through the crust progressively from east to west between 400 and 390 Ma.

Keywords: exhumation, ultrahigh pressure, Norway, coesite.

INTRODUCTION

One of the most provocative revelations of the post-plate-tectonic-discovery era is that continental crust was subducted to depths of >100 km and exhumed at numerous locations worldwide throughout the Phanerozoic (Ernst, 2001). The recent discovery of former majoritic garnet within crustal rocks in Rhodope (Mposkos and Kostopoulos, 2001) and the inferred decomposition of dolomite to aragonite + magnesite at Kokchetav (Zhu and Ogasawara, 2002) and in the Tian Shan (Zhang et al., 2003) (but see Klemd et al., 2003) require exhumation of bona fide continental crust from depths >150–250 km and further highlight the role of ultrahigh-pressure (UHP) processes in Earth evolution. It is now recognized that the formation and exhumation of UHP rocks is an inherent and fundamental dynamic aspect of collisional orogenesis that affects a panoply of Earth processes including, but not limited to, exchange of material between the crust and mantle, generation and collapse of mountain belts, formation of continental crust, and tectonic plate motions. In spite of the fact that UHP tectonics is a fundamental aspect of orogenesis, we understand it in only cursory fashion.

This paper uses recently acquired data to address two main questions. (1) Did the UHP Western Gneiss Region of Norway experience more than one UHP event and how long did the UHP metamorphism in toto last? (2) How were the UHP rocks exhumed?

To answer the first question, this paper examines the geochronologic record from the Western Gneiss Region. This question is significant because it is becoming clear that a typical orogenic belt experiences multiple (U)HP events. Consider four examples. (1) In the Alps, there were at least four stages of (U)HP metamorphism: Cretaceous in the Penninic unit of the eastern Alps, ca. 65 Ma in the Austro-Alpine units, ca. 44 Ma in the Lago di Cignana unit and the Monviso ophiolite, and ca. 35 Ma in the Dora Maira Massif (O'Brien, 2001; Compagnoni and Rolfo, 2003; Janak et al., 2004). (2) There are three known Cenozoic (U)HP occurrences around the Tibet-Pamir Plateau: 55–45 Ma in the Himalaya (Kohn and Parkinson, 2002), 15 Ma continental subduction of the southern margin of the Pamir Plateau (Searle et al., 2001; Hacker et al., 2005), and probable Eocene-Holocene intracontinental subduction along the northern margin of the Tibetan Plateau (Tapponnier et al., 2001). (3) The most recent UHP metamorphism in the Qinling-Dabie-Sulu orogen at ca. 230 Ma (Hacker and Wang, 1995; Hacker et al., 1998; Wan et al., 2005; Hacker et al., 2006) followed on the heels of a 400 Ma UHP event in the same orogen (Ratschbacher et al., 2003; Hacker et al., 2004). (4) The Scandinavian Caledonides

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experienced at least four (U)HP episodes within a 100 m.y. time span (Brueckner and van Roermund, 2004).

The existence of multiple UHP events in four of the best-known orogens suggests that repeated continental subduction is a fundamental process during collisional orogenesis. Some tectonic settings are more conducive to multiple (U)HP events—particularly those involving microcontinents or an oceanic upper plate. Figure 1 illustrates that UHP rocks can be created during (1) subduction of a microcontinent beneath an intraoceanic arc (e.g., the imminent subduction of eastern Sulawesi beneath the Molucca plate), (2) subduction of a continent beneath an intraoceanic arc (e.g., Australia-Timor), (3) subduction of a continent beneath a microcontinent (Taiwan), (4) subduction erosion (Miocene Pamir), (5) subduction of a microcontinent beneath a continent (Yakutat), (6) subduction of a continent beneath a continent (India-Asia), and (7) intracontinental shortening (Tibet). Each of these settings has a distinct style of tectonism, producing UHP terranes of different scales, different fluxes and compositions of associated magmas, and different styles of exhumation.

To answer the second question, this paper addresses (1) the structure and the scale of the UHP Western Gneiss Region terrane(s), (2) the rate of exhumation through the mantle and crust, (3) whether there was a pause at the Moho during exhumation, and (4) whether the UHP material rose as a slab or diapir through the mantle or the crust. The exhumation of UHP terranes can in principle be quite variable, depending on whether the UHP material is a microcontinent (Fig. 2A) or continent (Fig. 2B), whether the upper plate is continental or oceanic (Fig. 2C), and whether the downgoing plate fails at deeper (Fig. 2B) or shallower (Fig. 2D) levels than the UHP crust. In Figure 2A, detachment of the UHP crust from a microcontinent increases the negative buoyancy of the downgoing plate, leading to rollback and opening of a "gap" between the plates through which the UHP crust can rise. In Figure 2B, tearing of the downgoing plate beneath the rising UHP crust causes the lower plate to rebound, trapping the UHP crust at the Moho; melting occurs along the edges of the torn subcontinental mantle lithosphere. In Figure 2C, the high density of the oceanic upper

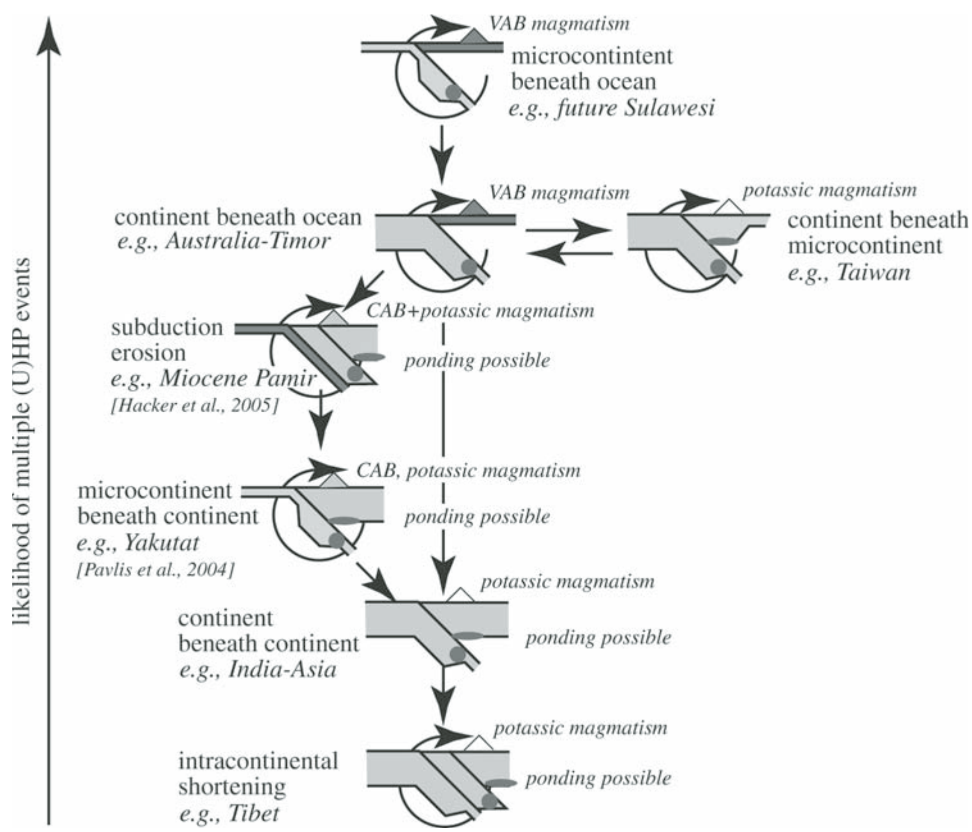

Figure 1. UHP rocks may form in a wide variety of tectonic settings. The evolution of a typical orogenic belt may involve a sequence of these settings (shown by straight arrows) or repetition of an individual setting (shown by circular arrows) such that multiple UHP events are expected in a typical orogen. The flux and compositions of magmas formed in each setting are a function of subduction rate and the compositions of the upper and lower plates (i.e., whether they are oceanic or continental). VAB—volcanic arc basalt; CAB—continental arc basalt. Ponding of the UHP slab at the Moho is possible where the upper plate is continental, whereas rise of the UHP slab to Earth's surface by buoyancy is possible where the upper plate is oceanic.

