# Protolith ages and exhumation histories of (ultra)high-pressure rocks across the Western Gneiss Region, Norway

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## ABSTRACT

**The timing of protolith formation, ultrahigh-pressure (UHP) subduction, and subsequent exhumation for the ultrahigh-pressure to high-pressure units across the eastern part of the Western Gneiss Region, Norway, were assessed using U/Pb zircon, Th/Pb monazite, and $^{40}Ar/^{39}Ar$ white mica ages. U/Pb zircon ages from eclogites demonstrate that oceanic and continental allochthons were emplaced onto the Baltica basement before the entire mass was subducted to (ultra)high pressure. Eclogites within the allochthons across the entire Western Gneiss Region are Caledonian and show a degree of zircon (re)crystallization that increases with peak pressure, permitting the interpretation that the entire region underwent synchronous subduction. $^{40}Ar/^{39}Ar$ white mica ages of 399 Ma indicate that the eastern part of the Western Gneiss Region had been exhumed to shallow crustal levels while UHP metamorphism was ongoing farther west, indicating a westward dip to the slab. The $^{40}Ar/^{39}Ar$ white mica ages also show a clear east-to-west gradient across the entire Western Gneiss Region, indicating that the Western Gneiss Region rose diachronously to crustal levels from east to west between 399 and 390 Ma.**

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## INTRODUCTION

Since the discovery of coesite in regional metamorphic rocks (Smith, 1984), geologists have sought to understand how large-scale ultrahigh-pressure (UHP) terranes are formed and exhumed. The study of these terranes has yielded valuable insights into geological processes active in the mantle and lower crust, including continental collisions and the recycling of continental crust. The rates and mechanisms of UHP subduction and exhumation remain elusive, however, even in well-studied terranes such as the Western Gneiss Region of southwestern Norway.

The Western Gneiss Region, a ~50,000 km$^2$ terrane of Proterozoic orthogneisses (the autochthonous Western Gneiss Complex, Fig. 1) overlain by mixed Proterozoic to Phanerozoic orthogneissic and paragneissic units (Lower, Middle and Upper Allochthons, Fig. 1), contains one of the largest known UHP terranes. UHP is evident from coesite or quartz-pseudomorphs-after-coesite, most common in eclogites that crop out in three distinct zones along the western edge of the Western Gneiss Region (Root et al., 2005). These UHP eclogites are surrounded by high-pressure eclogites that stretch at least another 100 km north, east, and south across the Western Gneiss Region (Cuthbert et al., 2000; Walsh and Hacker, 2004). Excellent exposure provides an unparalleled opportunity to investigate not only the UHP rocks but also the less-studied, high-pressure (HP) rocks that surround the UHP terrane. These lower pressure rocks provide important constraints on both the protolith of the HP-UHP terrane and the tectonic processes that led to exhumation of the UHP rocks.

The purpose of this study is to determine the timing of protolith formation, metamorphism, and subsequent exhumation across the Norwegian HP-UHP terrane—from the foreland into the core of the orogen. We seek to answer the following questions and thus better constrain the mechanisms of UHP rock exhumation: (1) What are the protolith ages of the high-pressure terrane? (2) Was the high-pressure metamorphism in the eastern part of the Western Gneiss Region coeval with the UHP metamorphism in the west? (3) What is the age of the subsequent high-temperature metamorphism and deformation in the eastern part of the Western Gneiss Region? (4) When were the rocks across the *entire* region exhumed into the upper crust?

To address these questions, we dated zircon, monazite, and muscovite from eclogites and metapelites within an E-W transect across the width of the Western Gneiss Region (Fig. 2). U/Pb ages of zircons were measured by secondary ion mass spectrometry (SIMS) and by laser-ablation multiple-collector inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS, henceforth "ICP") both of which provide the spatial resolution necessary for deciphering protolith ages from metamorphic

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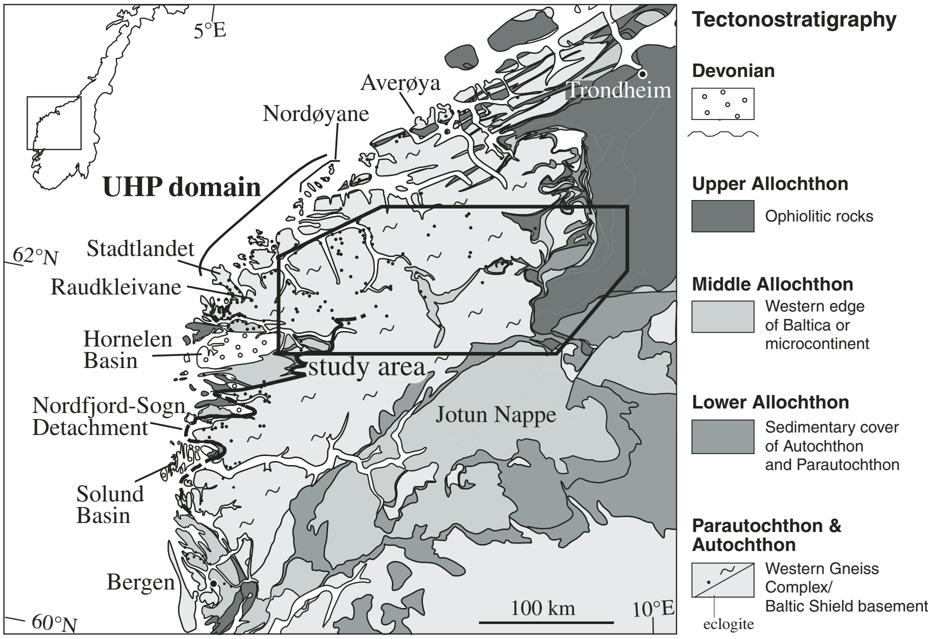



**Figure 1. Geologic map of the Western Gneiss Region. Study area lies within the black box. UHP—ultrahigh pressure.**

ages. High-temperature metamorphic ages were obtained by ICP analysis of Th/Pb decay in monazite from metapelites, and $^{40}Ar/^{39}Ar$ analysis of muscovite collected from metapelites and quartzites across the region provided the timing of exhumation into the upper crust. Zircon ages demonstrate that the high-pressure metamorphism in the east was broadly coeval with the UHP metamorphism in the west. Exhumation through the upper crust began in the east while UHP metamorphism was occurring in the west, and continued from east to west over ~9 m.y.

## GEOLOGIC SETTING

Closure of the Iapetus Ocean initiated the Scandian Orogeny at ca. 435 Ma, resulting in the emplacement of a series of allochthons onto the Baltic Shield basement (the Autochthon or Western Gneiss Complex, Fig. 1) by ca. 415 Ma (Roberts, 2003). These allochthons include (from top to bottom) the eastern margin of Laurentia (the Uppermost Allochthon, not present in the study area), Iapetus ophiolites (the Upper Allochthon), the western margin of Baltica or a microcontinent (the Middle Allochthon), and allochthonous slivers of the Baltic Shield (Parautochthon) and its sedimentary cover (the Lower Allochthon). The continental margin of Baltica was then buried to UHP conditions up to 3.6 GPa and 800 °C (Cuthbert et al., 2000; Terry et al., 2000b) by ca. 410–400 Ma (Fig. 3). It was rapidly exhumed soon afterward (e.g., Root et al., 2005), in part along crustal shear zones that include the large-scale Nordfjord-Sogn Detachment Zone (Hacker et al., 2003; Johnston et al., in press).

In the foreland east of the Western Gneiss Region (Fig. 1) the Western Gneiss Complex is overlain by demonstrably allochthonous units. There the allochthonous units include ca. 480 Ma ophiolites, ca. 440 Ma ophiolites (Upper Allochthon), and the telescoped former margin of the Baltica craton (Middle and Lower Allochthons; e.g., Hacker and Gans, 2005). These units have been traced westward across the entire Western Gneiss Region and correlated with compositionally similar mixed orthogneiss and paragneiss units in the UHP core of the orogen (Krill, 1985; Rickard, 1985; Robinson, 1995; Terry et al., 2000a); throughout this paper we shall refer to these rocks as *allochthons,* following the above authors, although alternative interpretations cannot be refuted. The UHP eclogites crop out within three culminations along the western edge of the Western Gneiss Region; similar UHP and HP eclogites occur within both the Western Gneiss Complex basement and the inferred allochthonous rocks (Root et al., 2005).

The objective of our work is to understand the behavior of the *entire* body of rock that was subducted into the mantle and then exhumed. Toward this end, we chose to study a complete, 220 × 100 km E-W swath across the eclogite-bearing portion of the Western Gneiss Region (Fig. 2). The western limit of the study area is the eastern edge of the Stadtlandet-Nordfjord UHP domain (as defined by Root et al., 2005), and the eastern limit is marked by the large thrust sheets exposed in the foreland. Previously (Walsh and Hacker, 2004), we showed that the eclogites in this swath recrystallized at peak temperatures and *minimum* pressures of ~700 °C and ~1.8 GPa, with two rocks exhibiting evidence of UHP. The eclogites and their quartzofeldspathic and pelitic host gneisses then underwent a late amphibolite-facies metamorphism at 650–750 °C and ~1.1 GPa (Walsh and Hacker, 2004); we call this a *supra-Barrovian* metamorphism because the pressures are higher than classic Barrovian metamorphism, culminating in kyanite-stable rather than sillimanite-stable assemblages (Fig. 3). This was followed by or transitioned into a second, low-pressure, Buchan-style amphibolite-facies metamorphism at 650–750 °C and ~0.6 GPa (Fig. 9 of Walsh and Hacker, 2004). This same sequence of supra-Barrovian amphibolite-facies overprint and Buchan-style amphibolite- to granulite-facies overprint is also seen in the UHP domains (Terry et al., 2000b; Root et al., 2005), indicating that it is characteristic of the (U)HP Western Gneiss Region as a whole. The amphibolite-facies fabric, including a strong foliation, isoclinal folds with E-W axes, and a moderately to shallowly E- or W-plunging stretching lineation, is defined by quartz, biotite, amphibole, plagioclase, or muscovite; throughout the bulk of the study area, this amphibolite-facies fabric is only weakly overprinted by greenschist-facies deformation or metamorphism in the study area.

