Continental collisions and the creation of ultrahigh-pressure terranes: Petrology and thermochronology of nappes in the central Scandinavian Caledonides

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ABSTRACT

The formation of the vast Devonian ultrahigh-pressure terrane in the Western Gneiss Region of Norway was investigated by determining the relationship between these ultrahigh-pressure rocks and the structurally overlying oceanic and continental Köli and Seve Nappes in the Trondelag-Jämtland region. Thermobarometry and thermochronology reveal that the oceanic Köli Nappes reached peak conditions of 9–10 kbar and 550–650 °C prior to muscovite closure to Ar beginning at ca. 425 Ma. The continental Seve Nappes attained slightly higher pressures and temperatures (~11–12 kbar and 700–725 °C) and closed to Ar loss in muscovite by 415 Ma in the east and by 400 Ma in the west. In contrast, the ultrahigh-pressure rocks were still deep in the mantle at eclogite-facies pressures at 410–400 Ma. These data, in combination with structural, petrological, and thermochronological data from elsewhere in the orogen, show that the ultrahigh-pressure metamorphism occurred in the late stages of continental collision, after the earlier stages of ophiolite emplacement and passive-margin subduction.

Keywords: ultrahigh-pressure, Barrovian, continental collision, argon geochronology, Scandinavian Caledonides.

INTRODUCTION

Ultrahigh-pressure (UHP) terranes, characterized by the presence of regional metamorphic coesite (pressures ≥27 kbar), are widely equated with the collisions between continents—but to what extent is this paradigm correct? Continent-collision orogens form through a series of stages involving (1) early arc ophiolite emplacement and continental passive margin contraction (typified by the modern Australia-Banda arc collision) and subsequent relaxation (typified by Oman), (2) emplacement of oceanic sediments and telescoping of the ophiolite-on-passive-margin assemblage, (3) emplacement of the upper-plate continent with its Andean-style arc, and (4) plateau formation and intracontinental shortening (e.g., Tibet–Pamir). Can UHP terranes form during all of these stages, as implied by Searle et al. (2001)?

This question can be profitably addressed in the Scandinavian Caledonides, an archetype orogenic belt composed of thin, laterally extensive, far-traveled nappes or thrust sheets (Törnebohm, 1888) and three or four HP to UHP provinces of different ages (Brueckner and Roermund, 2004). We focus on the UHP province formed during the 430–390 Ma Scandian orogeny—either the largest or second largest on Earth (Ernst, 2001). These UHP rocks might be a result of early arc ophiolite emplacement (case 1 above), but the latest ophiolite emplacement onto Baltica also happened 10–20 m.y. before ultrahigh pressures were attained. They might be a result of passive margin subduction during the initial stages of continental collision (case 2 above), but sedimentological (Soper et al., 1992) and paleomagnetic (Torsvik et al., 1996) studies suggest that the collision between Baltica (Norway–Sweden) and Laurentia (Greenland–eastern North America) began as much as 20–35 m.y. before the UHP metamorphism. Perhaps they formed as a result of intracontinental subduction, like the Hindu Kush (case 4 above?).

The purpose of this paper is to examine possible cause-and-effect relationships between Scandian UHP tectonism and the emplacement of oceanic and continental thrust sheets onto the Baltica continental margin. We review the petrology and geochronology of the major thrust sheets and then present new thermobarometry and thermochronology from a key section inboard of the UHP terrane. We conclude that the largest Norwegian UHP terrane formed in the end stages of the continental collision, following ophiolite emplacement and passive margin subduction. Throughout, we use the time scales of Tucker and McKerrow (1995) and Tucker et al. (1998).

THE SCANDINAVIAN CALEDONIDES

The Scandinavian Caledonides are conventionally subdivided into a number of structurally defined units: the autochthon, Lower Allochthon, Middle Allochthon, Upper Allochthon, and Uppermost Allochthon (Roberts and Gee, 1985) (Fig. 1). The autochthon consists of Precambrian Baltica basement overlain by Vendian through Upper Silurian sedimentary rocks. The Lower Allochthon is composed of metasedimentary and crystalline rocks, compositionally similar to the autochthon, that have been thrust east-southeastward over the autochthon. In the more deformed and metamorphosed core of the orogen, the Lower Allochthon contains the UHP signature of the Scandian orogeny. These UHP rocks recrystallized at pressures as high as 3.6 GPa at ca. 410–400 Ma (Cuthbert et al., 2000; Terry et al., 2000a; Terry et al., 2000b; Carswell, 2001; Krogh et al., 2003; Root et al., 2004). The Middle Allochthon consists of crystalline and sedimentary rocks also interpreted to have been derived from Baltica, but from farther outboard than the autochthon. The Upper Allochthon consists of continental rocks thought to represent the outermost margin of Baltica, plus ophiolitic rocks interpreted to represent chiefly Iapetus Ocean lithosphere. The Upper Allochthon has been subdivided into many nappes; for the purposes of this study we group them into two simplified units: the Köli

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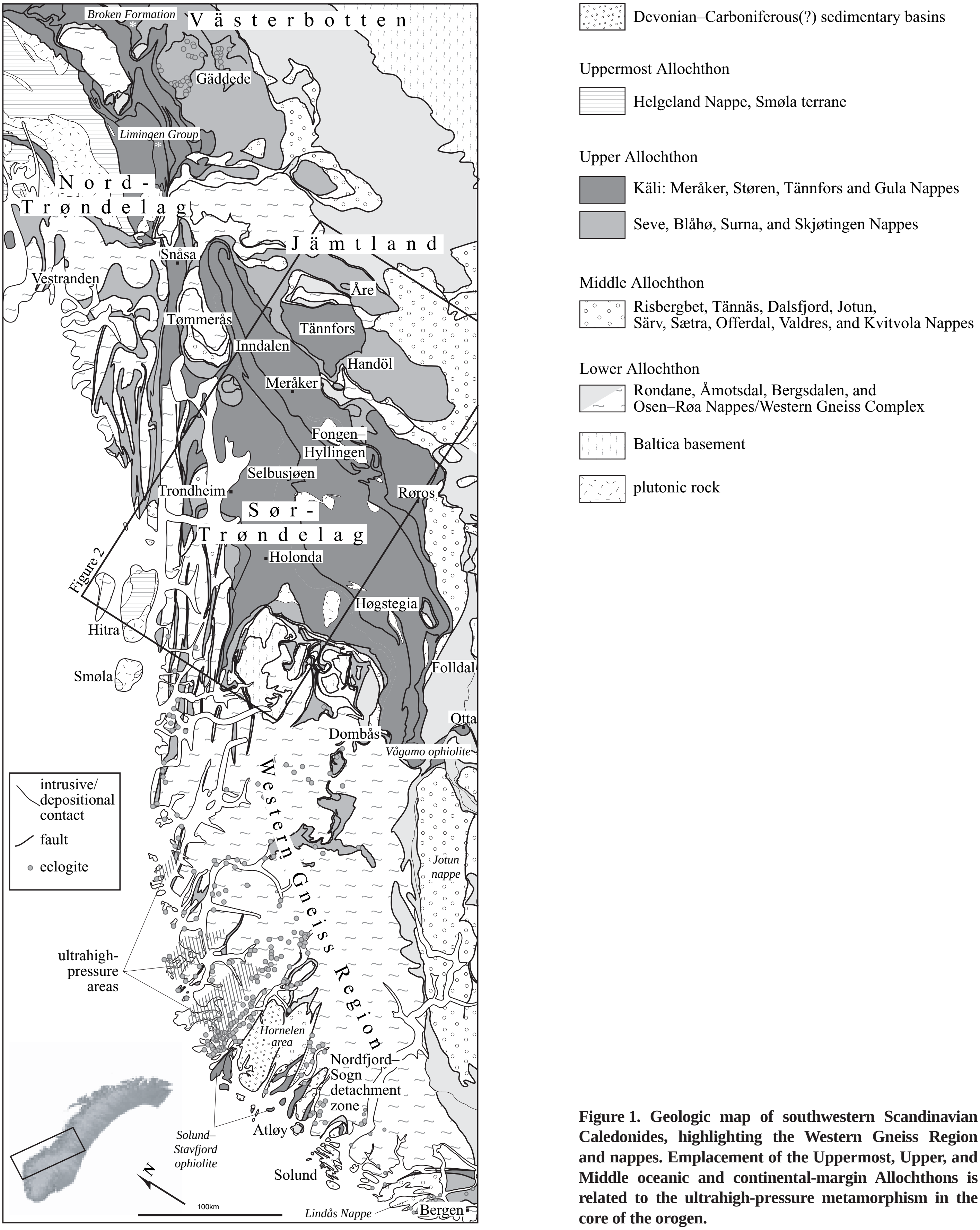

Figure 1. Geologic map of southwestern Scandinavian Caledonides, highlighting the Western Gneiss Region and nappes. Emplacement of the Uppermost, Upper, and Middle oceanic and continental-margin Allochthons is related to the ultrahigh-pressure metamorphism in the core of the orogen.

and Seve Nappes (Stephens and Gee, 1985). The Uppermost Allochthon is lithologically distinct from Baltica and is considered to be a fragment of Laurentia. This study focuses on the tectonic histories of the better-known nappes in the Trondheim region (Fig. 2) but draws on relationships across the Western Gneiss Region.