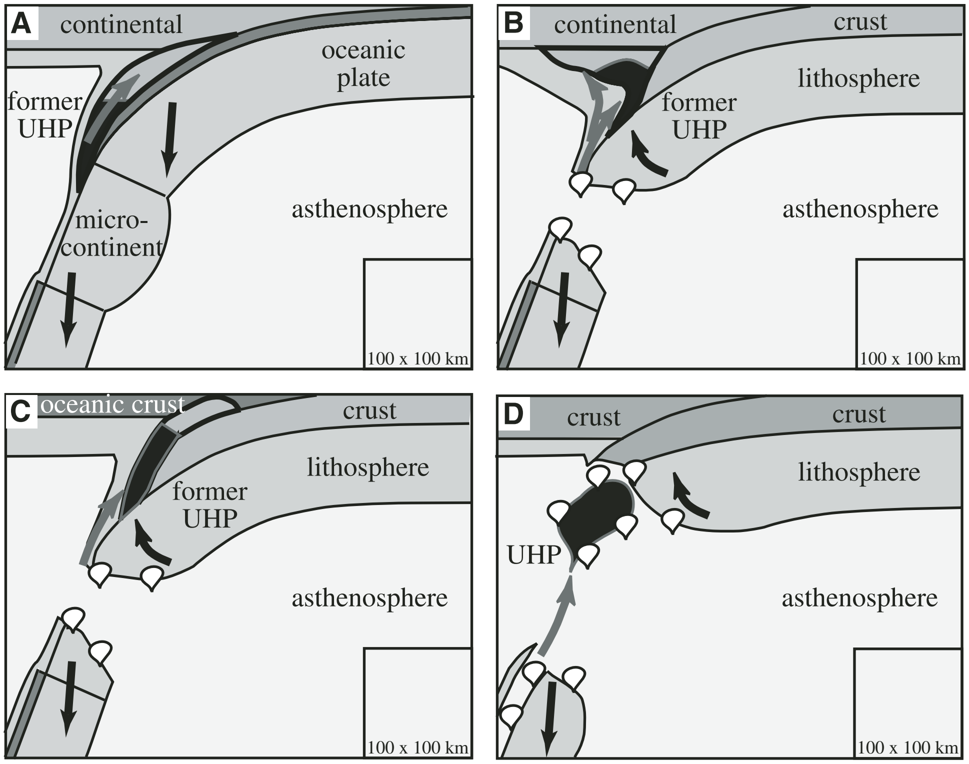

Figure 2. A sampling of the possible range of exhumation modes. (A) Subducted UHP microcontinental crust tears loose from downgoing, largely oceanic lithosphere; no slab failure. (B) UHP continental crust tears loose from subducted continental margin before failure of subducted lithosphere; UHP rocks pond at Moho. (C) UHP continental crust tears loose from subducted continental margin before failure of subducted lithosphere; UHP rocks bypass Moho and rise buoyantly through oceanic upper plate. (D) UHP continental crust tears loose from subducted continental margin after failure of subducted lithosphere; ponding at the Moho is expected (Cloos et al., 2006).

plate allows the UHP crust to rise buoyantly to the surface. In Figure 2D, tearing of the downgoing plate above the UHP crust necessitates diapiric rise of the UHP crust through the asthenosphere and entrapment of the UHP crust at the Moho; melting occurs along the perimeter of the UHP diapir as well as along the edges of the torn subcontinental mantle lithosphere.

INTRODUCTION TO THE SCANDINAVIAN CALEDONIDES

The Scandinavian Caledonides formed from ca. 500 to 350 Ma through a series of collisional events—including the emplacement of multiple ophiolites, and the Laurentia-Baltica collision—separated by intervening extensional phases (Roberts, 2003; Hacker and Gans, 2005); there were at least four (U)HP events (Brueckner and van Roermund, 2004). The orogen consists of a stack of allochthons or nappes that were emplaced onto the Baltica margin *chiefly* from ca. 435 Ma to ca. 395 Ma during the Scandian orogeny (Fig. 3). The *Uppermost Allochthon* (exposed north of Fig. 3) is inferred to represent part of the Laurentian continent. The *Upper Allochthon* includes oceanic nappes and continental nappes of Baltican affinity; whether the continental nappes were microcontinents or outboard parts of Baltica is unknown. The *Middle Allochthon*, also of Baltican continental affinity, shares this ambiguity. The *Lower Allochthon* includes Baltican sedimentary and crystalline rocks.

These unit subdivisions are relatively clear in the less deformed and less metamorphosed eastern foreland of the orogen. In the core of the orogen, however, these simple subdivisions break down because of strong deformation and high-temperature metamorphism. It is here that one of Earth's great concentrations of UHP coesite- and diamond-bearing eclogites and garnet peridotites is exposed. These eclogites (Cuthbert et al., 2000) and high-pressure metasedimentary rocks (Hacker et al., 2003) occur in many different units: (1) Baltican crystalline rock, (2) structurally overlying metasedimentary rocks interpreted as Baltican cover sediments (e.g., in the Nordfjord and Solund areas), (3) crystalline Middle Allochthon rocks (e.g., in the Lindås Nappe of the Bergen area, south of Fig. 3), (4) metasedimentary rocks interpreted as Middle Allochthon cover (e.g., Ottadalen-Romsdalen and Hornelen areas), and (5) mafic igneous and metasedimentary rocks interpreted as Upper Allochthon (e.g.,