The age of the eclogite-facies event in the UHP domains is constrained by two three-point Sm/Nd isochrons of 408 ± 8 Ma (Mearns, 1986) and 400 ± 16 Ma (Mørk and Mearns, 1986), U-Pb zircon ages of 401.6 ± 1.6 Ma (Carswell et al., 2003) and 405–400 Ma (Root et al., 2004), and a monazite Th-Pb age of 415 ± 6.8 Ma (Terry et al., 2000a). There were, however, at least three other (U)HP events in the Scandinavian Caledonides—ca. 423 Ma, ca. 452–450 Ma, and ca. 503 Ma (see summary in Brueckner and van Roermund, 2004)—making it crucial to determine the ages of the eclogites that span the eastern part of the Western Gneiss Region before constructing tectonic models for their exhumation.

There are also insufficient constraints on the ages of the two amphibolite-facies events that subsequently affected the HP rocks; having this information would provide important pins on the exhumation process. High-temperature chronometers that closed during these events include (1) sphene, zircon, and monazite from Precambrian basement gneiss and granodiorite north of Tafjord that underwent partial Pb loss at ca. 395 Ma (Fig. 2 of Tucker et al., 1990; Tucker et al., 2004), and (2) monazite growth in the microdiamond-bearing gneiss on Fjørtoft at 398 ± 6 Ma (Terry et al., 2000a). $^{40}Ar/^{39}Ar$ mica ages

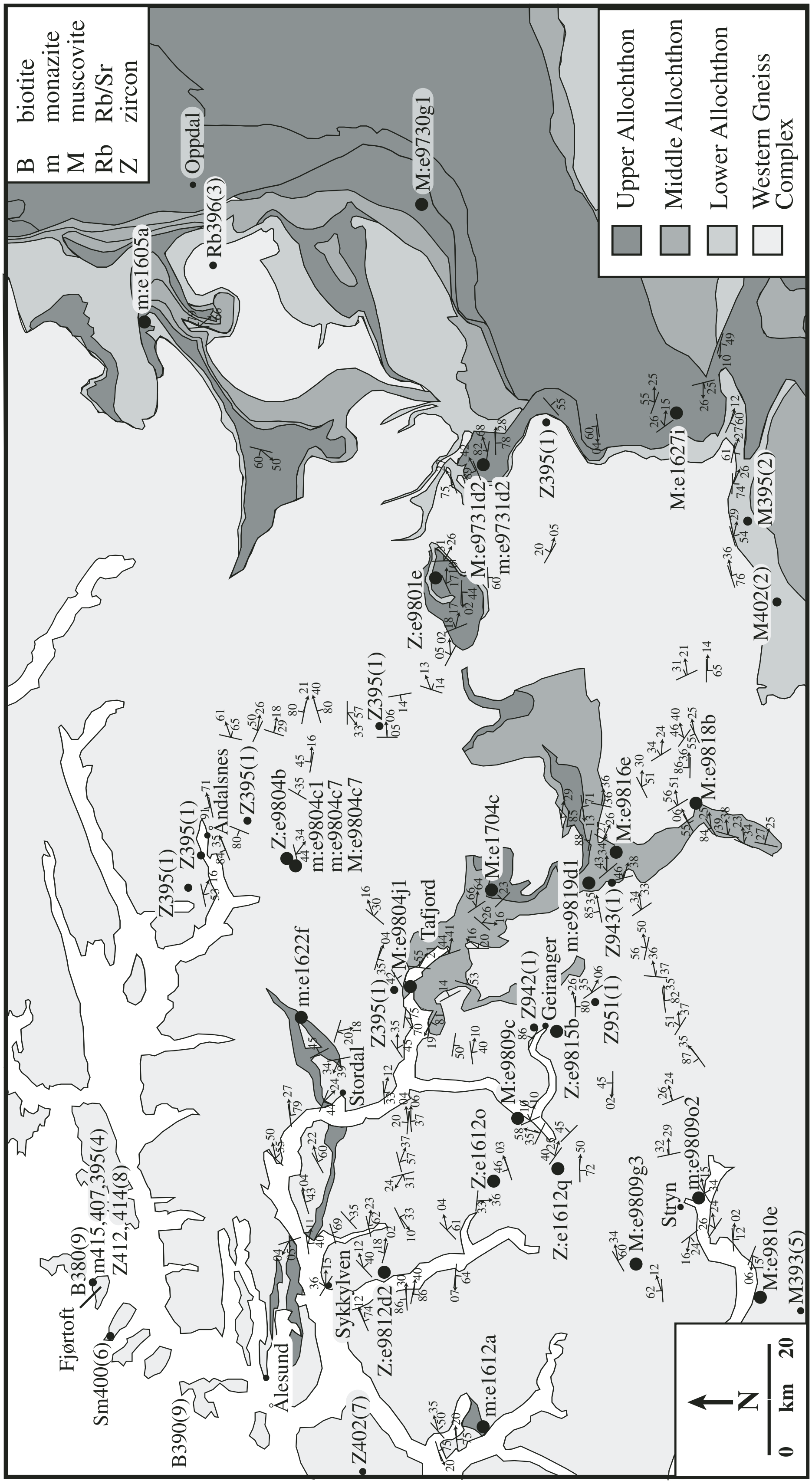



**Figure 2. Geologic map of the study area. Sample localities are shown (see also box at upper right), and strike and dip symbols are shown. Small black dots mark sample ages from: (1) Tucker et al. (1990), (2) Fossen and Dunlap (1998), (3) Solheim (1980), (4) Terry et al. (2000a), (5) Chauvet and Dallmeyer (1992), (6) Mørk and Mearns (1986), (7) Carswell et al. (2003), (8) Krogh et al. (2003), (9) Root et al. (2005).**

from the Western Gneiss Region, which provide a lower bound on the ages of the amphibolite-facies events, vary across the orogen from 401 to 369 Ma (Andersen et al., 1998; Chauvet and Dallmeyer, 1992).

## METHODS

Eclogites and muscovite-bearing metapelites and quartzites were sampled from all tectonostratigraphic units across the entire 220 × 100 km E-W swath, with care taken to ensure an even distribution. Thin sections were then checked for zircon or monazite >~50 µm and muscovite of ~1 mm for separation and dating.

Metamorphic zircons from the Norwegian Caledonides generally contain inherited cores surrounded by thin, low-U rims (Root et al., 2004). Methods well suited to dating the rims and cores of zircons separately include SIMS and ICP, which provide a spatial resolution of ~20–30 µm. The zircons from selected samples were separated by standard techniques, hand-picked, and mounted in 1-in.-diameter epoxy mounts with the 1099 Ma zircon standard AS3 (Paces and Miller, 1993). Because our goal was to decipher both the age of the protolith and the age of metamorphism, the grains in one mount were polished approximately halfway through to expose grain cores, and the grains in a second mount were barely polished to expose only the thin metamorphic rims. Cathodoluminescence (CL) images of all zircons were obtained with a JEOL 6300 scanning electron microscope and a home-built imaging system at the University of California, Santa Barbara. Grains polished through their cores provided detailed CL images, which were used to interpret the genesis of the grains (following Corfu et al., 2003a) and to choose the placement of spot analyses: oscillatory-zoned cores for protolith ages and thin, low-U rims for metamorphic ages. The barely polished grains did not yield detailed CL images, as only the exterior, generally homogeneous rim was imaged. In this case, spot ages were taken from the widest part of the grain (the center, in most cases), or the part of the grain most free