NAPPE TECTONOSTRATIGRAPHY, PLUTONISM, DEFORMATION, AND METAMORPHISM

Uppermost Allochthon

The Uppermost Allochthon is considered to be a fragment of Laurentia, based on C and Sr isotopic chemostratigraphy (Melezhik et al., 2002; Roberts et al., 2002a), early NW-directed thrust faults (Roberts et al., 2001), and sedimentary successions that are distinctly different from those of Baltica (Stephens and Gee, 1985). It is extensively intruded by the Bindal batholith and related plutons, which are inferred to have developed above a W-dipping subduction zone at 447–430 Ma by melting of diverse crustal and mantle rocks (Nordgulen et al., 1993). A UHP eclogite developed in Cambrian volcanoplutonic arc rocks near Tromsø (Ravna and Roux, 2002) gave a 452 Ma zircon age (Corfu et al., 2002).

Upper Allochthon: Köli Nappes

The Köli Nappes are the uppermost nappes in the Trondheim region. Northeast of the study area, in Jämtland-Västerbotten (Fig. 3), the Köli Nappes are grouped into the Upper, Middle, and Lower Köli Nappes (Gee et al., 1985). There, all three nappes have foliated mafic to felsic igneous basement that has yielded Early Ordovician zircon ages of 492–476 Ma (see references in Fig. 3). In the Middle Köli Nappe (locally, the Stikke Nappe), this igneous suite postdates U-Mo-V-rich sedimentary rocks that have been correlated with Tremadoc (490–485 Ma) sedimentary rocks on the Baltica craton (Sunblad and Gee, 1984). The igneous rocks in all three Köli Nappes are intercalated with and depositionally overlain by calcareous turbidites, limestone, and volcanic rocks (Lutro, 1979; Stephens and Gee, 1985). In the Lower Köli Nappe, the limestone is of Ashgill age (449–443 Ma), the same age as black shales exposed farther east on the autochthon (Stephens and Gee, 1985). Three features have been interpreted to indicate that the Lower Köli Nappe formed on or near the Baltica continental margin: (1) The stratigraphy is similar to that of the Lower Allochthon, except for the presence of volcanic rocks; (2) some turbidites were derived from the east; and (3) the Lower Köli Nappe locally grades lithologically and structurally downward into the Seve Nappes (Stephens, 1980; Stephens and Gee, 1985).

Outcrops south of the study area near Otta (Fig. 1) reveal that older parts of the Köli Nappes were emplaced onto the Baltica margin prior to the late Arenig (Sturt and Roberts, 1991) before younger parts of the Köli Nappes had even formed. There, the MORB-affinity Vågåmo ophiolite lies in fault contact on psammites and crystalline rocks interpreted as part of Baltica and is unconformably overlain by the Otta Conglomerate (Sturt and Roberts, 1991) that has a late Arenig–early Llanvirn (485–464 Ma) fauna of mixed Baltican–Laurentian affinity (Bruton and Harper, 1981). This ophiolite-emplacement event caused the appearance of detrital chromite in upper Caradoc shales and limestones on the craton in the Oslo area (Bjørlykke, 1974).

In the study area (Figs. 2 and 3), the Köli Nappes have been divided into four units: the Støren, Meråker, Tännfors, and Gula Nappes. The Støren and Meråker Nappes begin with Early Ordovician 493–480 Ma mafic and felsic igneous rocks (references in Fig. 3); rock associations and geochemistry suggest that these early rocks of the Støren and Meråker Nappes represent mid-ocean ridge and intraoceanic arc rocks, respectively (Grenne et al., 1999). These rocks were deformed and unconformably overlain (Bjerkgård and Bjørlykke, 1994) in the Meråker–Folldal area by turbidites and conglomerates (Liafjellet, Slågån, Kjølhaugen, and Sulåmo Groups) that include early–middle Llandovery (443–428 Ma) graptolites (Olesen et al., 1973; Hardenby, 1980; Lagerblad, 1984; Bassett, 1985; Gee et al., 1985); in the Hølonda area they are overlain by shoshonitic to calc-alkaline volcanic rocks intercalated with shales and turbidites with late Arenig–early Llanvirn (485–464 Ma) fossils of mainly Laurentian affinity (Nilsen, 1978; Bruton and Bockelie, 1980), capped by Caradoc (458–449 Ma) black shales. The Gula Nappe consists of metasandstone, pelite, migmatitic gneiss, and calcareous phyllite with minor conglomerate, mafic volcanic rock, and felsic volcanic rock, all intruded by trondhjemite-diorite-gabbro associations (Olesen et al., 1973; Nilsen, 1978; Size, 1979; Grenne et al., 1999; Pannemans and Roberts, 2000). The clastic rocks have been interpreted to comprise turbidites (Singsås Formation; Nilsen, 1978) and shallow marine deposits (Åsli Formation; Bjerkgård and Bjørlykke, 1994) from a continental margin or shelf (Grenne et al., 1999). Two features suggest an affinity with the Baltica craton: Tremadoc (490–485 Ma) fossils of Baltican affinity (Spjeldnes, 1985) in a U-V-Mo-rich graphitic phyllite (Gee, 1981). Volcanic rocks in the Gula Nappe are similar to the Upper Köli Nappe (Krutfjellet Nappe) in Västerbotten and Nordland (Stephens and Gee, 1985) and the Støren Nappe (Grenne et al., 1999). The Tännfors Nappe (Fig. 2) has been correlated with the Lower Köli Nappe (Beckholmen, 1978).

The youngest volcanoplutonic sections of the Köli Nappes are marginal-basin ophiolites such as the Solund–Stavfjord (443 ± 3 Ma; Fig. 1) and Sulitjelma (437 ± 2 Ma; north of Fig. 1) (Boyle, 1980; Dunning and Pedersen, 1988; Furnes et al., 1990; Pedersen et al., 1991). Formation of these ophiolites was accompanied by the intrusion of widespread ca. 445–432 Ma gabbroic to granitic, plutonic–hypabyssal bodies in the Upper Köli Nappe (Gee and Wilson, 1974; Senior and Andriessen, 1990; Pedersen et al., 1991; Stephens et al., 1993; Mørk et al., 1997), Middle Köli Nappe (Claesson et al., 1988; Tucker et al., 1990; Roberts and Tucker, 1991), Støren, Meråker (Nilsen et al., 2003), and Gula (Berthomier et al., 1972; Dunning and Grenne, 2000; Nilsen et al., 2003) Nappes. (We include the poorly dated 426 +8/–2 Ma Fongen–Hyllingen gabbro [Wilson, 1985] in this group.) The ca. 450–442 Ma Smøla-Hitra batholith (zircon ages of Tucker, 1988; Gautneb and Roberts, 1989) is slightly older. Sedimentary deposits that apparently postdate this widespread magmatism include the upper Llandovery (443–428 Ma) Broken Formation (Bassett, 1985) in the Lower Köli Nappe, lacustrine deposits of the Limingen Group in the Middle Köli Nappe (Lutro, 1979), and possibly the Horg and Slågån Groups (Vogt, 1945; Siedlecka, 1967) in the study area.

Upper Allochthon: Seve Nappes

The Seve Nappes are traditionally interpreted as late Precambrian to Cambrian rocks of the Baltoscandian continental margin to ocean–continent transition. However, much remains to be understood about their evolution; for example, whether they were actually attached to the rest of Baltica or were a rifted microcontinent is unknown. Their continental character is indicated by the dominance of mica schist, amphibolite, and quartzofeldspathic gneisses, and they have been suggested to be higher-grade equivalents of rocks within the Middle Allochthon (Dallmeyer, 1988); this correlation is reinforced by the presence of 608 Ma crosscutting mafic dikes (Svenningsen, 2001), similar to dikes of the Middle Allochthon.

Middle Allochthon

The Middle Allochthon consists of crystalline and sedimentary rocks interpreted to have been derived from the continental margin of Baltica.