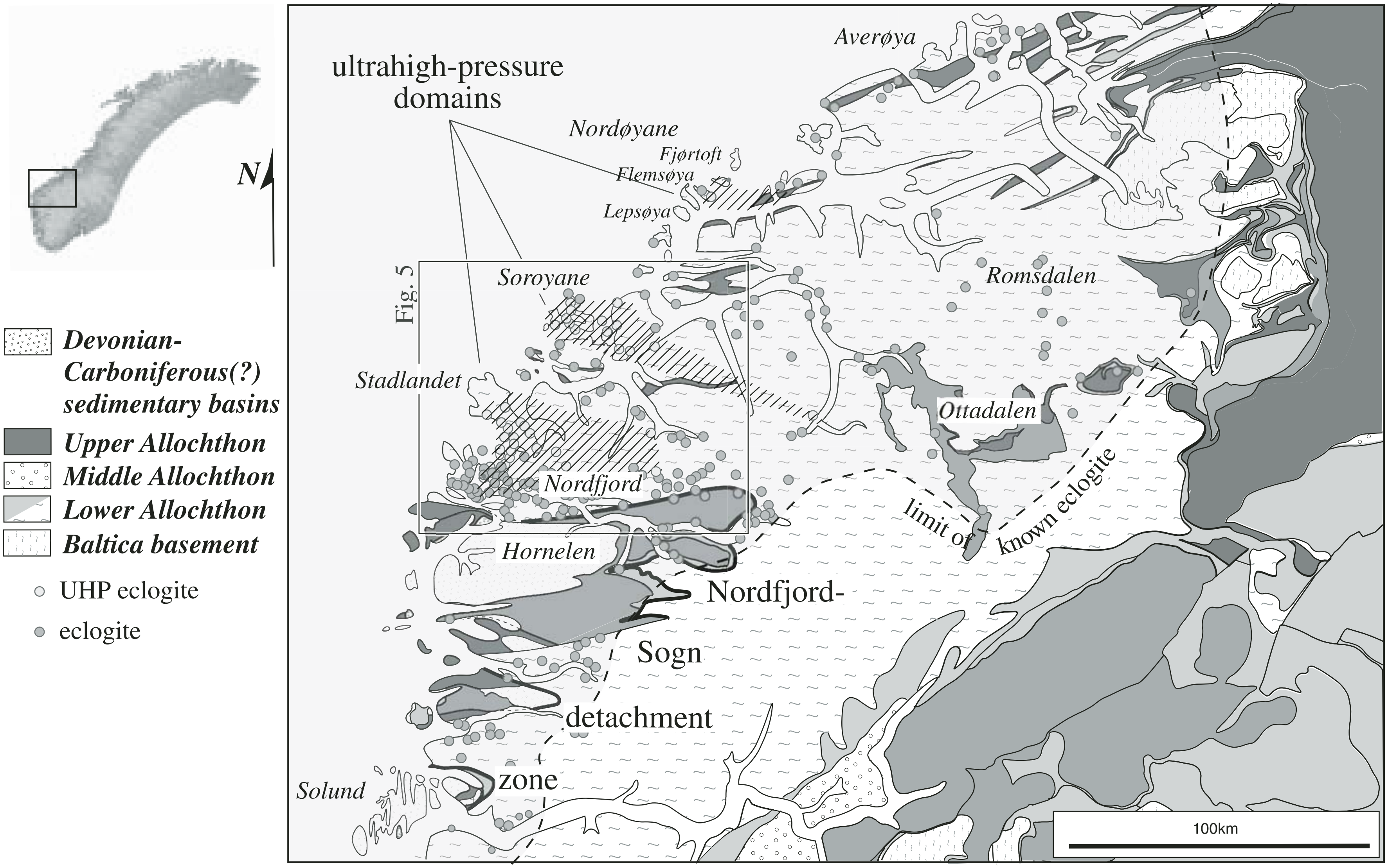

Figure 3. Western Gneiss Region of Norway. Crystalline rocks of Baltican affinity are overlain by a sequence of allochthons. HP rocks are restricted to the western half of the Western Gneiss Region, and UHP rocks are restricted to three domains along the coast (rectangle). All unit contacts are faults except for the depositional base of the sedimentary basins.

Nordøyane, Soroyane, Ottadalen, and Romsdalen). Some of these eclogites have been proven to have recrystallized during the Scandian orogeny, whereas the bulk of the eclogites, which are undated, are generally assumed to have formed at the same time. Eclogite-facies pressures and temperatures range from ~2.0 GPa and 400 °C to ~3.5 GPa and 800 °C (Cuthbert et al., 2000; Terry et al., 2000b; Hacker et al., 2003; Labrousse et al., 2004; Ravna and Terry, 2004; Walsh and Hacker, 2004).

STRUCTURE AND SCALE OF THE WESTERN GNEISS REGION UHP TERRANE

That UHP terranes comprise thin slices sandwiched between lower-pressure terranes is in danger of becoming a paradigm (e.g., Ernst, 1999), in spite of only local field evidence supporting this interpretation. Only two of the giant UHP massifs are well known: The UHP rocks of the Kokchetav Massif are exposed within a thin, 1–2 km thick unit (Kaneko et al., 2000), whereas those of the Dabie-Hong'an block have been interpreted to be >10 km thick (Hacker et al., 2000b). How thick are the UHP rocks of the Western Gneiss Region? Do the UHP rocks overlie lower-pressure rocks (Fig. 4)? Is the UHP-HP inverted sequence rooted or rootless? Are the UHP rocks overlain by lower-pressure rocks? Are they part of an upright sequence of rocks with downward-increasing pressures? Discovering which of these possibilities is correct is a prerequisite to understanding the genesis and exhumation of the UHP rocks. This and following sections present data that show that the Western Gneiss Region UHP rocks are part of a rooted upright sequence.

New mapping and eclogite petrology in the Western Gneiss Region reveal three distinct UHP domains clearly separated by areas of HP rocks (Figs. 3 and 5). My experience is limited to the two southern domains, which are defined by the presence or absence of coesite and by pressures and temperatures calculated from mineral compositions (Walsh and Hacker, 2004; Root et al., 2005; Young et al., 2007). The data set is incomplete, such that the shapes of the domains will surely change as more data become available. The two southern domains are ~2500 km^2 and 1000 km^2. Detailed mapping and petrology in the Nordfjord area show that the Nordfjord-Stadlandet UHP domain lies *beneath* surrounding HP rocks (Young et al., 2007); field relations in the Soroyane domain are consistent with this configuration (Root et al., 2005).

This structural relationship is corroborated by muscovite $^{40}Ar/^{39}Ar$ ages shown in Figure 6 (see references in figure caption). The extant data set shows that the UHP domains have the youngest $^{40}Ar/^{39}Ar$ muscovite ages in the Western Gneiss Region (390–375 Ma) and that the intervening HP domains have slightly older ages (395–385 Ma). This age difference and geometry require that the UHP domains are antiformal culminations that are younger than the youngest muscovite $^{40}Ar/^{39}Ar$ ages, i.e., younger than 375 Ma. This age is much younger than the UHP metamorphism (see below), requiring that the presence of these domains and their shapes were caused by folding much younger than, and unrelated to, the UHP metamorphism. The axes of the UHP culminations parallel the axes of the folds in the allochthons to the south, but they plunge eastward, rather than westward (Figs. 6 and 7). The absence of any other evidence for these antiforms makes their shapes difficult to assess, but outcrop relations and topography suggest that they are subdued, with wavelengths of 30–50 km and amplitudes of 1–2 km (Root et al., 2005). If the UHP terrane is continuous at depth between the antiformal culminations, it measures >11,000 km^2 and is overlain by a HP veneer that is >60,000 km^2.

TIMING OF UHP EVENTS

What was the duration of the Scandian UHP event and was there more than one event? Eclogites in all three domains reached similar pressures and temperatures, so petrology sheds

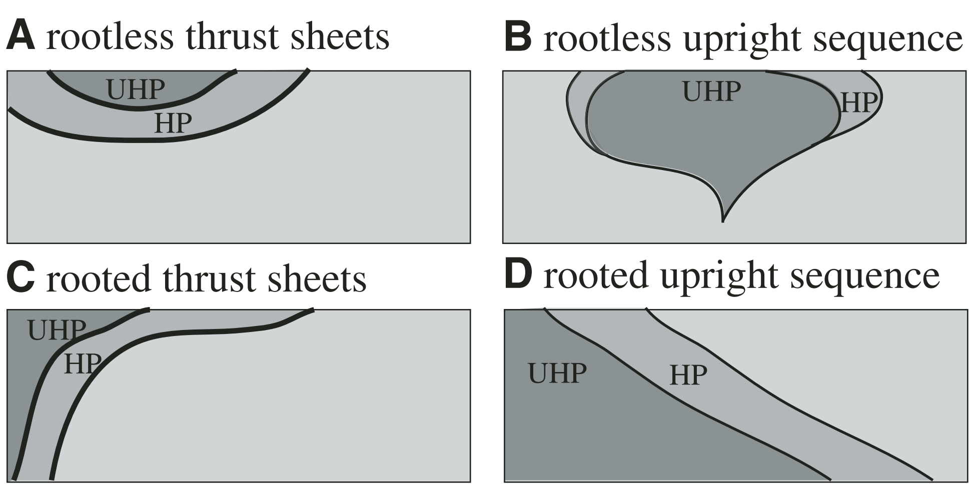

Figure 4. Possible outcrop relationships among UHP, HP, and surrounding lower-pressure rocks in an orogenic belt.