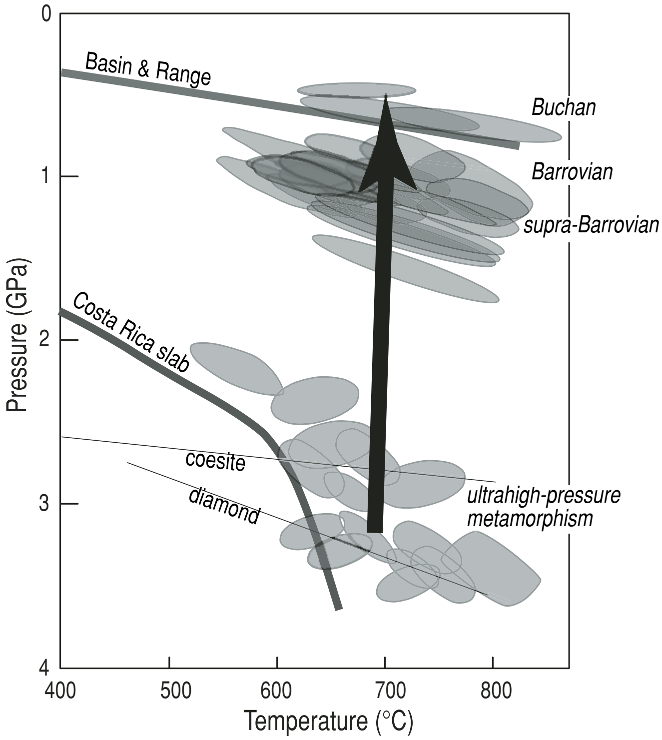



**Figure 3. Pressure-temperature conditions of the UHP, supra-Barrovian, Barrovian, and Buchan metamorphic episodes in the Western Gneiss Region of Norway (Engvik et al., 2000; Ravna and Terry, 2004; Root et al., 2005; Terry et al., 2000b; Wain, 1998; Walsh and Hacker, 2004; Young et al., 2007); calculated thermal gradients for the Costa Rica subduction zone (Peacock et al., 2004) and the Basin and Range Province (Lachenbruch, 1978) shown for reference.**

of blemishes, to optimize the amount of the rim analyzed. Finally, the mounts were cleaned, coated with 20–40 nm of gold, and analyzed on the Cameca IMS-1270 ion probe at the University of California, Los Angeles, using procedures detailed in Quidelleur et al. (1997) and Miller et al. (2000). After SIMS analysis, these mounts were repolished and analyzed using a New Wave Research 193 nm ArF excimer laser attached to the Micromass Isoprobe ICP at the University of Arizona (for further details, see Appendix DR1).[1] Additional zircons exposed in polished thin sections were analyzed in situ. Monazites were dated in thin sections by Th/Pb decay using ICP and an ~10-µm diameter laser beam (for further details, see Appendix DR1). The monazites were identified in thin section by optical microscopy or back-scattered electron microscopy; zoning was not investigated because the grains were similar in size to the ion probe and laser beams.

U-Th/Pb data were analyzed using Isoplot by Ludwig (2001). Isotopic ratios for both SIMS and ICP data were corrected for common lead using a $^{204}$Pb correction and the model of Stacey and Kramers (1975). In most cases, measured $^{206}$Pb/$^{204}$Pb is large, and the $^{204}$Pb correction does not significantly change the ages. Th/U ratios for zircon analyses were used, in conjunction with the CL images, to help determine whether the zircon analyzed formed by igneous or metamorphic processes (see Hoskin and Schaltegger, 2003).

Eleven muscovite samples were separated using standard techniques, irradiated for 20 h at Oregon State University, and analyzed by resistance-furnace step heating at the University of California, Santa Barbara, using techniques described by Calvert et al. (1999). Production ratios used were $^{36}$Ca/$^{37}$Ca = 2.6832 × $10^{-4}$, $^{40}$K/$^{39}$K = 3.7 × $10^{-4}$, and $^{39}$Ca/$^{37}$Ca = 8.7549 × $10^{-4}$. Ar isotopic data were analyzed using Eyesorecon by B.R. Hacker and Isoplot (Ludwig, 2001). Sanidine from the Taylor Creek Rhyolite was used as a fluence monitor, for which we assumed an age of 28.34 Ma (Renne et al., 1998).

All age uncertainties reported and discussed in this paper represent the 95% confidence interval and include errors in decay constants unless stated otherwise.

## RESULTS

### Eclogite Zircons

Zircons were extracted from four eclogites (samples e1612q, e9812d2, e9804b, and e9801e) distributed across the study area—from the least-retrogressed eclogite in the west to the eclogite closest to the foreland in the east (Fig. 2). All eclogites exhibit the breakdown of omphacite to clinopyroxene plus plagioclase as well as the decomposition of clinopyroxene to amphibole plus plagioclase. All the eclogites also contain amphibole, generally as a secondary phase, and all except sample e9812d2 contain secondary biotite. Plagioclase is present only as a breakdown product; all samples except e1612q contain quartz. Garnet from eclogite samples e9801e, e9804b, and e9812d2 have coronae of amphibole plus plagioclase plus spinel. Accessory phases include zoisite/epidote, apatite, and rutile; inclusions in garnet consist of zoisite, rutile, zircon, opaque minerals, and amphibole.

Eclogite sample e9812d2 was collected from the allochthons in the west. Zircons from eclogite sample e9812d2 are colorless and prismatic (with aspect ratios of ~2:1) or rounded, ranging in width from ~50 to 150 µm. Twenty-two grains were analyzed with 23 spots. Half-polished grains show fairly homogeneous CL with faint, patchy, darker (higher U) zones at the center, suggesting extensive metamorphic recrystallization (Fig. 4). A broad range of spot ages indicates Caledonian overprinting of a Precambrian protolith; 11 points can be fit to a discordia with a fixed lower intercept of 400 ± 5 Ma (approximating the youngest ages of samples e9801e and e1612q; see the following) and a Sveconorwegian upper intercept of ca. 1.1 Ga (Fig. 5A). A concordia age calculated for the five youngest spot ages is 412 ± 25 Ma (MSWD = 1.1; see Wendt and Carl, 1991, for a discussion of the significance of MSWD [mean square of weighted deviates]).

The least retrogressed eclogite, sample e1612q, was collected from allochthons south and east of sample e9812d2. This eclogite contains relict kyanite surrounded by spinel-plagioclase symplectites and relict phengite partially decomposed to biotite plus plagioclase. The garnet and clinopyroxene form compositional layers, and the garnet contains kyanite inclusions.

[1]GSA Data Repository item 2007063, Appendix DR1, details for LA-MC-ICP-MS; Appendix DR2, $^{40}$Ar/$^{39}$Ar data; Table DR1, zircon and titanite data; and Table DR2, ICP monazite data; is available on the Web at http://www.geosociety.org/pubs/ft2007.htm. Requests may also be sent to editing@geosociety.org.

Zircons are generally colorless and rounded, and range in size from ~50 to 100 μm, with a fraction as fine as 25 μm, so that only one spot was analyzed for each of 28 grains. Half-polished grains show fairly homogeneous CL with some higher U, angular, zoned cores—characteristics that, again, suggest extensive metamorphic recrystallization (Fig. 4). Eclogite sample e1612q yielded a progression of $^{206}$Pb/$^{238}$U spot ages from 463 ± 62 Ma to 392 ± 14 Ma (Fig. 5B). The three youngest ages yield a slightly over-corrected Scandian concordia age of 396 ± 10 Ma (MSWD of concordance plus equivalence = 0.94), and the remaining 12 spot ages give a Caledonian concordia age of 436 ± 10 (MSWD of equivalence = 0.92; Fig. 5B).

Sample e9801e was taken from allochthons near the eastern edge of the study area. Its zircons are colorless to pale pink, have aspect ratios of ~2:1, rounded terminations, and range in size from ~50 to 100 μm. In CL, the zircons polished through the core show thin, bright (lower-U) rims surrounding oscillatory-zoned cores (Fig. 4). The cores yield Th/U > 0.1, which, along with the zoning patterns, indicates an igneous origin (Hoskin and Schaltegger, 2003). The rounded morphologies of most grains, low Th/U rims (<0.09; Table DR1, see footnote 1), and CL patterns of the half-polished grains indicate that these zircons then underwent partial metamorphic recrystallization or new metamorphic growth. The zircons from sample e9801e were too small to allow more than one analysis per grain; 21 were analyzed. These range in $^{206}$Pb/$^{238}$U age from 1625 ± 76 Ma to 374 ± 22 Ma and yield three clusters of concordant ages—403 ± 21 Ma (MSWD = 0.21), 459 ± 8 Ma (MSWD = 2.1), 905 ± 31 Ma (MSWD = 2.8)—and one older cluster with a $^{206}$Pb/$^{238}$U age of ca. 1.4 Ga and a $^{207}$Pb/$^{206}$Pb age of ca. 2.1 Ga (Fig. 5C). Th/U ratios of the oldest two age groups extend from 0.1 to 0.8, suggesting that these analyses are igneous. The younger two age groups contain Th/U ratios implying mixtures of metamorphic and igneous material: 0.04–0.72 for the ca. 460 Ma group and 0.6–1.6 for the ca. 403 Ma group (Table DR1, see footnote 1). No single discordia fits these data, which instead suggest at least two Precambrian-age components affected by Pb loss during the Caledonian and Scandian (Fig. 5C). A discordia fixed to a lower intercept of 403 ± 21 Ma and fit through the oldest four points yields an upper intercept of 2060 ± 78 Ma (MSWD = 0.60).

Finally, eclogite sample e9804b is from basement gneiss west, near the center of the study area. This eclogite includes clinopyroxene with exsolved silica rods and phengite broken down to biotite plus plagioclase. Similar to sample e9801e, the zircons are colorless to pale pink, have aspect ratios of ~2:1, rounded terminations, and range in size from ~50–100 μm. In CL, the half-polished zircons display thin, bright (lower-U) rims surrounding sector-zoned cores (Fig. 4) with Th/U > 0.1. Again, the low Th/U ratios and zoning patterns indicate an igneous origin for the cores, whereas the generally rounded morphologies of most grains, the low Th/U rims (<0.09; Table DR1, see footnote 1), and CL patterns of the half-polished grains indicate a later partial metamorphic recrystallization or new metamorphic growth. Twenty-four grains were analyzed with single spots, yielding chiefly Precambrian ages (Fig. 5D). A concordia age for four of the points is 1562 ± 39 Ma (MSWD = 0.00053), and a discordia fit through all 13 points and tied to a lower intercept of 400 ± 5 Ma (approximating the youngest ages of samples e9801e and e1612q) yields an upper intercept of 1612 ± 22 Ma (MSWD = 1.5).