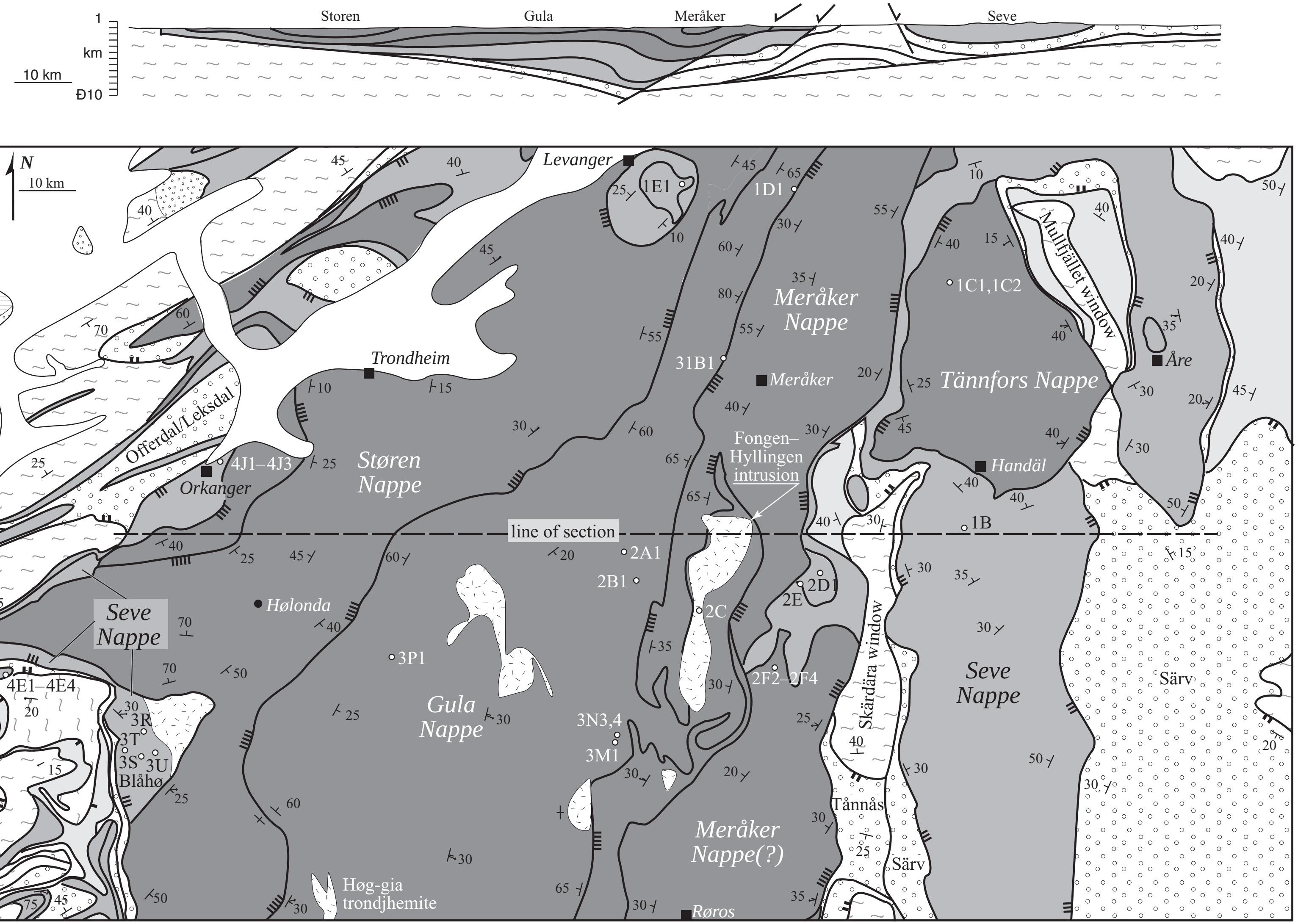

Figure 2. Geologic map and cross section of the study area, a key section through the Scandian allochthons. Symbols same as Figure 1, except that Middle and Lower Allochthons are not differentiated in cross section. The hanging walls of gently dipping faults are marked with teeth, with the number of teeth (1–5) indicating the structural level of the hanging wall. Strike and dip, trend and plunge of foliation and lineation shown. Cross section uses data from Olesen et al. (1973), Hardenby (1980), Roberts and Wolff (1981), Sjöström (1983), Gee et al. (1985), Sjöström et al. (1991), Gee et al. (1994), and Hurich and Roberts (1997). "H15" and "H160" prefixes of samples names are not shown; e.g., "H1601C1" is shown as "1C1".

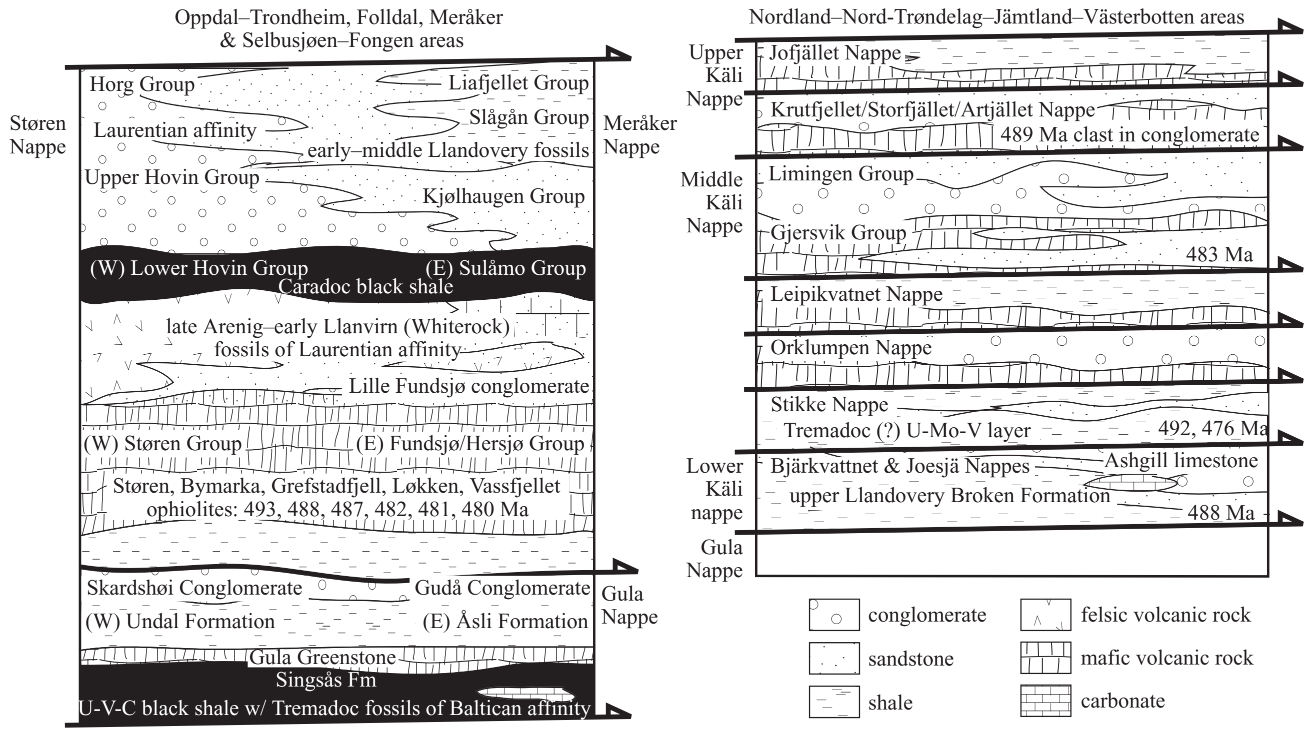

Figure 3. *Schematic* sections of the pre-Llanvirn sections of the Köli Nappes. Zircon ages for older, generally felsic, intrusions are shown. Oppdal-Trondheim, Folldal, Meråker and Selbusjøen-Fongen areas after Vogt (1941, 1945), Siedlecka (1967), Siedlecka and Siedlecki (1967), Wolff (1967), Rui (1972), Olesen et al. (1973), Guezou (1978), Nilsen (1978), Bruton and Bockeliem (1980), Grenne (1980), Hardenby (1980), Lagerblad (1984), Roberts et al. (1984), Bassett (1985), Gee et al. (1985), Spjaeldnes (1985), Stephens and Gee (1985), Dunning and Pedersen (1988), Bjerkgård and Bjørlykke (1994), Grenne and Roberts (1998), Grenne et al. (1999), Roberts and Stephens (2000), and Roberts et al. (2002b). Jämtland-Västerbotten area after Sjöstrand (1978), Lutro (1979), Stephens (1980), Claesson et al. (1983), Sundblad and Gee (1984), Stephens and Gee (1985), Claesson et al. (1988), and Stephens et al. (1993).

In the study area, the Särv, Saetra, and Leksdal Nappes are composed of sandstones intruded by mafic dikes (Gee et al., 1985; Roberts, 1988; Greiling, 1989), while sandstones without dikes compose the Offerdal, Kvitvola, and Dearka Nappes (Gee et al., 1985). The Tännäs, Risberget, and Jotun Nappes include a variety of dominantly alkalic plutonic rocks (Gee et al., 1985).

Lower Allochthon

The Lower Allochthon is composed of weakly metamorphosed (Andréasson, 1980; Arnbom, 1980) sedimentary and subordinate crystalline rocks of the Baltica craton that were shortened and displaced east-southeastward over the autochthon (Gee et al., 1985; Gayer and Greiling, 1989). The sedimentary rocks include Neoproterozoic and Lower Cambrian sandstones overlain by Middle to Upper Cambrian black shales and local Lower Ordovician carbonates, shales, and graywackes (Garfunkel and Greiling, 1998; Greiling et al., 1998). Clastic deposition in the Lower Allochthon and autochthon migrated eastward, beginning in the Lower Allochthon with the Middle to Upper Ordovician Gausdal Formation, continuing with the deltaic upper Llandovery–Wenlock Bruflat Sandstone and ending with the Ludlow and younger, tidal to fluvial, Ringerike Sandstone in the Oslo region (Bockelie and Nystuen, 1985).

Autochthon

The crystalline basement of the Fennoscandian Shield is overlain by thin Vendian siliciclastic rocks, Cambrian alum shale, Tremadoc–Ashgill graywacke and shale, lower Llandovery shallow marine sandstone derived from the west, upper Llandovery limestone and black shale, upper Llandovery–lower Wenlock graywacke, and lower(?) Wenlock fluvial sandstone (Bassett, 1985; Gayer and Greiling, 1989).