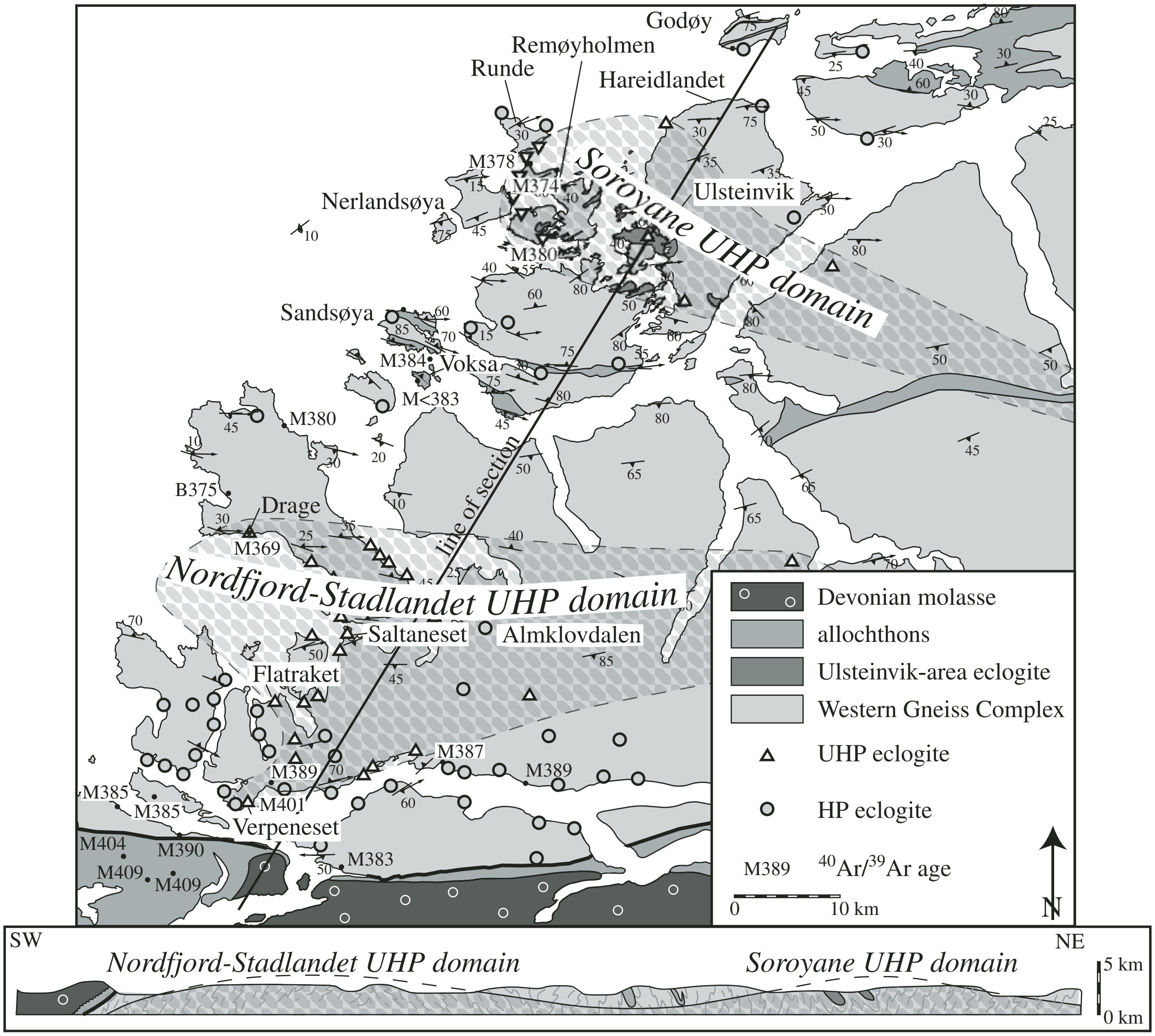

Figure 5. Nordfjord-Stadlandet and Soroyane UHP domains consist of dominantly UHP eclogites and are surrounded by areas of HP eclogites (after Root et al., 2005).

no light on this issue. A modest number of the Western Gneiss Region eclogites have been dated, principally by Sm/Nd and U/Pb (Figs. 6 and 8). Detailed chemical abrasion thermal ionization mass spectrometry (TIMS) dating of Flatraket eclogite zircons with depleted HREE (heavy rare earth element) patterns indicates recrystallization at 405–400 Ma; zircons from three other eclogites (Verpeneset, Otnheim, and Langenes) in the Nordfjord-Stadlandet and Soroyane domains yield less comprehensive data that are nevertheless compatible with this interpretation (Root et al., 2004). Two single zircons from a Bjørkedalen eclogite gave a concordia age of 405 ± 2 Ma (all quoted uncertainties are 2σ; Young et al., 2007), and the Ulsteinvik eclogite gave a multizircon TIMS ^{207}Pb/^{206}Pb age of 401.6 ± 1.6 Ma (Tucker et al., 2004). Two multipoint (garnet–clinopyroxene–whole rock) Sm/Nd eclogite ages from the Nordfjord-Stadlandet domain of 408.3 ± 6.7 Ma (Saltaneset; Carswell et al., 2003) and 408 ± 6 Ma (Almklovdalen; Mearns, 1986) overlap the zircon ages of 405–400 Ma.

These ages are younger than those from the Nordøyane UHP domain 100 km to the north, where Krogh et al. (2004) reported a ^{206}Pb/^{238}U zircon age of 415 ± 1 Ma from an Averøya eclogite, two 410 ± 1 Ma and 408 ± 1 Ma fractions from Flemsøya, and two fractions at 411.5 ± 1.2 Ma from Lepsøya, Terry et al. (2000a) reported a monazite ^{206}Pb/^{238}U secondary ion mass spectrometry (SIMS) age of 415 ± 6.8 Ma from Fjørtoft, and Mørk and Mearns (1986) reported a low-MSWD (mean square of weighted deviates), multipoint (garnet–clinopyroxene–whole rock) Sm/Nd age from Flemsøya of 410 ± 16 Ma. No