These data are discussed in detail later, but in summary the zircon ages indicate that eclogites across the Western Gneiss Region recrystallized in the Caledonian rather than being relicts of an earlier eclogite-facies event. The errors for the zircon ages are too large to assess whether the eclogites recrystallized simultaneously or diachronously, or whether they recrystallized during specific Caledonian events recognized elsewhere in the orogen; but the least-retrogressed eclogite, sample e1612q, yields a Scandian age of 396 ± 10 Ma.

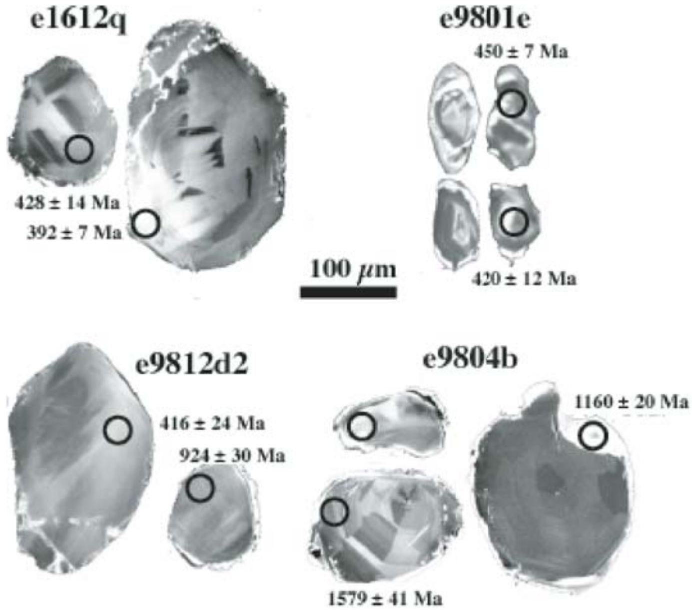



**Figure 4. Cathodoluminescence images of representative zircons from eclogites; $^{206}$Pb/$^{238}$U spot ages are shown. Eclogites in the western part of the study area (samples e9812d2, e1612q) exhibit recrystallized textures, whereas eclogites from farther east show oscillatory or sector zoning (samples e9804b, e9801e).**

### Metapelite Monazites and Zircons

Pelites across the Western Gneiss Region underwent a post-UHP amphibolite-facies metamorphism at supra-Barrovian depths of ~40 km and ~650–750 °C (Terry and Robinson, 2003; Walsh and Hacker, 2004; Root et al., 2005). This was followed by continued recrystallization down to depths of ~20 km. To constrain the timing of these events, we dated monazites from the same set of pelitic samples used by Walsh and Hacker (2004) to assess pressures and temperatures. The bulk of these samples shows amphibolite-facies fabrics with minimal lower temperature deformation; only sample e1622f1 contains biotite and quartz with undulatory extinction suggestive of minor greenschist-facies reworking. The monazite grains are generally ~20–50 μm in size and xenoblastic. They are dominantly associated with biotite, and most occur along biotite-biotite grain boundaries; exceptions include monazite A-6 from sample e9819d1 against fibrolite, and the monazites from sample e9809o2, which are surrounded by clusters of fine metamorphic epidote.

The monazites are small enough so that only one spot was analyzed per grain, although up to 11 grains were analyzed in one sample. More than half the grains analyzed (47 of 76) yielded $^{208}$Pb/$^{232}$Th ages younger than ca. 435 Ma (Table DR2, see footnote 1; Fig. 6), indicating pervasive Caledonian (re)crystallization. Pelite

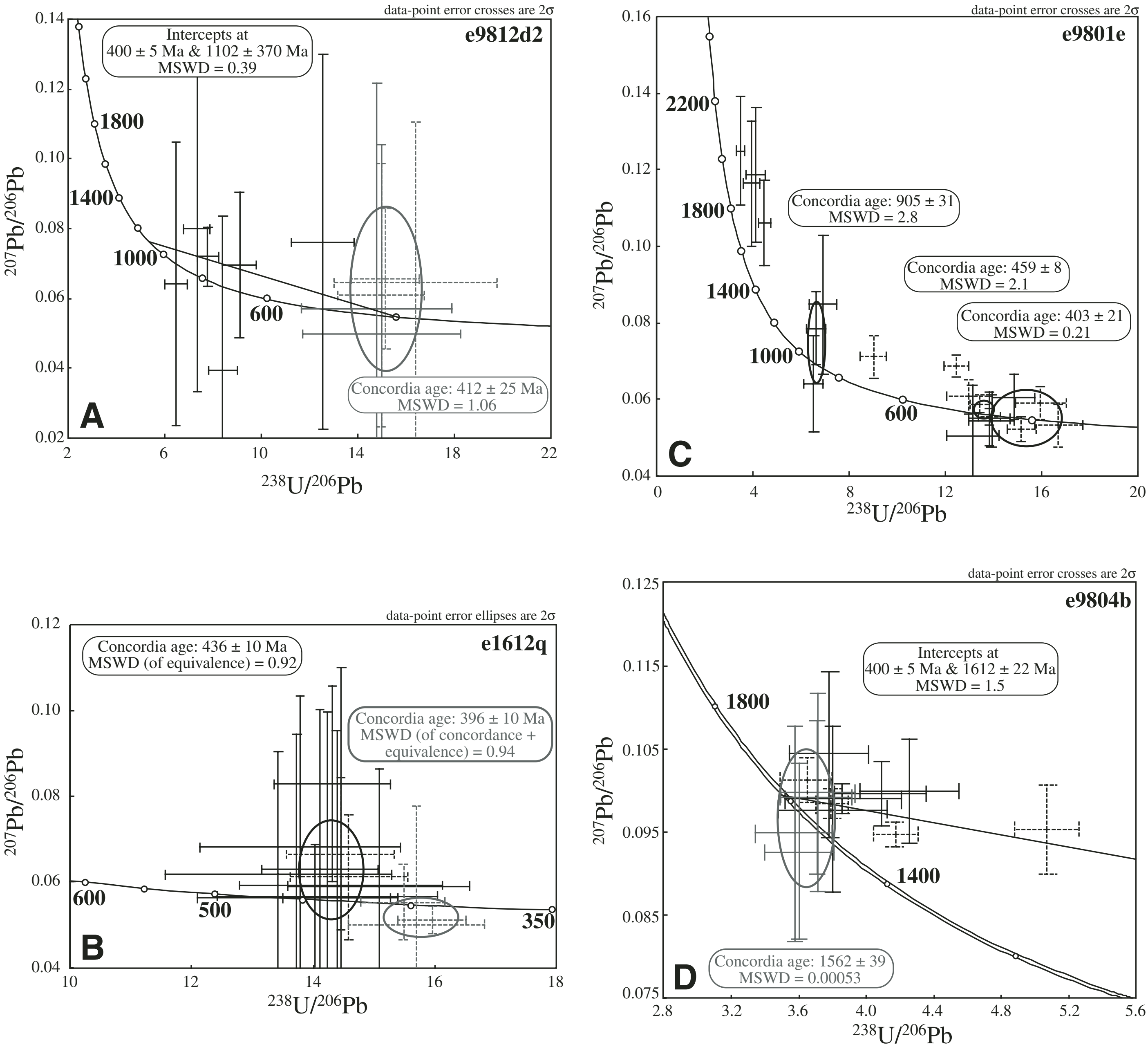



**Figure 5. $^{204}Pb$-corrected U/Pb data for eclogites. Dotted crosses mark SIMS (secondary ion mass spectrometry) data, solid crosses ICP (laser-ablation multiple-collector inductively coupled plasma–mass spectrometry) data. (A) Eclogite sample e9812d2 yields a concordia age for the youngest five spot ages of ca. 412 Ma. A discordia fixed at a lower intercept of 400 ± 5 Ma demonstrates the Sveconorwegian origin of the eclogite. (B) Eclogite sample e1612q shows concordia ages at ca. 396 Ma and ca. 436 Ma. (C) Easternmost eclogite sample e9801e yields a wide range of ages, indicating Precambrian cores and Caledonian Pb loss, with the youngest ages clustered at 403 ± 21 Ma. A discordia fit through the oldest three spot ages and fixed at 403 ± 21 Ma yields a Svecofennian age of ca. 2.1 Ga, uncommon in the Western Gneiss Region. (D) Basement eclogite sample e9804b yields mainly Precambrian ages. Fixed to a lower intercept of 400 ± 5 Ma, the discordia has an upper intercept of ca. 1.6 Ga, a common Gothian age seen in the Western Gneiss Complex. MSWD—mean square of weighted deviates.**

sample e9804c1 gave a broad range of seven $^{208}Pb/^{232}Th$ ages from 1692 ± 189 Ma through 399 ± 26 Ma; the mean of the two youngest $^{208}Pb/^{232}Th$ ages is 403 ± 17 Ma. Pelite sample e9809o2 gave five $^{208}Pb/^{232}Th$ ages from 979 ± 46 to 801 ± 34 Ma. Pelite sample e9804c7 yielded a continuous spread of $^{208}Pb/^{232}Th$ ages chiefly from ca. 503 to ca. 385 Ma; the youngest four $^{208}Pb/^{232}Th$ spot ages have a weighted mean of 392 ± 10 Ma (MSWD = 0.51). Pelite sample e9819d1 yielded a continuous spread of 32 $^{208}Pb/^{232}Th$ ages ranging chiefly from ca. 472 Ma to ca. 397 Ma. The other four monazite-bearing pelites (samples e1605a, e1612a, e1622f1, e9731d2) gave strictly Caledonian $^{208}Pb/^{232}Th$ ages mostly in the ca. 435–395 Ma range.