PREVIOUS METAMORPHIC PETROLOGY

Understanding the *P-T* histories of the oceanic and continental allochthons is central to reconstructing the role of these thrust sheets in the Scandian orogen and in forming the UHP rocks. The Köli Nappes underwent both regional and contact metamorphism (Fig. 4). The Bymarka ophiolite of the Støren Nappe underwent ~9 kbar epidote-blueschist facies metamorphism in early Arenig time (ca. 485–475 Ma) (Eide and Lardeaux, 2002). Regional Barrovian metamorphism in other Köli Nappes known to predate the 445–432 Ma intrusive event reached kyanite + staurolite + garnet (Stephens and Gee, 1985) and garnet + staurolite + biotite (Mørk, 1985) grade (Fig. 4). The 445–432 Ma intrusions then caused contact metamorphism (Birkeland and Nilsen, 1972). Scandian postintrusion regional metamorphism in the Köli is also Barrovian and spatially variable in grade. In the study area, metamorphic grade increases westward within the Meråker Nappe from greenschist to amphibolite facies (Siedlecka, 1967; Dudek et al., 1973; Olesen et al., 1973; Lagerblad, 1984). The Fongen–Hyllingen gabbro was foliated and metamorphosed to kyanite + garnet + staurolite + biotite (Wilson, 1985). The lowest unit in the Fundsjø Group, the Gudå Conglomerate, shows garnet + staurolite

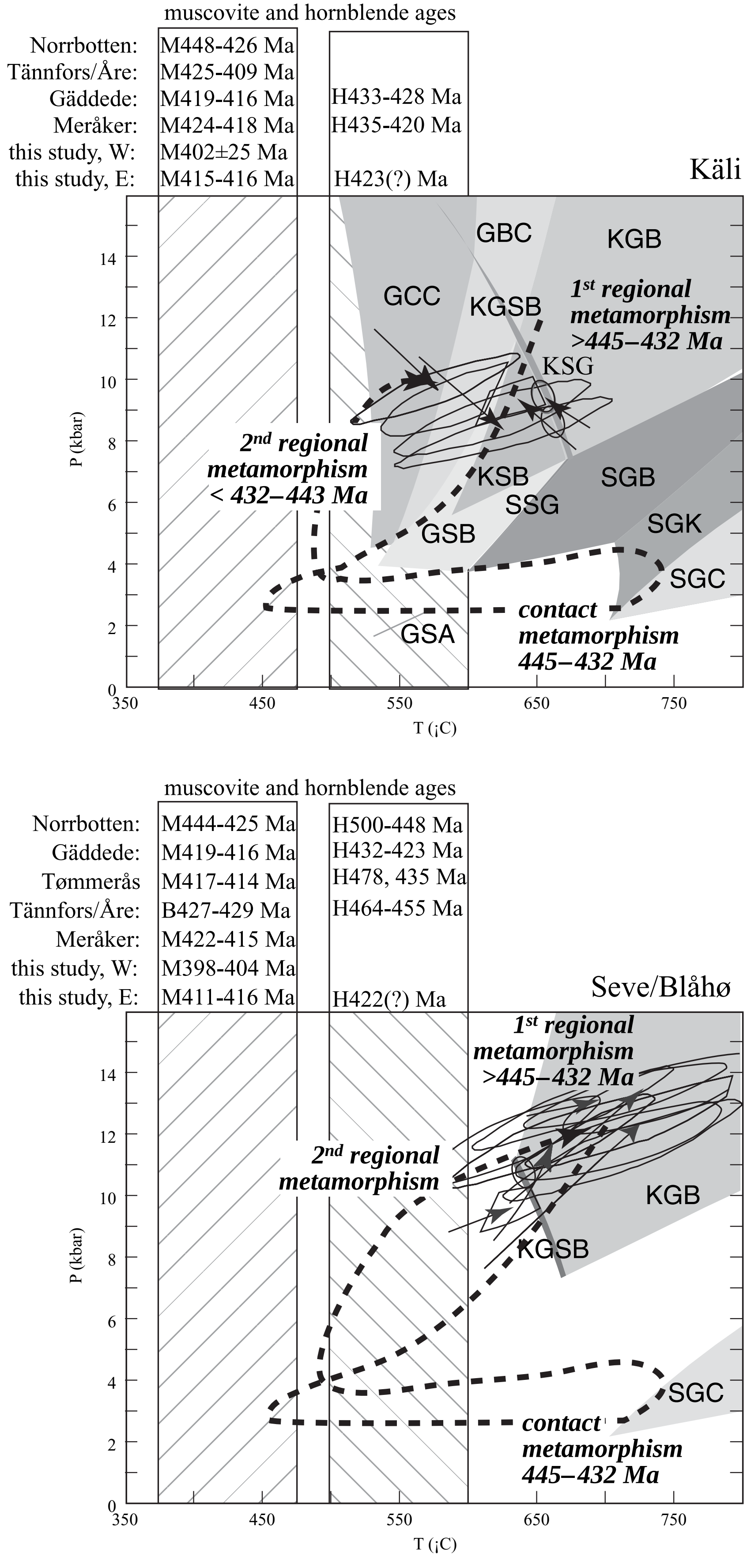

Figure 4. Pressure-temperature diagrams for Köli and Seve/Blåhø Nappes show early regional metamorphism older than ca. 440 Ma, followed by contact metamorphism at ~3 kbar, and final regional metamorphism at ~9 or ~12 kbar, respectively (pre–440 Ma metamorphism not shown). Stability fields of mineral assemblages reported previously are shown in shades of gray (from the program "Gibbs" by Spear and Menard, 1989). Calculated *P-T* conditions from this study shown by ellipses depicting ±1σ absolute uncertainties and circles showing conditions inferred from mineral assemblages; calculated apparent *P-T* paths from this study shown by thin arrows. Dashed line shows hypothetical *P-T* path connecting 1st regional metamorphism (defined by gray fields) with contact metamorphism (defined by SGC and SGK fields) with 2nd regional metamorphism (defined by ellipses). Diagonal ruling shows approximate closure temperatures for hornblende and mica; corresponding $^{40}Ar/^{39}Ar$ ages are shown at top of each panel. Field labels: GBC—garnet-biotite-chlorite; GCC—garnet-chloritoid-chlorite; GSA—garnet-sillimanite-andalusite; GSB—garnet-staurolite-biotite; KGB—kyanite-garnet-biotite; KGSB—kyanite-garnet-staurolite-biotite; KSB—kyanite-staurolite-biotite; KSG—kyanite-staurolite-garnet; SGB—sillimanite-garnet-biotite; SGC—sillimanite-garnet-cordierite; SGK—sillimanite–garnet–K-feldspar; SSG—sillimanite-staurolite-garnet.

+ biotite (Dudek et al., 1973) and kyanite + garnet + staurolite + biotite overprinted by sillimanite (Lagerblad, 1984). The Tännfors Nappe is characterized by an inverted metamorphic gradient from greenschist to garnet-amphibolite facies, but the lowermost greenschist-facies unit underwent prograde metamorphism at the base to lower amphibolite facies (Dallmeyer et al., 1985; Bergman and Sjöström, 1997). Garnet + chlorite + chloritoid grew in Jämtland, Västerbotten, and Nordland (north of Fig. 1) during nappe emplacement (Stephens, 1980; Mørk, 1985). The Gula Nappe shows inward increases in metamorphic grade from both the west and the east, beginning at the lowest grade with garnet + biotite + chlorite assemblages (Lagerblad, 1984; Bjerkgård and Bjørlykke, 1994) (Fig. 4). In a northern part of the Gula Nappe near Snåsa, kyanite + garnet + biotite, kyanite + staurolite + biotite, garnet + staurolite + biotite, and kyanite + garnet + staurolite + biotite ± sillimanite assemblages (Lagerblad, 1984) are overgrown by sillimanite + staurolite + garnet (Andréasson and Johansson, 1982). Sillimanite + garnet + biotite (Dudek et al., 1973) and sillimanite + garnet + K-feldspar (Lagerblad, 1984) migmatite in the Inndalen and Fongen areas are associated with trondhjemite bodies (Dudek et al., 1973; Olesen et al., 1973). In the southern part of the Gula Nappe (Folldal area), metamorphic grade reaches kyanite + staurolite + biotite(?) (Bjerkgård and Bjørlykke, 1994). Contact metamorphism around the Fongen–Hyllingen intrusion reached garnet + sillimanite + cordierite grade and predated the growth of regional kyanite + garnet + staurolite + biotite assemblages (Olesen et al., 1973); farther south Bøe (1974) reported this same secondary mineral assemblage replacing contact metamorphic andalusite. In the Dombås area, Guezou (1978) described kyanite + staurolite + biotite overprinting garnet + staurolite + andalusite contact metamorphism. Isograds within the Gula Nappe cut lithologic boundaries (Dudek et al., 1973; Olesen et al., 1973; Lagerblad, 1984; McClellan, 1994) and also cross into the Meråker Nappe, implying a premetamorphic juxtaposition of these two thrust sheets.

Evidence of a pre-Scandian orogeny in the Seve Nappes comes from geochronology and metamorphic petrology. An early high-pressure event is indicated by eclogites and garnet peridotites in lower thrust sheets of the Seve Nappes in Gäddede and Norrbotten (north of Fig. 1) (Nicholson, 1984; van Roermund, 1985; Santallier, 1988; van Roermund, 1989; Kullerud et al., 1990); we calculate pressures of 18–21 kbar and temperatures of 500–600 °C for this event using Thermocalc and mineral compositions from the aforementioned studies. Two of these eclogites in Norrbotten yielded Sm/Nd isochrons of ca. 503 Ma (Mørk et al., 1988), and titanite from calc-silicates in the same general area gave ages of 495–480 Ma (Essex et al., 1997). The eclogites and garnet peridotites in Jämtland gave an age of ca. 450 Ma (Brueckner et al., 2004).