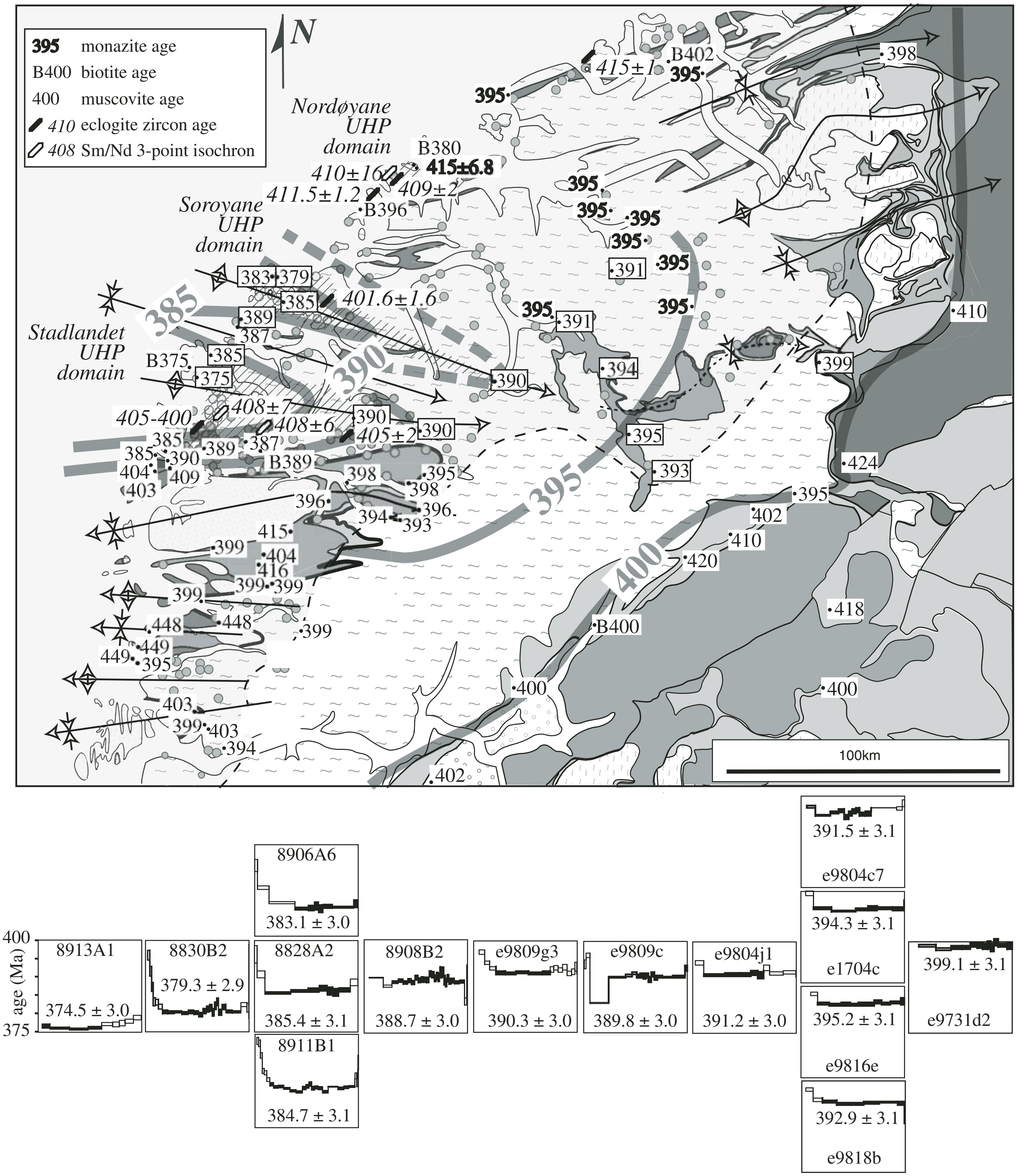

Figure 6. Geochronologic data set (Lux, 1985; Chauvet and Dallmeyer, 1992; Andersen et al., 1998; Fossen and Dunlap, 1998; Hacker and Gans, 2005; Root et al., 2005; Walsh et al., 2007; Young et al., 2007) for the Western Gneiss Region, focusing on high-precision ages. Contours of muscovite $^{40}Ar/^{39}Ar$ ages are shown by heavy lines labeled in Ma. Muscovite $^{40}Ar/^{39}Ar$ spectra at bottom represent a transect across the entire Western Gneiss Region and correspond to ages on map enclosed in rectangles.

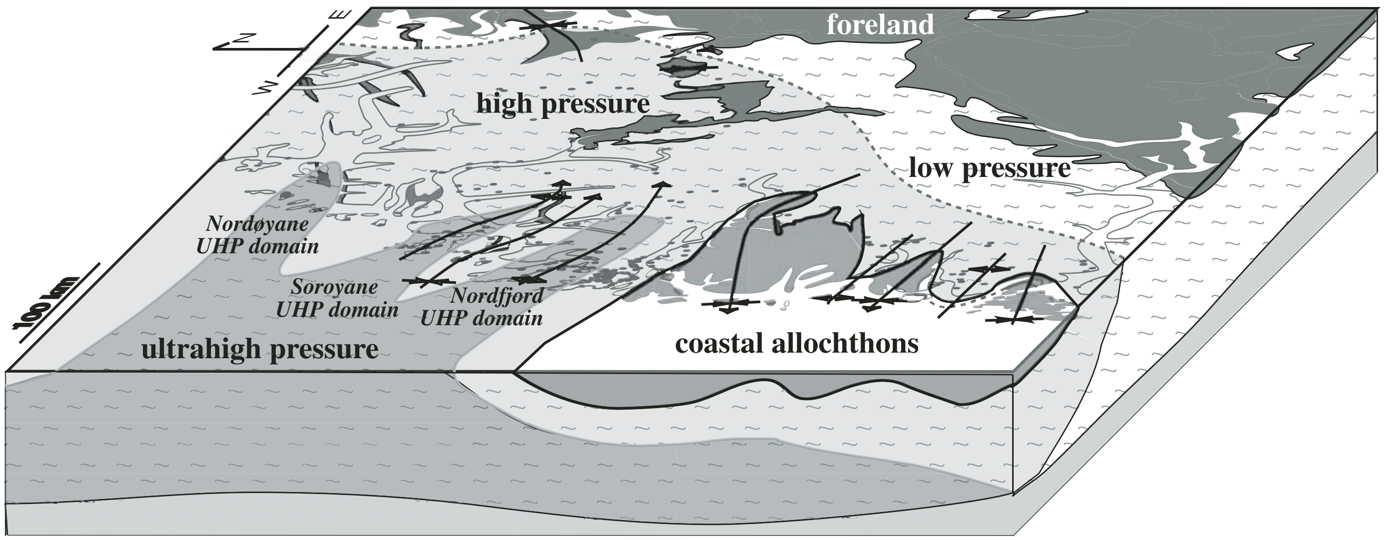

Figure 7. Block diagram of the Western Gneiss Region, looking eastward from the hinterland to the foreland, showing the E-plunging UHP antiformal domains beneath the HP veneer overlain by coastal allochthons exposed in W-plunging synforms.