Several tiny zircons were analyzed in situ in thin sections from pelite samples e1612a and e9804c7. Four spots (one per grain) from sample e1612a yielded a concordia age of 480 ± 12 Ma (MSWD = 0.1; Fig. 7A); Th/U ratios of 0.03–0.67 imply mixed igneous and metamorphic domains. Four spots from four grains from pelite e9804c7, a basement sample, yielded a spread of $^{206}Pb/^{238}U$ ages from 2159 ± 140 Ma to 403 ± 42 Ma and a concordia age of 2094 ± 77 Ma (MSWD of equivalence = 1.6) for the three oldest spot ages (Fig. 7B).

Again, the errors for the individual spot ages for the metapelite monazites and zircons are too large to assess specifically when these metamorphic events occurred during the Caledonian orogeny, but they are compatible with either long-term recrystallization or incomplete short-term recrystallization. The youngest monazite age (weighted mean of 392 ± 10 Ma) overlaps previously recorded ages for the UHP metamorphism, implying that the amphibolite-facies metamorphism followed closely on the heels of the UHP event. The protolith zircon age of ca. 2.1 Ga for pelite sample e9804c7 is equivalent to the old age noted for basement gneiss sample e9801e, and distinctly older than more typical Western Gneiss Region protolith ages of 1.7–1.6 Ga.

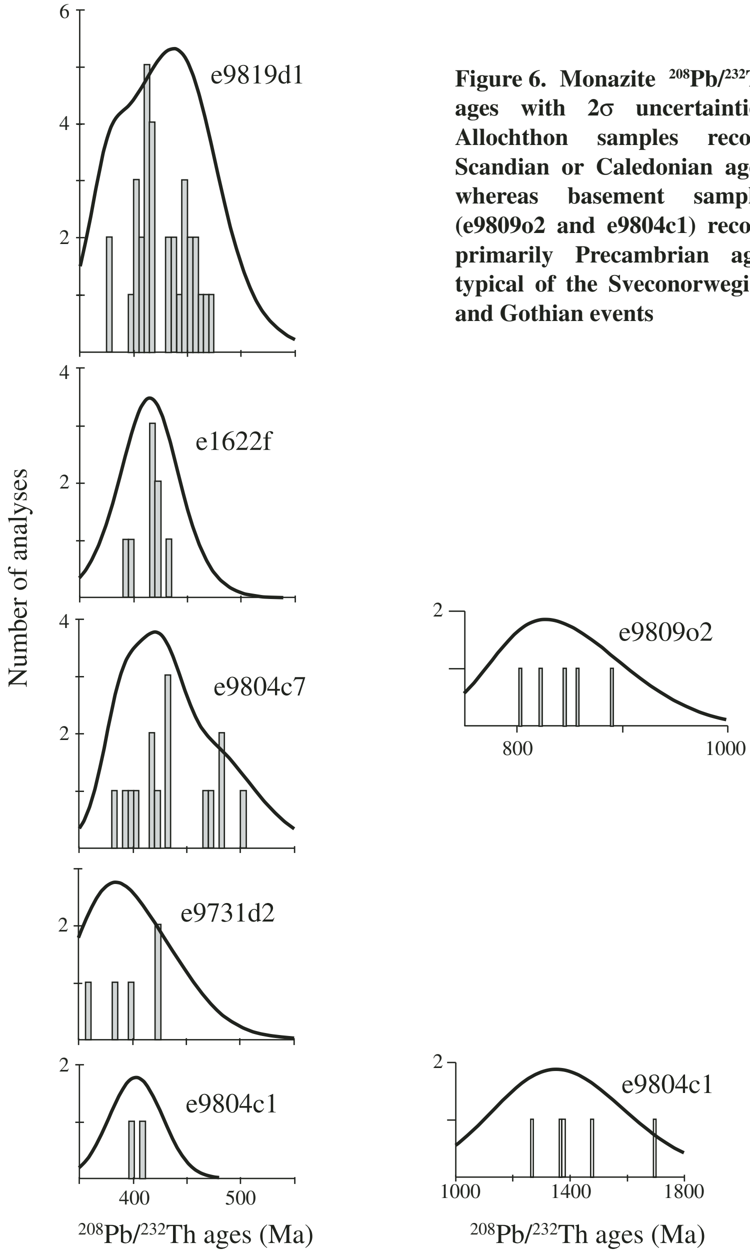



**Figure 6. Monazite $^{208}Pb/^{232}Th$ ages with 2σ uncertainties. Allochthon samples record Scandian or Caledonian ages, whereas basement samples (e9809o2 and e9804c1) record primarily Precambrian ages typical of the Sveconorwegian and Gothian events**

### Muscovite $^{40}Ar/^{39}Ar$ Ages

Eleven K-white mica (henceforth, "muscovite") separates were extracted from metapelites and quartzites from the basement and allochthons across the study area to constrain the time by which the (U)HP rocks had cooled below ~400 °C. In the bulk of the samples (from the Western Gneiss Region proper) the muscovites are millimeter sized and form part of the amphibolite-facies fabric; retrogression is minimal, and only muscovite in samples e9816e and e9809g3 shows weak to strong undulatory extinction. In contrast, the two samples from the allochthons east of the Western Gneiss Region both have an order of magnitude of finer-grained muscovite showing strong kinking or undulatory extinction, and chlorite (sample e9730g1) or chloritoid (sample e1627i). The Si contents of the Western Gneiss Region muscovites are relatively low, ranging from 3.03 atoms per formula unit in sample e9804j1 to 3.25 in sample e9731d2, with no apparent relationship between Si content, spectrum type, or age (Fig. 8A–K; Appendix DR2, see footnote 1). These features imply that these muscovites—and hence their ages—are the result of crustal amphibolite-facies metamorphism and not UHP metamorphism (cf. Hacker et al., 2000).

Eight of the 11 muscovite sample separates gave plateau ages (>50% of released Ar): 390.3 ± 3.0 Ma (e9809g3), 389.8 ± 3.0 (e9809c), 391.2 ± 3.0 Ma (e9804j1), 394.3 ± 3.1 Ma (e1704c), 395.2 ± 3.1 Ma (e9816e), 392.9 ± 3.1 Ma (e9818b), 399.1 ± 3.1 Ma (e9731d2), and 423.6 ± 3.3 Ma (e1627i). Three other samples did not yield plateau ages but have relatively flat spectra for which we estimate weighted mean ages of 399.4 ± 3.4 Ma (e9810e), 391.5 ± 3.1 (e9804c7), and 410.5 ± 3.4 Ma (e9730g1).

The most important feature of the muscovite ages is that they fall in a narrow range and show a steady westward decrease across the Western Gneiss Region from ca. 399 Ma in the east to

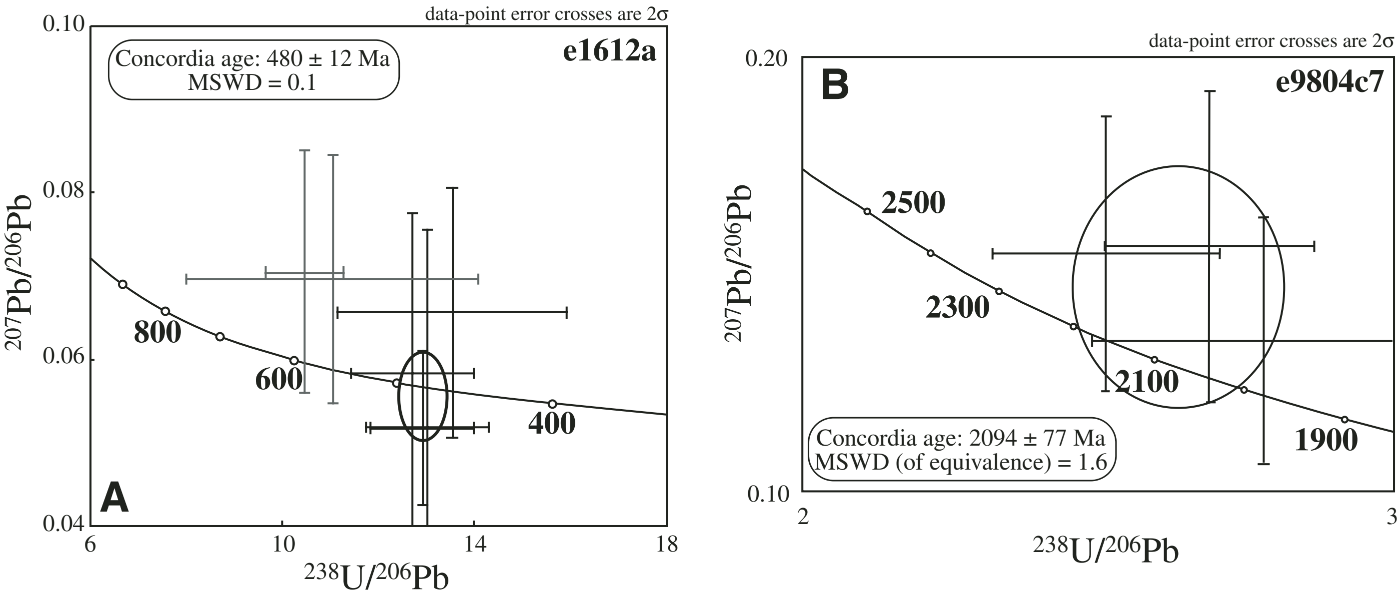



**Figure 7. U/Pb ages for zircons analyzed in situ. (A) Zircons from Upper Allochthon metapelite sample e1612a reveal an Early Ordovician protolith age. (B) Sample e9804c7 yielded surprisingly old $^{206}Pb/^{238}U$ ages and a concordia age of ca. 2.1 Ga, which is uncommon within the Western Gneiss Region. MSWD—mean square of weighted deviates.**