The Middle Seve Nappe in the Åre and Handøl areas shows an early low-pressure granulite-facies metamorphism in which sillimanite + garnet + cordierite were stable (Fig. 4) (Arnbom, 1980; Sjöström, 1984), suggestive of contact metamorphism, large-scale extension, or rifting. This low-*P* metamorphism in the Åre and Handøl areas is overprinted by Barrovian metamorphism that produced kyanite + garnet + staurolite + biotite in the Upper Seve Nappe, kyanite + garnet + biotite in the Middle Seve Nappe, and created an inverted metamorphic gradient in the Lower Seve Nappe ranging down to greenschist facies (Arnbom, 1980; Sjöström, 1984; Bergman and Sjöström, 1997). This Barrovian metamorphism was widespread, also producing kyanite + garnet + biotite in Jämtland (Sjöstrand, 1978) and kyanite + garnet + staurolite + biotite in the Tømmerås area (Andréasson, 1980). It was accompanied by amphibolite-facies mylonitization along internal nappe contacts (Sjöström, 1984; Bergman and Sjöström, 1997), implying that the mylonitization and metamorphism were coincident with construction of the nappe stack. Coeval or subsequent greenschist-facies retrogression accompanied motion along the Seve–Köli and Seve–Middle Allochthon contacts (Sjöström, 1984; Bergman and Sjöström, 1997).

NEW METAMORPHIC PETROLOGY

Because the extant metamorphic petrology includes few quantitative pressure determinations—and yet such information is needed to constrain depths of burial and exhumation—we studied selected parts of the Köli and Seve Nappes in the Trondelag–Jämtland region (Figs. 4 and 5). Pelites, both aluminous and calcareous, are widespread and therefore enable an areally comprehensive assessment of the *P-T* evolution of these nappes. All the pelites studied (Tables 1 and 2) include mineral assemblages indicating a Barrovian metamorphic sequence, but quantitative *P-T* determinations reveal development at pressures ~50% higher than a classic Barrovian metamorphic sequence. These pelite assemblages range from garnet + biotite + chlorite through staurolite + biotite + garnet or kyanite to kyanite + garnet + biotite; sillimanite did not develop during this paragenetic sequence. Calcareous rocks, characterized by the presence of hornblende, typically lack staurolite and kyanite. Nearly all outcrops of the Støren, Meråker, and Tännfors Nappes not only lack pelites, but also garnet.

Mineral compositions were measured with the University of California, Santa Barbara, SX-50 electron microprobe operated at 15 kV and 15 nA using natural and synthetic mineral standards (Table DR1, electronic supplement).[1] We determined peak pressures and temperatures using Thermocalc (Powell and Holland, 1988) (Table 2). Where possible, we used the intersections between the well-characterized garnet-biotite (GARB in Table 2), garnet-biotite-muscovite-plagioclase (GBMP in Table 2), garnet-aluminumsilicate-silica-plagioclase (GASP in Table 2), garnet-hornblende (GARH in Table 2), and garnet-hornblende-plagioclase-quartz (GHPQ in Table 2) reactions. Otherwise we used Thermocalc to calculate intersections among as many reactions defined by well-known activities as possible. Generally, we find that the garnet-aluminumsilicate-silica-plagioclase and garnet-biotite-muscovite-plagioclase barometers yield pressures that are statistically indistinguishable; the pressure differences are <1 kbar, and the pressures are well correlated, with a slope of 0.86 and χ^2 = 0.05. Garnet-hornblende-plagioclase-quartz and garnet-biotite-muscovite-plagioclase are similarly close, with a slope of 1.2 and χ^2 = 0.24. Pressures and temperatures calculated with Thermocalc were checked for consistency with the petrogenetic grid constructed from the Holland and Powell (1998) database using Gibbs (ver. March 2001; Spear and Menard, 1989). Pressure-temperature paths were modeled using the differential thermodynamics program of Gibbs (Spear and Menard, 1989).

Garnets in the Seve Nappes are typically 4–10 mm in diameter and idioblastic; some show textural evidence for two stages of growth. Those from hornblende-free samples show rimward increases in Mg# [Mg/(Mg + Fe)] of 3–9 percentage points and rimward increases in grossular content of 2–12 mol%. Garnets in hornblende-bearing rocks are invariably significantly more calcic. None of the garnets shows rimward Mn increases indicative of resorption. Plagioclase in samples without hornblende shows rimward decreases in anorthite content, whereas plagioclase in samples with hornblende shows rimward increases in anorthite content. Calculated pressures and temperatures for the Seve Nappes range from ~645 °C and 10 kbar to 745 °C and 13 kbar (Figs. 4 and 5); the zoning described above implies that those conditions were reached via heating and compression (Fig. 4).

[1]GSA Data Repository item 2005024, electron probe data, is available on the Web at http://www.geosociety.org/pubs/ft2005.htm. Requests may also be sent to editing@geosociety.org.

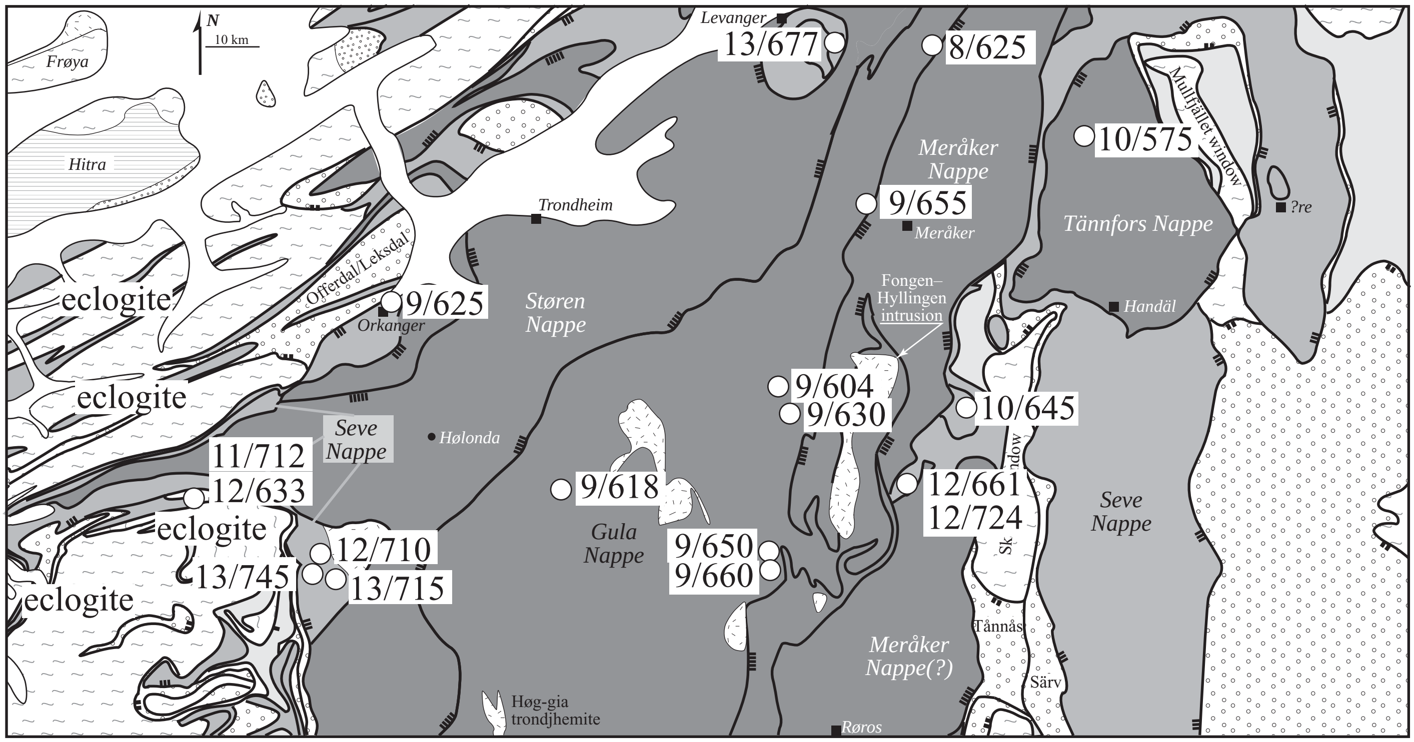

Figure 5. Pressure (kbar) / temperature (°C) determinations from the Trondelag-Jämtland region show temperatures of 604–660 °C at 30–35 km depth for the Gula Nappe and 645–745 °C at 40–50 km for the Seve Nappes.

Garnets in the Gula Nappe are typically <1 mm in size (locally reaching 3 mm) and range from xenoblastic to idioblastic. Garnet from one sample (H1603P1) shows a rimward increase in Mg# of 4 mol% and a decrease in Ca of 10 mol%; these changes are compatible with decreasing pressure and increasing temperature. Garnets from four Gula Nappe samples show core–rim decreases in Mg# of ≤8 percentage points and core–rim increases of 2–7 mol% grossular. These changes are compatible with increasing pressure and decreasing temperature and are likely the result of regional metamorphic overprinting of a contact metamorphic mineral assemblage. Calculated pressures and temperatures for the Gula Nappe cluster in a restricted range— ~604–660 °C and ~9 kbar—distinctly lower than those in the Seve Nappes. In the eastern part of the Gula Nappe, this regional metamorphism overprints an earlier low-pressure contact metamorphism. One, possibly two, samples from the western part of the Gula Nappe record heating and decompression. Thus, the Gula Nappe may have been assembled at ~9 kbar from two distinct pieces. The fault identified by Bjerkgård and Bjørlykke (1994) along the Singsås–Åsli contact is a potential candidate.