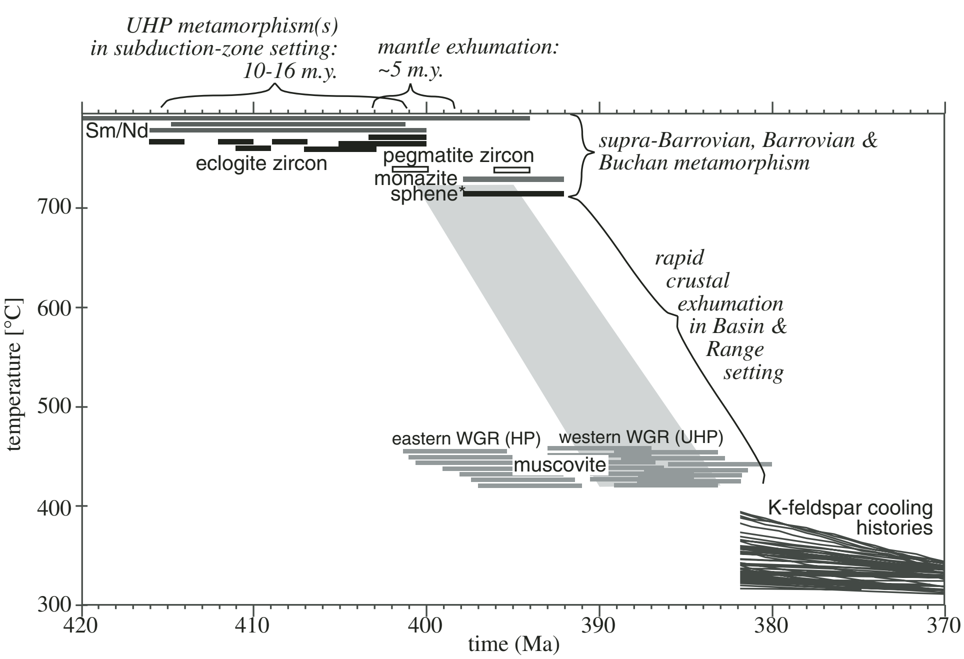

Figure 8. Geochronology summary (Griffin and Brueckner, 1985; Mearns, 1986; Mørk and Mearns, 1986; Tucker et al., 1990, 2004; Andersen et al., 1998; Terry et al., 2000a; Austrheim et al., 2003; Carswell et al., 2003; Krogh et al., 2004; Root et al., 2005; Walsh et al., 2007; Young et al., 2007) shows 10–15 m.y. of eclogite ages followed by a 5 m.y. window during which the UHP rocks were exhumed through the mantle and into the middle crust, followed by a slower period of crustal exhumation in a Basin and Range–type setting. WGR—Western Gneiss Region.

other eclogites in the Western Gneiss Region have been dated using precise, modern U/Pb techniques, although a few along the eastern half of the Western Gneiss Region have been dated in reconnaissance with SIMS and laser-ablation multicollector inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) as 440–400 Ma (Walsh et al., 2007).

This data set permits either a single eclogite-facies metamorphism that lasted 15 m.y. or two separate eclogite-facies events—the first in the Nordøyane domain at 415–410 Ma and the second in the Nordfjord-Stadlandet and Soroyane domains at 405–400 Ma. A single 15 m.y. long event in a single piece of crust is implausible for a *subducting* slab: For the slab to remain in the eclogite stability field between ~60 and 130 km depth for 15 m.y. requires an impossibly slow subduction rate of <10 mm/yr for a slab dipping ≥30°. Either a subducted piece of crust was sequestered at depth and refrigerated by ongoing deeper subduction for 15 m.y. (Hacker and Peacock, 1995) or there were two UHP "events"—i.e., the northern domain and the two southern domains are separate crustal blocks that experienced and were exhumed from UHP conditions at different times, possibly in the same subduction zone.

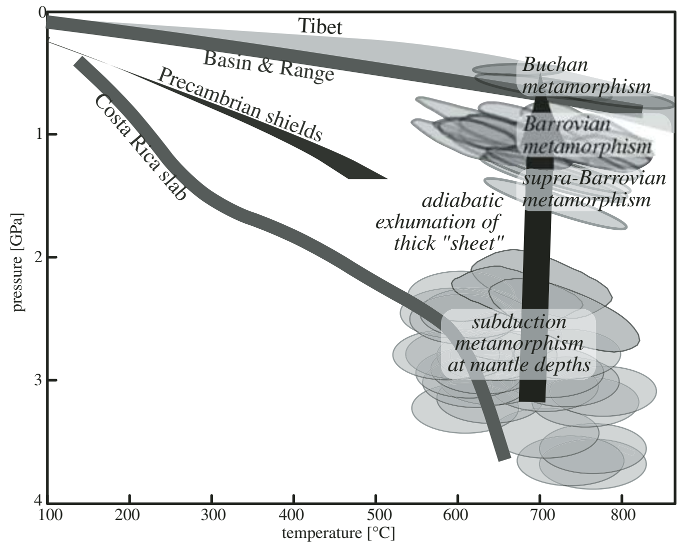

Figure 9. *P-T* history of the Western Gneiss Region. Eclogite-facies, subduction-zone-type conditions were succeeded by recrystallization at successively lower pressures but the same temperature (Cuthbert et al., 2000; Terry et al., 2000b; Hacker et al., 2003; Ravna and Terry, 2004; Walsh and Hacker, 2004; Root et al., 2005; Young, 2005), eventually reaching *P-T* conditions similar to the Basin and Range province (Lachenbruch, 1978) or the Tibetan Plateau (Hacker et al., 2000a).

TRANS-MANTLE EXHUMATION

How were the UHP rocks exhumed through the mantle? Did the subducting slab tear or "break off" above UHP depths, such that the UHP rocks then rose diapirically through the mantle (Fig. 2D) (Cloos et al., 2006)? Or did the UHP crust delaminate from the downgoing plate and rise as a coherent sheet (Figs. 2A and 2C)? Or did the subducting lithosphere simply reverse direction, remaining intact during exhumation? Important information for addressing these questions could come from knowing the local tectonic plate configuration prior to or during the UHP event. The Scandian orogeny began at ca. 435 Ma with contractional imbrication of the entire Uppermost Allochthon–Upper Allochthon–Middle Allochthon–Lower Allochthon nappe stack; it reached its easternmost thermal influence on the Baltica margin ca. 420 Ma (Hacker and Gans, 2005). UHP metamorphism began 5 m.y. later. Unfortunately, it is unclear whether the Middle Allochthon was derived from the outermost margin of Baltica or was a microcontinent separated from Baltica by an intervening ocean. In the latter case, the marginal oceanic lithosphere could have pulled Baltica to UHP depths. In the former case, there is no clear tectonic reason why the Baltican continental crust should have descended so far into the mantle after its margin (the Middle Allochthon) was thrust on top of it (Hacker and Gans, 2005).

Although tectonic reconstructions fail to shed light on this issue, the *P-T* history of the UHP rocks places important constraints on the exhumation process (Figs. 8 and 9). The UHP conditions of 2.0 GPa and 450 °C to 3.5 GPa and 800 °C (Cuthbert et al., 2000; Terry et al., 2000b; Ravna and Terry, 2004) are characteristic of a subduction zone—though not a particularly cold subduction zone. This was followed by "supra-Barrovian" amphibolite-facies metamorphism at 1.7–1.0 GPa, Barrovian amphibolite-facies metamorphism, and then Buchan amphibolite-facies metamorphism at 0.5 GPa (Hacker et al., 2003; Labrousse et al., 2004; Walsh and Hacker, 2004; Root et al., 2005). The most important aspect of this decompression sequence is that relatively high temperatures of 650–750 °C were maintained throughout—in other words, from 130 km depth in the mantle to 20 km depth in the crust the exhumation was near-isothermal, and potentially adiabatic. The UHP rocks either (1) rose (at any rate) through a medium that had a temperature of ~700 °C, (2) rose so rapidly through a medium of any temperature that conductive heat loss was minimal, or (3) were part of a body large enough that conductive cooling was minimal in the interior.