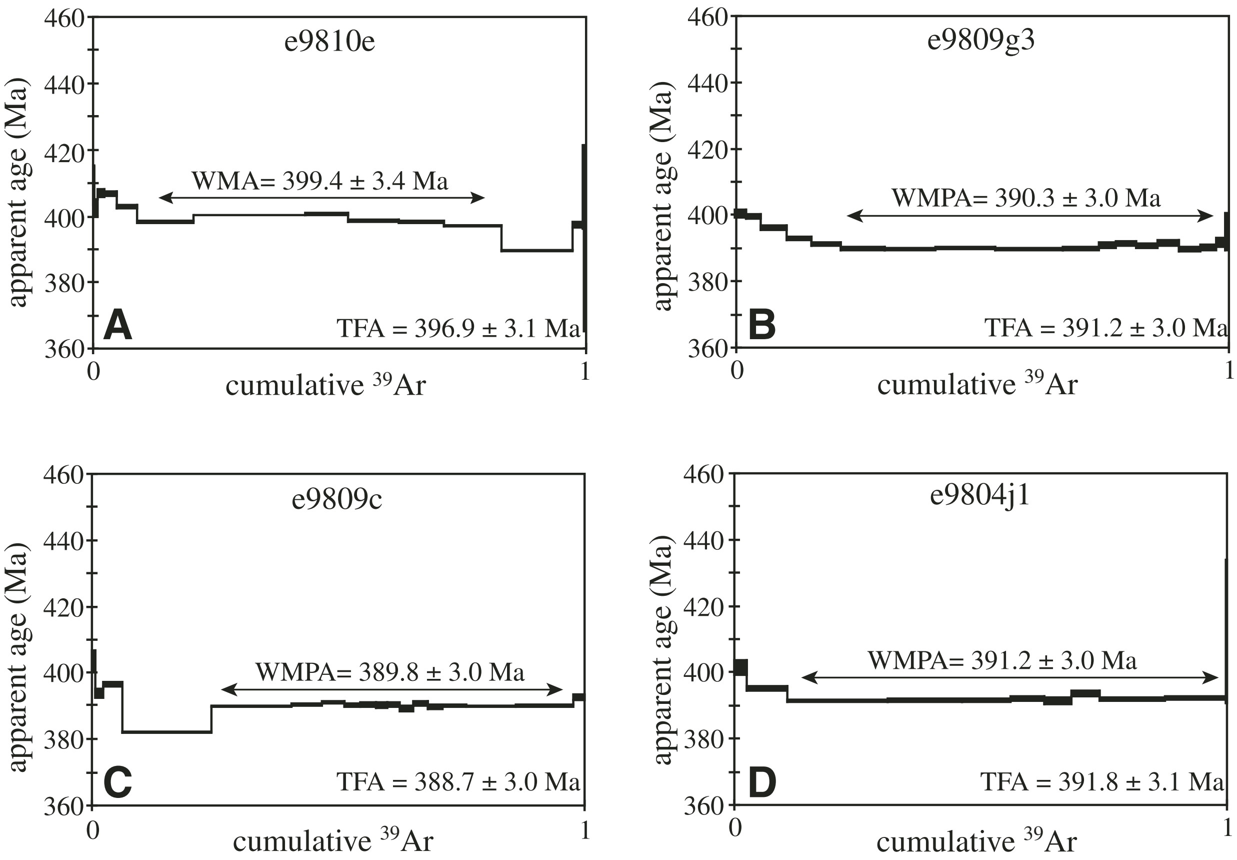
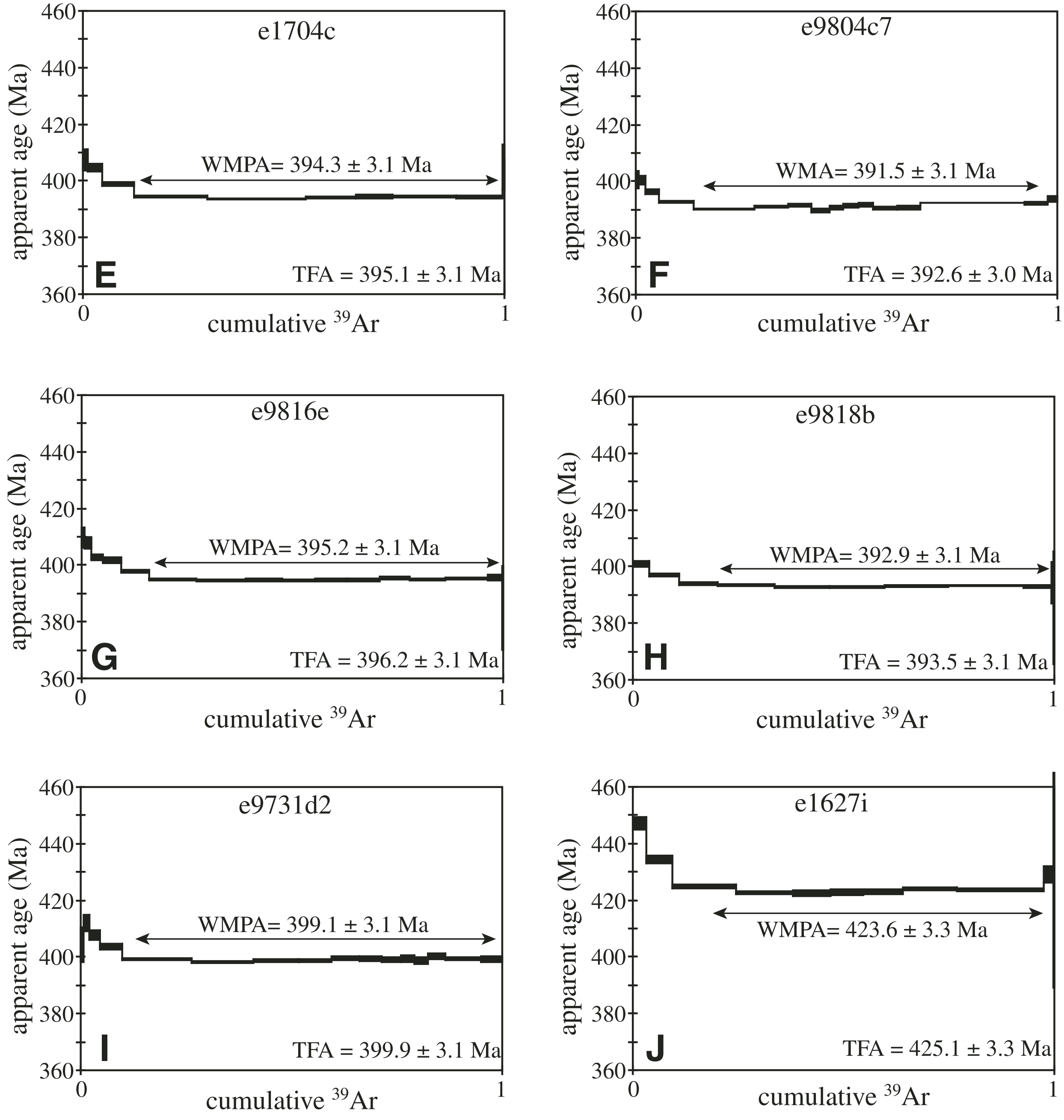



**Figure 8 (*on this and following page*).**



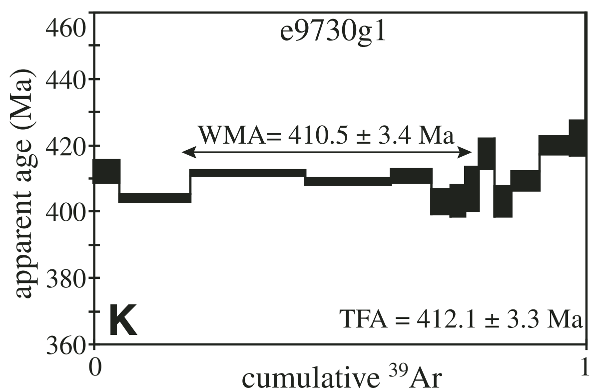




**Figure 8 (*on this and previous page*). $^{40}Ar/^{39}Ar$ muscovite spectra. Step ages show ±1σ without error in irradiation parameter, *J*; calculated ages are ±2σ and include intralaboratory uncertainty as well as error in the decay constant and standard age. *Relative uncertainties are <1 m.y.* WMPA—weighted mean plateau age; WMA—weighted mean age; TFA—total fusion age. Arrows show steps included in the age calculations.**

ca. 390 Ma in the west. This is a highly robust result because—although the total uncertainty for each of these ages is ~3 m.y.—the intralaboratory uncertainties *among the different samples* are <1 m.y. (see Appendix DR2, see footnote 1). Two of the three youngest ages (samples e9804j1 and e9809c) come from rocks that contain sillimanite grown during the low-pressure metamorphic event that followed the supra-Barrovian metamorphism (Walsh and Hacker, 2004). The two muscovite ages from the thrust sheets east of the Western Gneiss Region are older: 410.5 ± 3.4 Ma and 423.6 ± 3.3 Ma, a likely result from an older metamorphic event (Hacker and Gans, 2005).