The difference in pressure between the Gula and Seve Nappes implies different lev-

TABLE 1. SAMPLES AND UTM COORDINATE LOCATIONS

Sample	UTM easting	UTM northing	Unit	Rock type
H1531B1	629134	7038262	Gula	Pelite
H1601B	370955	7014712	Seve	Amphibolite
H1601C1	369988	7047900	Tännfors	Calcareous pelite
H1601C2	369988	7047900	Tännfors	Calcareous metavolcanic
H1601D1	642868	7066811	Gula	Pelite
H1601E1	622316	7068535	Seve (Skjøtingen)	Pelite
H1601E2	622316	7068535	Seve (Skjøtingen)	Pelite
H1602A1	612416	7004747	Gula	Pelite
H1602B1	615154	6999644	Gula	Pelite
H1602C	624618	6994276	Fongen-Hyllingen	Gabbro
H1602D1	646431	7002166	Seve (Øyfell)	Pelite
H1602E	644244	6999848	Seve (Essandsjø)	Amphibolite
H1602F2	638465	6986475	Seve over Saetra	Amphibolite
H1602F3	638465	6986475	Seve over Saetra	Pelite
H1602F4	638465	6986475	Seve over Saetra	Pelite
H1603M1	612598	6971848	Gula	Pelite
H1603N3	612396	6972866	Gula	Pelite
H1603N4	612396	6972866	Gula	Pelite
H1603P1	573565	6987388	Gula	Pelite
H1603S1	532116	6973976	Seve (Blåhø)	Pelite
H1603T1B	532116	6973976	Seve (Blåhø)	Pelite
H1603T3	532116	6973976	Seve (Blåhø)	Amphibolite
H1603T7	532116	6973976	Seve (Blåhø)	Pelite
H1604E1	507598	6984251	Seve (Blåhø)	Pelite
H1604E2	507598	6984251	Seve (Blåhø)	Amphibolite
H1604E4	507598	6984251	Seve (Blåhø)	Pelite
H1604J1	05454xx	70225xx	Seve (Blåhø)	Amphibolite
H1604J2	05454xx	70225xx	Seve (Blåhø)	Pelite
H1604J3	05454xx	70225xx	Seve (Blåhø)	Pelite

els of burial and exhumation—~30–35 km and 40–50 km, respectively. These are "lower crustal" metamorphic conditions, signifying that these rocks represent either the exhumed base of a crustal section or a distinct layer buried beneath an overlying section of normal crustal thickness. The lower pressures recorded in the Gula Nappe imply structural separation from the Seve Nappes.

In conjunction with the petrological observations of previous workers discussed above, it is clear that parts of each of the major composite units—Köli Nappes and Seve Nappes—experienced regional metamorphism before and after a contact metamorphic event. In some cases, the early regional metamorphism predated the contact metamorphism to such an extent that a cooling period between the two is likely; this is shown in the hypothetical, long-term *P-T* paths of Figure 4. We deduce that cooling must also have followed the contact metamorphism for three reasons: (1) Contact metamorphic textures are locally preserved; (2) calculated *P-T* paths for the subsequent regional metamorphism of many samples show heating from sub-contact-metamorphic temperatures; and (3) calculated *P-T* paths for the subsequent regional metamorphism of other samples show cooling.

TABLE 2. THERMOBAROMETRY RESULTS

Sample	Minerals	Thermometer	Barometer	*T* (°C)	*P* (kbar)	cor
H1531B1	Ky St Grt Bt Pl Qtz (no Ms)	GARB	GASP	685 ± 50	9.6 ± 1.0	0.75
"		KFMASH	GASP	~655	9.5 ± 1.0	n/a
H1601C1	Grt Bt Ms Hbl Pl Qtz	GARB	GBMP	577 ± 49	9.6 ± 0.9	0.89
"		GARH	GHPQ	551 ± 39	9.6 ± 0.8	0.73
H1601D1	Grt Bt Ms Hbl Pl Qtz	GARB	GBMP	625 ± 63	8.2 ± 1.0	0.92
H1601E2	Grt Bt Ms Hbl Pl Qtz	GARB	GBMP	677 ± 59	12.8 ± 1.1	0.91
"		GARH	GHPQ	627 ± 86	12.7 ± 2.0	0.8
H1602A1	Grt Bt Ms Chl Pl Qtz	GARB	GBMP	604 ± 46	9.5 ± 1.0	0.76
H1602B1	St Grt Bt Ms Pl Qtz	GARB	GBMP	574 ± 50	8.4 ± 1.0	0.87
"		KFMASH	GBMP	~630 ± 20	9.4 ± 0.8	n/a
H1602D1	Ky St Grt Bt Ms Hbl Pl Qtz	GARB	GBMP	601 ± 51	9.8 ± 0.9	0.87
"		KFMASH	GBMP	~650	10.5 ± 0.9	n/a
"		GARB	GASP	600 ± 50	10.0 ± 1.0	0.75
"		KFMASH	GASP	~645	10.5 ± 1.0	n/a
"		GARH	GHPQ	560 ± 37	7.6 ± 0.7	0.65
H1602F3	Grt Bt Ms Pl Qtz	GARB	GBMP	661 ± 61	11.7 ± 1.2	0.88
H1602F4	Grt Bt Ms Pg Pl Qtz	GARB	GBMP	724 ± 65	12.4 ± 1.2	0.89
H1603M1	Ky St Grt Bt Ms Pl Qtz	GARB	GBMP	610 ± 52	9.2 ± 1.0	0.84
"		GARB	GASP	610 ± 50	9.1 ± 1.0	0.75
"		KFMASH	GBMP	~650	9.5 ± 0.9	n/a
"		KFMASH	GASP	~650	9.2 ± 1.0	0.75
H1603N3	Ky St Grt Bt Ms Pl Qtz	GARB	GBMP	600 ± 52	8.3 ± 0.8	0.85
"		KFMASH	GBMP	~660	9.2 ± 0.7	n/a
"		GARB	GASP	575 ± 50	7.9 ± 1.0	0.75
"		KFMASH	GASP	~660	8.7 ± 1.0	n/a
H1603P1	Grt Bt Ms Pl Qtz	GARB	GBMP	618 ± 57	8.7 ± 1.0	0.84
H1603S1	Ky Grt Bt Ms Pl Qtz	GARB	GBMP	742 ± 60	12.9 ± 1.1	0.86
"		GARB	GASP	745 ± 60	13.3 ± 1.1	0.79
H1603T1B	Ky Grt Bt Ms Pl Qtz	GARB	GBMP	713 ± 61	12.8 ± 1.0	0.9
"		GARB	GASP	710 ± 61	11.7 ± 1.0	0.78
"		all reactions	all reactions	701 ± 71	11.4 ± 1.5	0.78
H1603T7	Ky Grt Bt Ms Pl Qtz	GARB	GBMP	712 ± 60	12.7 ± 1.0	0.9
"	[St inclusions in Grt]	GARB	GASP	715 ± 60	13.2 ± 0.8	0.86
"		all reactions	all reactions	680 ± 69	12.6 ± 1.5	0.86
H1604E1	Grt Hbl Pl Qtz	GARH	GARHB	633 ± 53	11.7 ± 1.2	0.86
H1604E4	Grt Bt Ms Pl Qtz	GARB	GBMP	712 ± 69	11.4 ± 1.3	0.89
H1604J2	Grt Bt Ms Pl Qtz	GARB	GBMP	621 ± 53	9.3 ± 0.9	0.84
"		KFMASH	GBMP	625 ± 15	9.3 ± 0.9	n/a

Note: "KFMASH" refers to pelite phase diagram produced with Gibbs (Spear and Menard, 1989) from Holland and Powell (1998) database; all other calculations from THERMOCALC v3.1 with May 2001 database (Powell and Holland, 1988). Mineral formulae and activities were calculated with the program "A-X", by Tim Holland and Roger Powell; A-X calculates Fe^{3+} in clinopyroxene using charge balance considerations, which Carswell et al. (2000) demonstrated is a good approximation to Fe^{3+} measured by Mössbauer spectrometry. Uncertainties are ±1σ; "cor" is correlation coefficient from THERMOCALC. Mineral abbreviations after Kretz (1983). GARB—garnet-biotite; GARH—garnet-hornblende; GASP—garnet-aluminumsilicate-silica-plagioclase; GBMP—garnet-biotite-muscovite-platioclase; GHPQ—garnet-hornblende-plagioclase-quartz.