Quantification of the rate of decompression (Fig. 8) comes from the 405–400 Ma eclogite ages mentioned above, U/Pb zircon ages of 395 ± 1 Ma on several amphibolite-facies pegmatites (Krogh et al., 2004), U/Pb sphene ages of 395 ± 2 Ma on amphibolite-facies rocks (Tucker et al., 2004), Rb/Sr mineral isochrons (Griffin and Brueckner, 1985), and muscovite $^{40}Ar/^{39}Ar$ ages of 389 ± 3 Ma discussed below. These data reveal that the UHP rocks went from 130 km depth in a subduction zone to *P-T* conditions characteristic of the Basin and Range province or Tibetan Plateau between ca. 400 Ma and 395 Ma—i.e., within ~5 m.y. (Figs. 8 and 9). The characteristic thermal diffusion distance of 10–15 km for 5 m.y. (Carslaw and Jaeger, 1959) implies that the decompressing UHP body had a half dimension of this size or greater. Two-dimensional transient thermal models confirm this (Root et al., 2005). Models for a 10 m.y. rise time show that the UHP body must have been at least 30–40 km in its minimum dimension. A smaller body cannot have survived a 10 m.y. ascent without heating above 800 °C or cooling below 600 °C, neither of which is seen in the rocks.

Semiquantitative information regarding the internal deformation of the UHP body can be gleaned from the regional distribution of rock types within the Western Gneiss Region. Specifically, the nappes that were emplaced onto Baltica during earlier orogenic stages were subsequently subducted, at least locally, to UHP depths along with the Baltica basement (Terry et al., 2000b; Root et al., 2005). The shapes and contacts of these nappes can thus be used as qualitative displacement gradient markers. Cross sections drawn at a range of scales across the Western Gneiss Region all show that the nappe tectonostratigraphy has been strongly deformed into multiple-kilometer-scale recumbent folds with local very high strains (e.g., Hernes, 1956; Krill, 1980; Rickard, 1985; Robinson, 1995; Tveten et al., 1998; Labrousse et al., 2002; Terry and Robinson, 2004). The cross sections *do not* show equivalent recumbent folds within the Baltican crystalline rocks of the Western Gneiss Region—though this may simply reflect the lack of displacement markers. Significantly, however, the contact between the Western Gneiss Region crystalline rocks and the nappes is generally inferred to be upright, with only local overturning, and is nowhere drawn as a recumbent fold with the Western Gneiss Region crystalline rocks overlying the nappes. The generally upright folds of this contact have amplitudes on the order of a few kilometers. Moreover, the Western Gneiss Region does not include blocks that are demonstrably exotic to the overlying nappe tectonostratigraphy. Peridotite bodies within the Western Gneiss Region are the most probable candidates for exotic introduction into the Baltican gneisses because of their great density. All the structures discussed in this paragraph indicate that during (or before) ascent the UHP body was rumpled into kilometer-scale folds but was not disaggregated and maintained its inferior position to the nappe stack.

In summary, the UHP body (1) rose through the mantle without losing or gaining significant heat, (2) had a minimum dimension of 10–15 km, and (3) was warped into folds with amplitudes that are a few percent of its total width. These conclusions favor exhumation of a contorting, but coherent, UHP slab and do not favor diapiric rise through the mantle.

MOHO ARREST?

Were the UHP rocks arrested when they reached the Moho because of a loss of buoyancy (Fig. 2B) (Walsh and Hacker, 2004) or did they move past the Moho without an interruption (Figs. 2A and 2C)? The UHP crust was buoyant with respect to the surrounding mantle at UHP conditions because mafic and ultramafic rocks constitute only a few volume percent of a dominantly quartzofeldspathic host gneiss UHP terrane: Walsh and Hacker (2004) calculated that relative to the mantle, the UHP crust had a net buoyancy of 0.1–0.3 g/cm^3 regardless of whether the crust had transformed partially or completely to UHP minerals. The UHP crust was, however, *not* buoyant with respect to average continental crust once it reached the Moho, regardless of the transformation state of the host gneiss: Walsh and Hacker (2004) calculated that at Moho conditions (1.1 GPa and 700 °C) the UHP terrane had a density similar to or slightly greater than average middle to lower continental crust (Rudnick and Fountain, 1995). On this basis, Walsh and Hacker suggested that the upward flight of the exhuming UHP terrane may have been arrested at the Moho, where it would have undergone large-scale buoyancy-driven flattening and density-driven mixing. Here we examine the potential impacts of such processes: First, analytical models of channel flow ignoring flexural rigidity (Bird, 1991) suggest that under such conditions a 20 km thick UHP terrane with effective viscosities in the 10^{17}–10^{19} Pa·s range (reasonable numbers from Wdowinski and Axen, 1992; Kruse and Stünitz, 1999; Beaumont et al., 2001) would have been thinned to a few km in 1–5 m.y. Such large strains contrast with the two to three times thinning inferred by Young et al. (2007) based on field studies in the Nordfjord area. Second, simple Stokes' law–based calculations imply that at these viscosities, 1 km radius eclogite bodies differing in density from the host gneiss by 0.5 kg m^3 could have sunk within the host gneiss as fast as 1–100 km/m.y. Such rapid rates of sinking are not supported by field observations: The kilometer-scale Ulsteinvik eclogite body, for example, is wrapped in a sheath of locally derived paragneiss (Mysen and Heier, 1972). The discrepancies in anticipated and observed flattening magnitude and sinking magnitude suggest either that the UHP terrane was more viscous when it ponded at the Moho or that it did not pond at the Moho.

TRANS-CRUSTAL EXHUMATION

How were the UHP rocks exhumed through the crust? Was exhumation driven by gravitational potential energy gradients from surface or Moho topography (Fig. 10A) or by an upward push from a longer or wider UHP slab still in the mantle (Fig. 10B)? Was exhumation accomplished by contraction, extension, or erosion?

New structural geology, thermobarometry, and $^{40}Ar/^{39}Ar$ geochronology show that the Nordfjord area preserves an uninterrupted, gradational transition from high-pressure amphibolite (~1.5 GPa) through quartz eclogite to coesite eclogite (~3.3 GPa) (Young et al., 2007). This gradient is of major importance because it requires that the UHP part of the slab remained attached to its low-pressure, updip portion during exhumation. Moreover, the absence of any major structural discontinuity within the non-eclogite-facies part of the Western Gneiss Region suggests either that the entire Western Gneiss Region is allochthonous and was emplaced onto the Baltica basement as a single unit or that the Western Gneiss Region is autochthonous Baltica basement that was subducted and exhumed en masse.

The final amphibolite-facies overprint of 0.5 GPa and 700 °C recorded across the Western Gneiss Region mandates a thermal setting identical to the modern Basin and Range province (Lachenbruch, 1978) or the Tibetan Plateau (Hacker et al., 2000a) (Fig. 9).

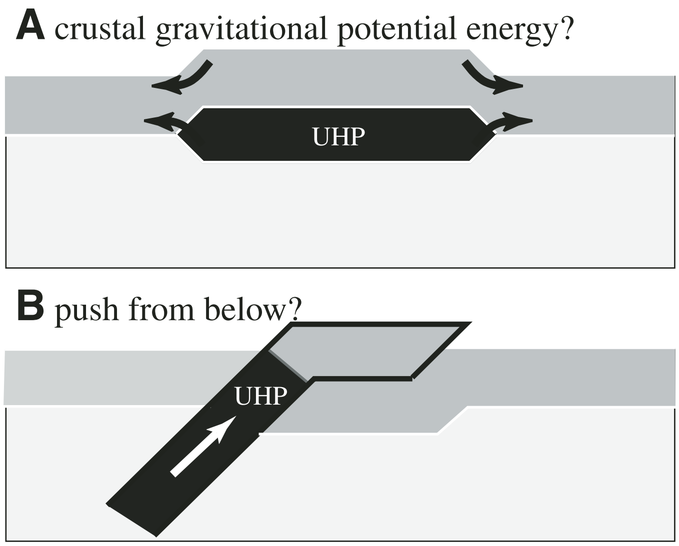

Figure 10. (A) Arrival of a hot body of UHP material at the Moho would have doubled crustal thickness and produced steep gravitational potential energy gradients from surface topography and Moho topography that could have driven crustal extension and exhumation of the UHP rocks through the crust. (B) If the UHP rocks were the uppermost tip of a more deeply subducted segment of crust, the buoyancy of the sub-Moho column could have driven exhumation of the UHP rocks through the crust in combination with shallow extension, contraction, or erosion.