## DISCUSSION

### Precambrian Protolith Ages

Orthogneisses in the study area that are of Baltica affinity are expected to yield (re)crystallization ages that correspond to one of the common events defined by existing U-Pb data: the Gothian orogeny at ca. 1690–1620 Ma (Skår, 2000), regional magmatic episodes at ca. 1530–1520 Ma and ca. 1290–1200 Ma, or the Sveconorwegian orogeny of ca. 950–930 Ma (Corfu and Andersen, 2002).

Ca. 1600 Ma U-Pb ages were found in eclogite sample e9804b, indicating igneous crystallization at the same time as some of the oldest known rocks in the Western Gneiss Complex. Sveconorwegian ages, the second-most common U-Pb ages for the Western Gneiss Region, are seen in eclogite samples e9812d2 (924 ± 60 Ma) and e9801e (904 ± 50 Ma). The upper intercept for sample e9801e is older than expected, ca. 2.1 Ga, and corresponds to the Svecofennian orogeny (Skår, 2002); basement sample e9804c7 yielded a similar concordant age of ca. 2.1 Ga (Fig. 7B). Skår (2000) reported Svecofennian quartzites along Sognefjord at Kvamsøy; although few other pre-Gothian rocks have been reported from the Western Gneiss Region, Gorbatschev and Gáal (1987) maintained that the Western Gneiss Complex formed during four separate orogenies between 3.5 Ga and 1.5 Ga, such that these 2.1 Ga ages, while unusual, are not unexpected.

The monazite grains record a wide spread of ages, with the oldest ages (in the basement pelites) corresponding to both the ca. 1600 Ma and ca. 950 Ma protolith ages of the Baltica gneisses. Whereas Precambrian monazite ages were found *only* in basement rocks, Precambrian zircon ages were measured in eclogite samples e9801e (Fig. 5C) and e9812d2 (Fig. 5A) from the Upper Allochthon.

### Early Paleozoic Protolith Ages

Any allochthon orthogneisses that were derived from Iapetus oceanic or arc crust should record igneous or metamorphic ages of 490–470 Ma or 450–430 Ma, whereas in contrast, Ordovician–Silurian magmatism is unknown in the Western Gneiss Complex (Hacker and Gans, 2005). Three Upper Allochthon samples, e1612a, e9801e, and e1612q, yielded a range of Caledonian zircon ages as well as early Paleozoic protolith ages. Zircons from metapelite sample e1612a, from the Blåhø Nappe, yield a concordia age of 480 ± 12 Ma, similar to the ages of the Early Ordovician ophiolite allochthons (Stephens et al., 1993). Eclogite sample e9801e, also from the Blåhø Nappe, shows a cluster of ages, implying mainly igneous (Th/U = 0.19–0.72) zircon growth at ca. 459 Ma and suggesting that both of these rocks are part of the Early Silurian oceanic allochthons. Eclogite sample e1612q yields a cluster of ages at ca. 440 Ma, with Th/U ratios of 0.03–0.13 indicative of metamorphic growth-recrystallization; these ages may be related to the emplacement of the allochthons onto the craton (e.g., Figure 8 of Hacker and Gans, 2005).

### Scandian Metamorphism

Although the metamorphic zircon ages span a considerable range and do not tightly constrain the ages of eclogite-facies metamorphism in the study area—owing to limited recrystallization and large errors—they do show that eclogites across the entire width of the Western Gneiss Region underwent Scandian metamorphism. Sample e1612q yielded a concordia age of 396 ± 10 Ma; the easternmost eclogite, sample e9801e, gave a concordia age of 403 ± 21; and a third, sample e9812d2, yielded 412 ± 25 Ma. These ages are indistinguishable from the 415–400 Ma UHP event farther west (e.g., Root et al., 2004) and the ca. 423 Ma Bergen Arcs eclogitization (Bingen et al., 2004), but are distinctly younger than the Precambrian garnet peridotites of the Western Gneiss Region (van Roermund and Drury, 1998), the ca. 450 Ma eclogites of the Uppermost Allochthon (Corfu et al., 2003b) and Seve Nappe (Brueckner and van Roermund, 2004), and the ca. 504 Ma eclogites in the Seve Nappe of northern Sweden (Mørk et al., 1988). Basement eclogite sample e9804b was least affected by the Scandian (re)crystallization, yielding chiefly Precambrian igneous zircons with metamorphic rims too thin to analyze.

Monazites from basement samples e9804c1 and e9809o2 indicate significant Precambrian inheritance (as old as ca. 1.7 Ga) and only minor Scandian (re)crystallization—perhaps because of low fluid activities. In contrast, whereas monazites from the allochthon samples show some evidence of Precambrian inheritance, the bulk of the spot ages are Caledonian. Unfortunately, the broad range of Caledonian ages from ca. 470 Ma to 395 Ma and their large errors cannot be interpreted further.

### Implications for Exhumation of the (Ultra)high-Pressure Rocks

The most robust and impressive geochronological discovery of this study is the steady westward decrease in Western Gneiss Region muscovite $^{40}Ar/^{39}Ar$ ages from ca. 399 Ma in the east to ca. 390 Ma in the west (Fig. 9A; recall that these ages have *relative* uncertainties of <1 m.y.). This gradient continues farther west into the UHP domains, where muscovite ages are as old as 389 Ma and as young as 369 Ma (Root et al., 2005). It also continues farther east into the stack of thrust sheets overlying the Western Gneiss Region, first stepping up to ca. 410–400 Ma and then to ca. 425–410 Ma (Dallmeyer, 1990; Hacker and Gans, 2005). All of these are cooling ages that postdate the UHP and amphibolite-facies metamorphic events. Figure 9B shows that this data set defines 395 Ma and 390 Ma muscovite "chrontours" (see also Root et al., 2005; Hacker, 2007). This gradient in ages roughly parallels the eclogite-facies pressure gradient across the Western Gneiss Region, with older ages and lower pressures in the HP domain in the east and younger ages and higher pressures in the UHP domains in the west. The shape of the chrontours and the disposition of the UHP domains strongly suggest that both are shaped by late, post-muscovite-closure folding, with the youngest ages and the highest pressures in the fold cores (cf. Root et al., 2005). These discoveries place significant and important constraints on the exhumation of the (U)HP rocks.

The UHP rocks in the western part of Figure 9B were at eclogite-facies conditions at 405–400 Ma (see summary in Root et al., 2004). Muscovite ages as old as 399.1 ± 3.1 Ma indicate that the eclogites of the *easternmost* Western Gneiss Region had reached crustal depths cool enough for muscovite closure at about that time or soon afterward. In other words, at 400–399 Ma, the Western Gneiss Region dipped westward at an average of ~20° from depths of <20 km in the east to depths of ~100 km in the west (Fig. 10). Within 9 m.y. (by 390.3 ± 3.0 Ma), the western edge of the study area had also reached muscovite closure at shallow depths, documenting a diachronous, E-W exhumation of the Western Gneiss Region to shallow crustal levels (Fig. 10).