PREVIOUS THERMOCHRONOLOGY

Extensive thermochronologic work has been conducted in the allochthons in the area of Figure 1. In addition to the (chiefly U/Pb) intrusion ages mentioned above, $^{40}Ar/^{39}Ar$ ages indicate the existence of *at least* two major thermal events (Fig. 4). Rather old hornblende ages of 500 Ma to 448 Ma come from the Seve Nappes in the Norrbotten (n ≈ 15; north of Fig. 1), Tømmerås, and Åre areas (n = 4), with a cluster in the 469–463 Ma time range (Dallmeyer et al., 1985; Dallmeyer and Gee, 1986; Dallmeyer, 1990; Dallmeyer and Stephens, 1991; Page, 1992; Svenningsen, 2000). This range of older hornblende ages suggests that a major amphibolite-facies metamorphism in the Seve Nappes ended by ca. 469–463 Ma and that temperature subsequently did not rise significantly above ~550 °C. Slightly younger hornblende ages of 464–455 Ma near Åre (Dallmeyer, 1990) may reflect Ar loss from a subsequent metamorphism or may indicate southward younging of this major amphibolite-facies metamorphism. Muscovite $^{40}Ar/^{39}Ar$ ages from the Seve Nappes and Middle Allochthon in Norrbotten are ~35 m.y. younger than the hornblende ages, at 444–425 Ma (most are 434–425 Ma) (Dallmeyer and Gee, 1986; Dallmeyer and Stephens, 1991; Page, 1992; Svenningsen, 2000), indicating slow cooling rates of ~3 °C/m.y.

In contrast, $^{40}Ar/^{39}Ar$ hornblende ages from the Meråker Nappe in the study area form a younger, fairly tight group at 435–420 Ma (Dallmeyer et al., 1985; Dallmeyer, 1990). In the Gäddede area (Fig. 1), the same range, 433–423 Ma (n = 4), is evident in $^{40}Ar/^{39}Ar$ hornblende ages from the Lower Köli Nappe, the lowest nappe of the Middle Köli Nappe, and the Seve Nappes. These hornblende ages suggest that a major amphibolite-facies metamorphism ended by ca. 435–420 Ma. Like the hornblende ages, muscovite ages from the Seve and Köli Nappes from the Gäddede area and the study area are slightly younger, mostly 425–416 Ma (Dallmeyer et al., 1985; Dallmeyer, 1988, 1990), suggesting more rapid cooling rates of ~15 °C/m.y. Biotite ages are similar but span a larger apparent age range, presumably because of undetected excess ^{40}Ar.

NEW THERMOCHRONOLOGY

To tie the metamorphic history of the inboard oceanic and continental allochthons more tightly to that of the UHP core of the orogen, we measured $^{40}Ar/^{39}Ar$ ages of eight hornblendes, two biotites, and eight K-white micas (henceforth muscovite), using analytical procedures detailed by Calvert et al. (1999). Summaries of the results are in Figures 6 and 7 and Table 3,

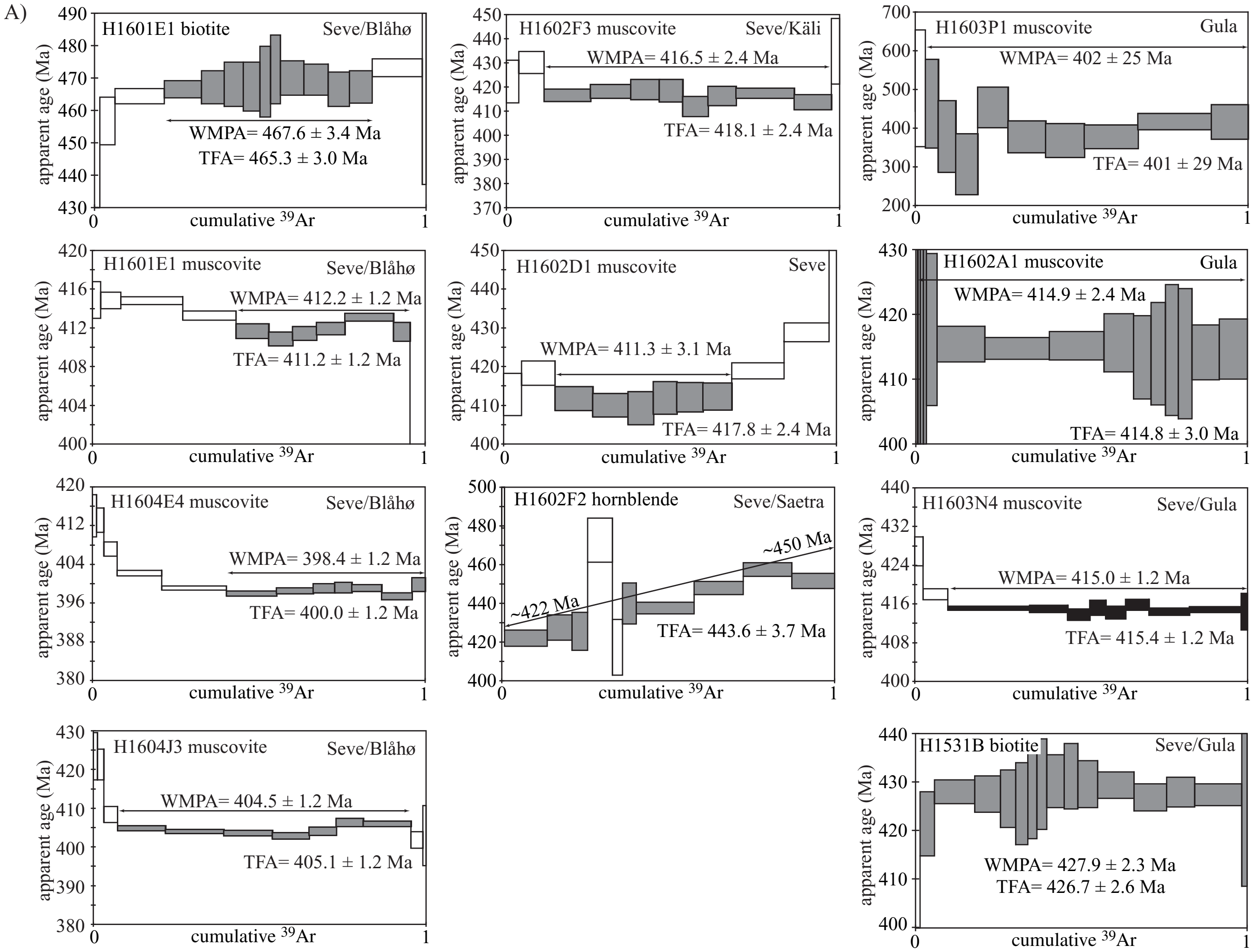

Figure 6. $^{40}Ar/^{39}Ar$ data. (A) Well-behaved spectra. Step ages show uncertainties of ±1σ, and age uncertainties are ±2σ (*continued on following page*).

which show age uncertainties of ±2σ. Most of the hornblendes yielded crankshaft-shaped spectra with isotopic ratios indicative of excess ^{40}Ar and no well-fit isochrons (Fig. 6B). Three hornblende samples, however, yielded interpretable spectra. Hornblende H1602E from the Seve Nappes gave a crankshaft-shaped spectrum but a well-fit isochron with an age of 865 ± 198 Ma for 24% of the gas; while not precise, the isochron suggests that this sample has not been heated above ~500–600 °C since the late Precambrian (Fig. 6C). Six steps with low K/Ca ratios yield an isochron age of 466 ± 28 Ma for H1604E2. Hornblende H1602F2, from either the Seve or Saetra Nappes, gave a more-or-less monotonically increasing age spectrum from ca. 422 to ca. 450 Ma (Fig. 6A); we provisionally interpret this spectrum to indicate initial closure at ca. 450 Ma, followed by Ar loss at ca. 422 Ma or slow cooling to ca. 422 Ma. Hornblende H1602C, from the Fongen–Hyllingen intrusion (Fig. 6D), gave a saddle-shaped or monotonically increasing age spectrum, with the bulk of the step ages ranging from 431 to 435 Ma; an isochron from most of the steps gave 422.9 ± 4.6 Ma. We provisionally accept the isochron age of 423 Ma as the best age of the sample; an imprecise U/Pb zircon age of 426 +8/–2 Ma (Wilson, 1985) from the same intrusion lends credence to this interpretation.

Four micas were dated from Seve Nappes outcrops in the southwestern half of the study area. The three muscovites, H1601E1, H1604E4, and H1604J3, gave plateau ages ranging from 398 to 412 Ma; a biotite from H1601E1 yielded a plateau age that is much older and therefore must be contaminated by excess ^{40}Ar. Muscovite H1602D1 from the Seve Nappes yielded a plateau age of 411 Ma. Muscovite H1602F3 from the Seve Nappes gave a plateau age of 416 Ma. Four micas from the Gula Nappe were dated: Paragonite H1603P1 from the western half of the Gula Nappe gave an imprecise plateau age of 402 ± 25 Ma, whereas muscovites H1602A1 and H1603N4 from the eastern half are 415 ± 2 Ma and 415 ± 1 Ma, respectively. Biotite H1531B1, like H1601E1, is anomalously old when compared to muscovite ages and is probably affected by excess ^{40}Ar.