Both of these modern settings are sites of rapid, large-scale upper crustal extension where mid-crustal rocks have been unroofed (Anderson, 1988; Harrison et al., 1995), implying that crustal exhumation of the Western Gneiss Region UHP rocks was accomplished or accompanied by similar processes. Because the bulk of the crustal deformation in the Western Gneiss Region occurred at amphibolite-facies conditions, $^{40}Ar/^{39}Ar$ ages on low-Si K-white micas (i.e., muscovites) provide a solid younger limit to the age of this deformation. These $^{40}Ar/^{39}Ar$ muscovite ages (Chauvet and Dallmeyer, 1992; Dallmeyer et al., 1992; Root et al., 2005; Walsh et al., 2007; Young et al., 2007) show a consistent decrease from 399 Ma at the eastern edge of the Western Gneiss Region to 390 Ma in the HP areas at the western edge of the Western Gneiss Region (Fig. 6); ages are even younger in the UHP domains, but these are the result of post-375 Ma folding (see above). This 399 Ma to 390 Ma age gradient straddles the 395 Ma age inferred for amphibolite-facies sphene and zircon grains throughout much of the Western Gneiss Region (Tucker et al., 2004).

In combination with the eclogite ages discuwssed above, these data sets require that at 400–399 Ma the easternmost Western Gneiss Region had cooled to <400 °C at a time when eclogite-facies metamorphism in the westernmost Western Gneiss Region was just ending (Fig. 11A). By 390 Ma the entire Western Gneiss Region (except for the UHP domains) had cooled below 400 °C

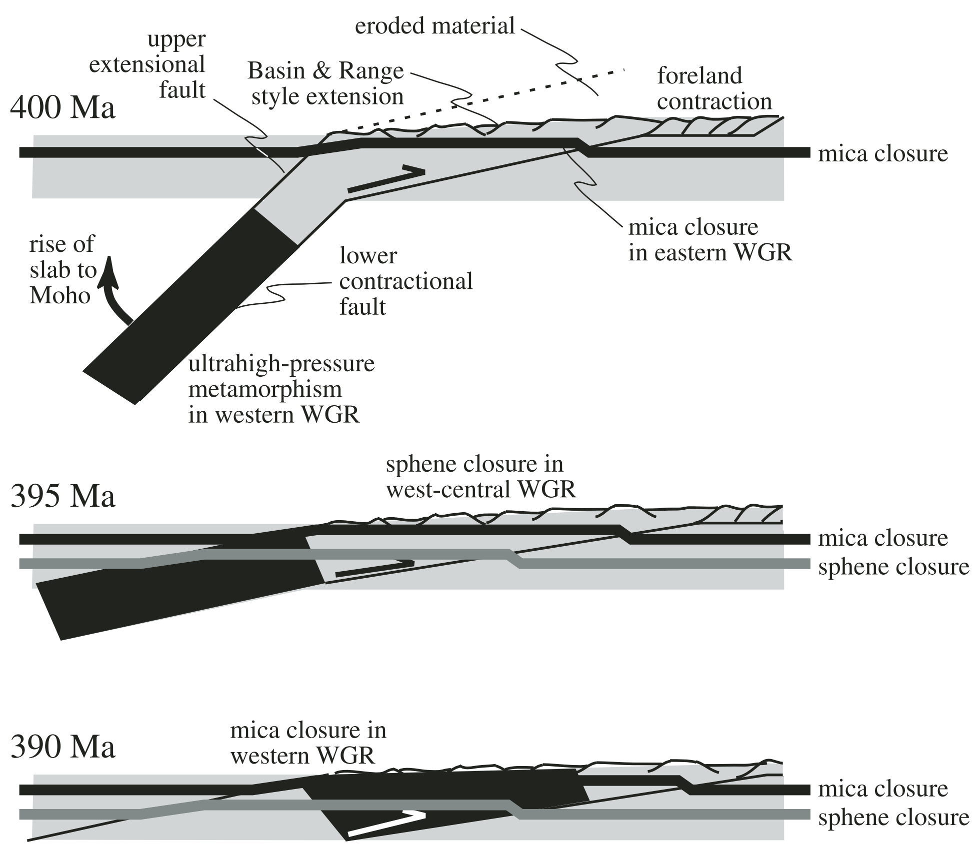

Figure 11. Geochronological, petrological, and structural data for the Western Gneiss Region (WGR) are best explained by progressive east-to-west unroofing of a relatively coherent UHP crustal segment.

(Fig. 11C). Complete cooling of the UHP domains to 400 °C did not occur until 375 Ma. The east-west gradient in muscovite ages suggests that this deformation propagated from east to west and, combined with the structural observations related in the preceding paragraph, is most compatible with exhumation of the UHP rocks as part of a relatively coherent slab (Fig. 11). Crustal exhumation in the documented Basin and Range–type *P-T* setting must also have propagated westward and downsection, perhaps as a rolling hinge (Lavier et al., 1999). The rapid rate of crustal cooling (>60 °C/m.y.) documented in the western Western Gneiss Region contrasts markedly with the earlier adiabatic cooling; it requires that once the UHP rocks reached 0.5 GPa and 700 °C they must have been cut by a rapidly moving fault that placed them in contact with much colder rock. This fault cannot have been the same structure along which the exhumation occurred from 130 to 20 km depth because that structure did not produce any cooling. These data, combined with the structural and petrological observations summarized earlier, lead to a tectonic model in which a coherent, 30 km thick UHP body was exhumed across the Moho progressively from east to west (Fig. 11). This conclusion applies to the Western Gneiss Region treated as a whole, whereas more complicated imbrication of the Western Gneiss Region has been documented locally (Terry and Robinson, 2003).

CONCLUSIONS

Petrology of new UHP and HP eclogites defines three discrete UHP domains within the Western Gneiss Region that are separated by HP rocks. $^{40}Ar/^{39}Ar$ muscovite ages show that these UHP domains are gentle antiforms that are younger than 375 Ma. The UHP antiforms range in size from ~2500 km^2 to >100 km^2 and are overlain by a HP veneer that extends over more than 60,000 km^2. If continuous at depth, the UHP terrane underlies at least 11,000 km^2. Eclogite ages, combined with characteristic thermal diffusion distance, imply that the northern UHP domain and the two southern domains are separate crustal blocks that experienced and were exhumed from UHP conditions at different times.

Petrologic studies show that the UHP rocks underwent isothermal decompression to 0.5 GPa in ~5 m.y.; this implies adiabatic exhumation of a UHP body 20–30 km in diameter or thickness. Discrepancies in anticipated and observed flattening magnitude and sinking magnitude suggest either that the UHP terrane was more viscous when it ponded at the Moho or that it did not pond at the Moho. The combined geochronologic, structural, and petrological data sets suggest that the UHP slab rose coherently from mantle to crustal depths and was exhumed through the crust progressively from east to west between 400 and 390 Ma.

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