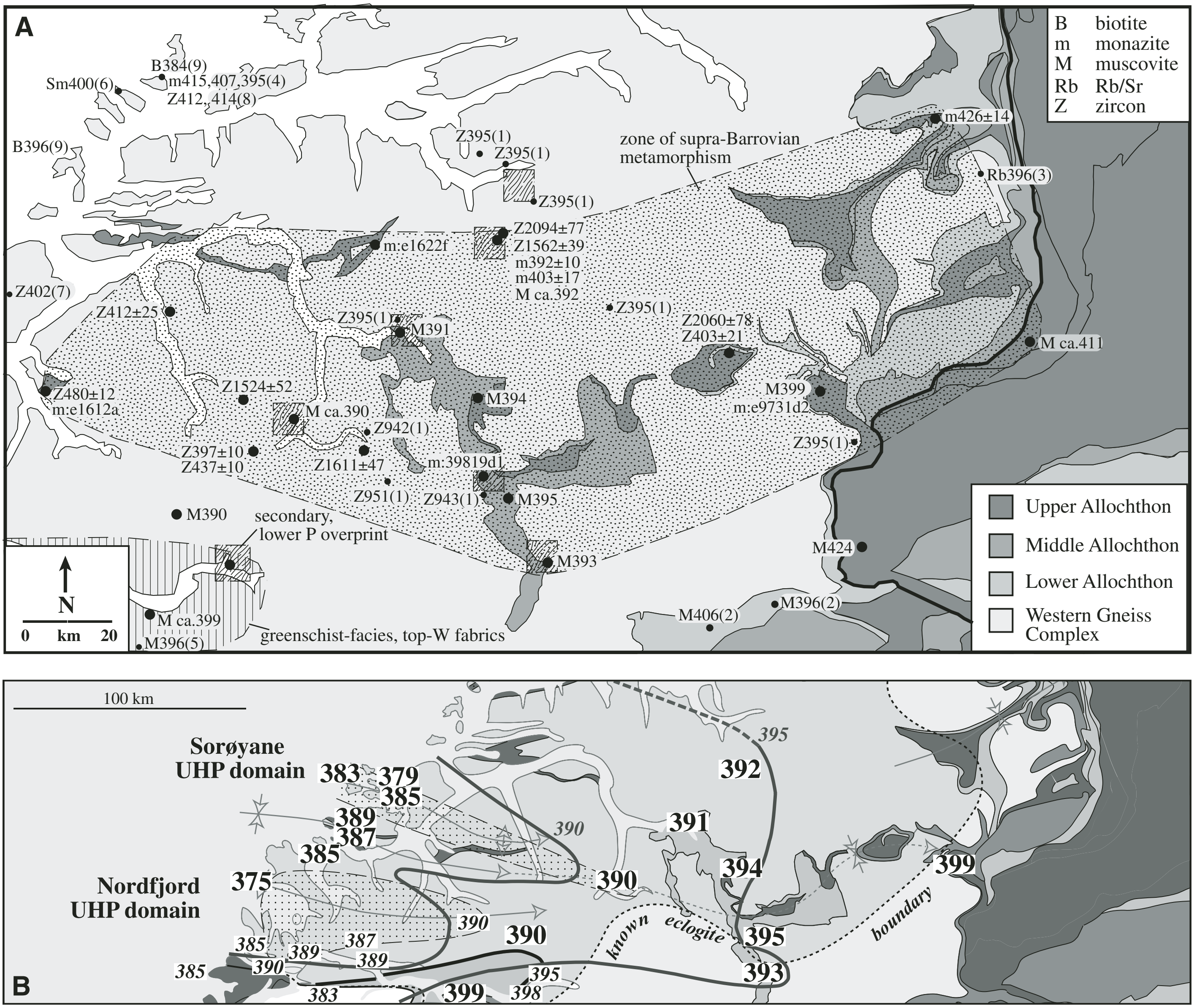



**Figure 9. (A) Summary of data across the Western Gneiss Region from this study and others (see references in Fig. 2 caption). Stippled region shows known area of the supra-Barrovian metamorphism at ~35–45 km depth; square, diagonally hatched zones mark localities of secondary, lower-pressure (Buchan) amphibolite-facies metamorphism at ~20 km depth, and the region shaded with vertical lines denotes greenschist-facies, top-west fabrics associated with late-stage extension along the Nordfjord-Sogn Detachment (Walsh and Hacker, 2004). Note that all biotite and muscovite ages have been recalculated in accordance with Renne et al. (1998). (B) Summary of muscovite $^{40}Ar/^{39}Ar$ ages (in Ma) within the study area and farther west into the ultrahigh-pressure (UHP) domains (after Root et al., 2005). Numbers in large type represent ages from this study and Root et al. (2005). The age uncertainties include only measurement error and error in irradiation parameter, *J*, to better illustrate the westward-decreasing age gradient. Small-type ages are from other studies (see references in Fig. 2 caption). The 395 Ma and 390 Ma chrontours are interpreted to reflect folding (this study; Root et al., 2005).**

The 399 Ma ages for muscovites within the eastern Western Gneiss Region must postdate (1) the ca. 405–400 Ma HP metamorphism at >60 km depth, (2) the supra-Barrovian amphibolite-facies metamorphism at Moho depth, and (3) the final low-*P* (pressure) metamorphism at 20 km depth (documented in the sillimanite-bearing basement rocks); this is a relatively rapid exhumation rate of >8–10 km/m.y. The 389 Ma ages for muscovites in the UHP domains must postdate (1) the ca. 405–400 Ma UHP metamorphism at >100 km depth, (2) the supra-Barrovian amphibolite-facies metamorphism at Moho depth (see also Root et al., 2005), (3) the subsequent low-*P* metamorphism, and (4) the earliest stages of motion along the Nordfjord-Sogn Detachment Zone, which occurred chiefly at amphibolite-facies, but partly at upper greenschist-facies, temperatures. This requires a similarly rapid exhumation rate of >6–9 km/m.y. These exhumation rates agree with the west Western Gneiss Region exhumation rates proposed by others (including Terry et al., 2000a, 2000b; Carswell et al., 2003; Root et al., 2004).

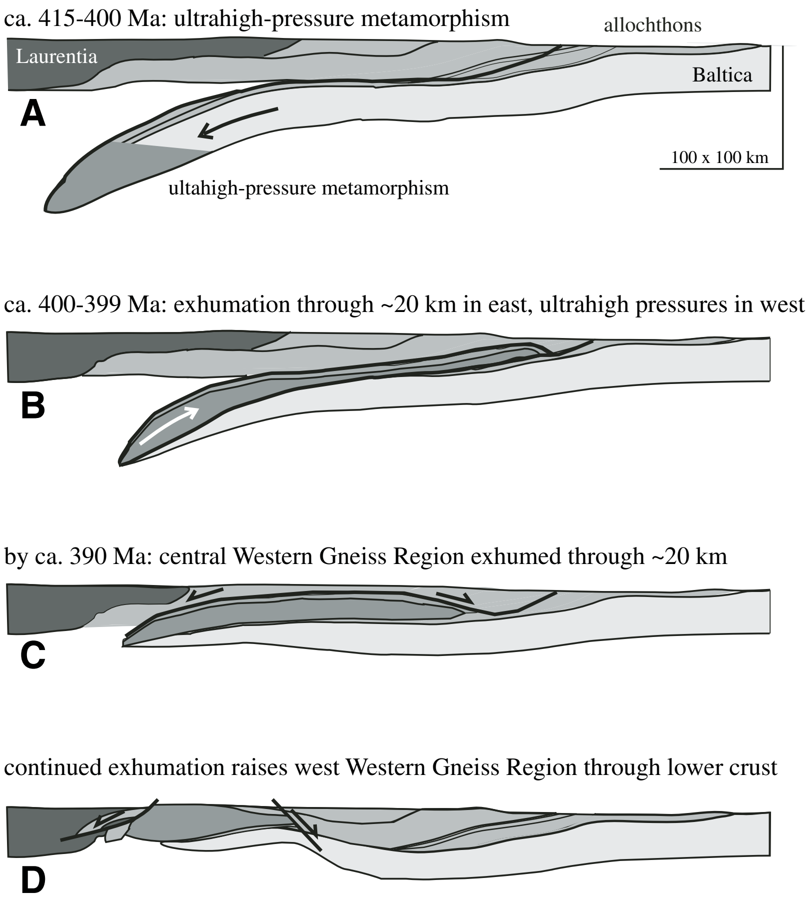



**Figure 10. Tectonic model of UHP metamorphism and exhumation of the Western Gneiss Region. (A) Western Gneiss Region and overlying allochthons were subducted to (U)HP during the Caledonian, as demonstrated by U/Pb zircon ages from eclogites. The westernmost eclogites, closest to the UHP slab tip, were most affected by the Scandian (re)crystallization. (B) By ca. 399 Ma, the subducted slab was tilted ~20° to the west, so that Western Gneiss Region rocks were exhuming through muscovite closure depth (~20 km) in the east while rocks in the west were still undergoing UHP metamorphism. At the Moho, these (U)HP rocks underwent a regional supra-Barrovian metamorphism (Walsh and Hacker, 2004). (C) Underplating of the (U)HP rocks may have caused overthickening of the crust, driving extension. (D) Continued extension along top-west low-angle detachments like the Nordfjord-Sogn Detachment raised the rocks of the westernmost Western Gneiss Region through the crust by ca. 370 Ma (Root et al., 2005).**

The diachronous cooling history and similar, fast exhumation rates across the entire Western Gneiss Region demonstrate that the *entire* Western Gneiss Region acted as *a single unit* during exhumation. The syn-UHP kinematics of the collision zone were essentially reversed *en block* during the exhumation, requiring either detachment and rise of part of the downgoing plate (à la Chemenda et al., 2001) or a reversal in plate motion (Fig. 10).

## CONCLUSIONS

U/Pb zircon and monazite ages from across the Western Gneiss Region reveal a wider range of Precambrian protolith ages than previously reported; our data demonstrate the presence of Svecofennian and older protoliths in the east that will be helpful in reconstructing the pre-Caledonian Baltica margin. Eclogite zircons show exclusively Caledonian metamorphism, indicating that oceanic and continental allochthons were emplaced onto the Western Gneiss Complex before the entire package was subducted to (U)HP. These zircons demonstrate that the age of the high-pressure metamorphism in the east overlaps the Scandian UHP event (ca. 415–400 Ma) in the west. Monazite ages imply that, as in the western part of the Western Gneiss Region, the regional high-temperature metamorphism and associated amphibolite-facies metamorphism were Scandian. The study area shows a distinct gradient in $^{40}$Ar/$^{39}$Ar white mica ages, from 399 Ma in the east to 390 Ma in the west. This gradient reveals that the eclogite-facies, eastern part of the Western Gneiss Region cooled through muscovite closure at nearly the same time that UHP metamorphism was active ~200 km to the west, requiring that the slab dipped westward at ~20° at 400–399 Ma. The gradient also requires that the study area rose diachronously through muscovite-closure depths from east to west between 399 and 390 Ma. The *entire* Western Gneiss Region, including the eastern, high-pressure portion, was involved in the Scandian UHP subduction and exhumation.

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