The closure temperature for hornblende and muscovite in these rocks, with their mm-scale grains and probable 15 °C/m.y. cooling rates, are ~575 and 475 °C, respectively (Harrison, 1981; Kirschner et al., 1996). The high metamorphic temperatures documented for the study area exceeded muscovite closure everywhere and hornblende closure everywhere except perhaps in the Tännfors Nappe. This requires that the Barrovian metamorphism ended in the eastern part of the study area by ca. 425 Ma and in

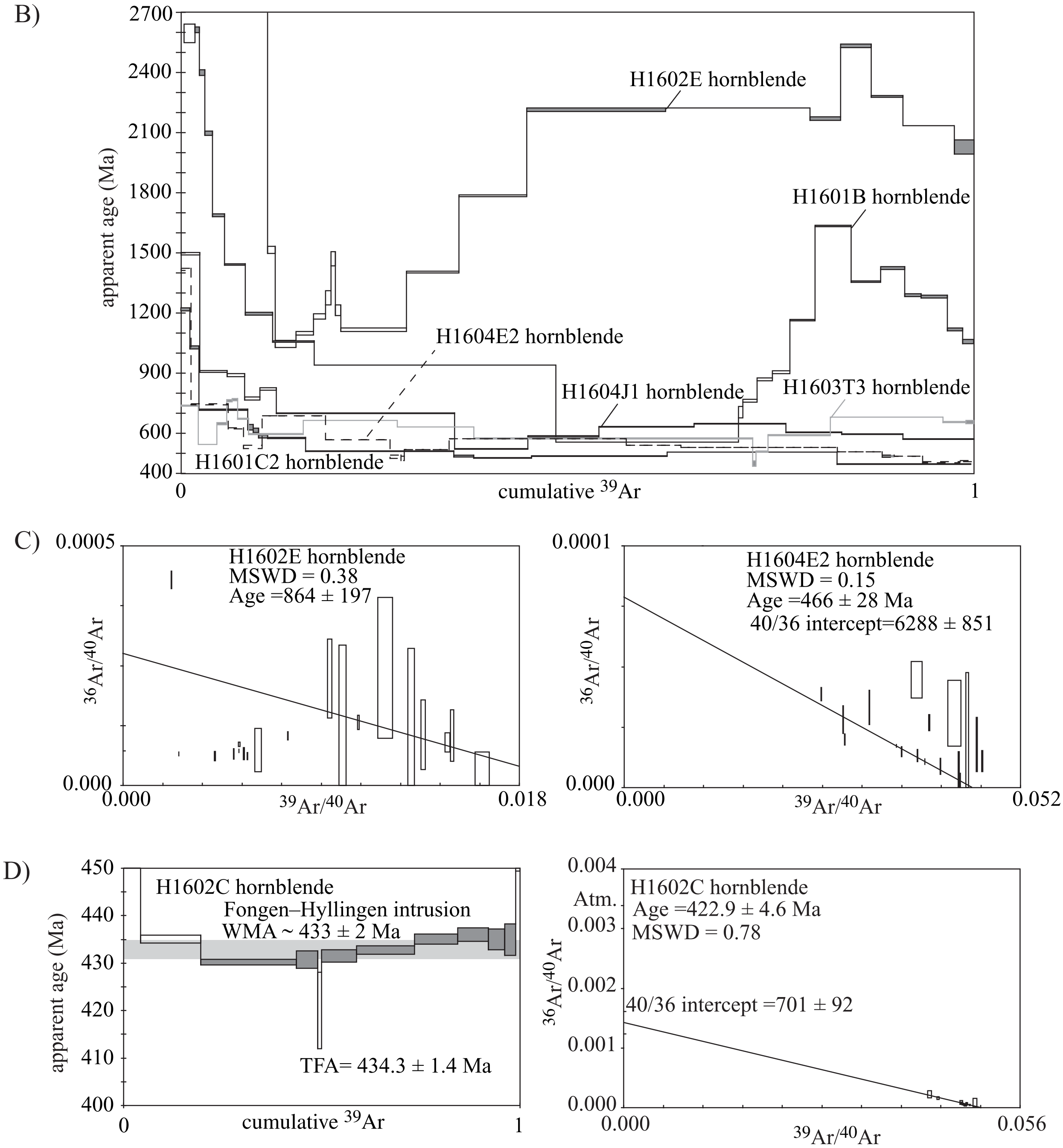

Figure 6 (*continued*). (B) Complex hornblende spectra. (C) Isochrons for H1602E and H1604E2. (D) Spectrum and isochron for Fongen–Hyllingen intrusion.

the western part by ca. 400 Ma. Central parts of the study area may have cooled through muscovite closure at an intermediate time, ca. 415 Ma. In combination with the data reviewed above, the ^{40}Ar/^{39}Ar ages indicate major Köli Nappes, Seve Nappes, and Middle Allochthon imbrication at amphibolite facies prior to ca. 425 Ma. Subsequent differential imbrication/exhumation of <10 km occurred prior to muscovite closure in the southwestern Seve Nappes at 400 Ma. Cooling rates were ~15 °C/m.y.

DISCUSSION

Our new data, combined with the existing data reviewed above, allow us to create a more detailed and quantitative tectonic history of this part of the Scandinavian Caledonides (Figs. 8 and 9) that can be used to address the question posed at the beginning of this article—when during continent collisions are UHP rocks created?

1. The first, still poorly understood, period of tectonism relates only peripherally to the Scandian UHP event. The Finnmarkian event produced high-pressure metamorphism at ca. 503 Ma in the Seve Nappes in Norrbotten (north of Fig. 1); this orogeny has been attributed to

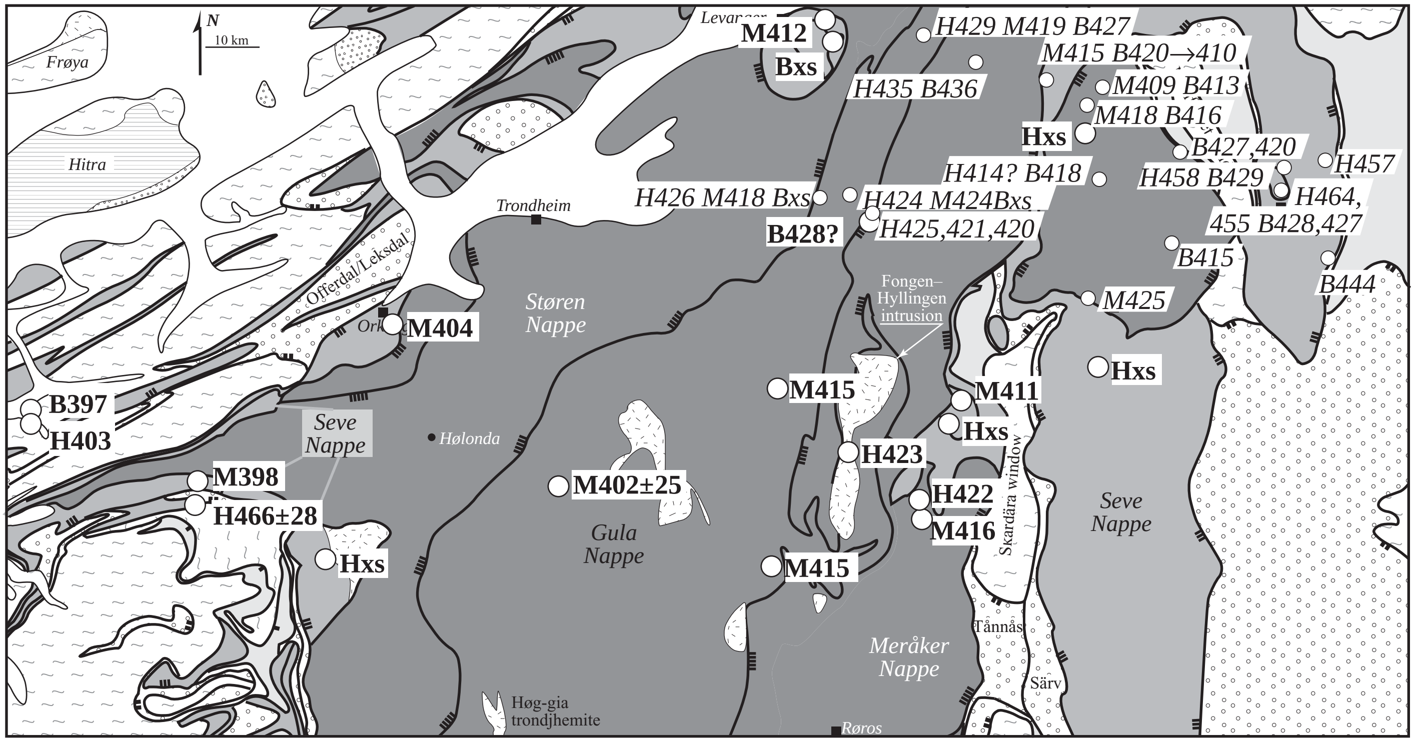

Figure 7. $^{40}Ar/^{39}Ar$ ages from the Trondelag-Jämtland region. Ages are clearly older in the east (micas ca. 425 Ma) compared to the west (micas ca. 400 Ma), separated by intermediate ages (micas ca. 415 Ma) in the center of the study area. B—biotite; H—hornblende; M—muscovite; xs—excess ^{40}Ar. Ages in italic are from Dallmeyer et al. (1985) and Dallmeyer (1990); westernmost two ages are from Root (2003).

TABLE 3. SUMMARY OF $^{40}Ar/^{39}Ar$ DATA

Sample	Mineral	J	TFA (Ma)	IA (Ma)	MSWD	$^{40}Ar/^{36}Ar$	WMPA (Ma)	Steps (used)	%^{39}Ar (used)
H1531B1	bio	0.01338	426.7 ± 2.6	426.6 ± 5.6	0.08	531 ± 147	428.0 ± 3.2	3–16/16	94
H1601B	hbl	0.01322	1164.6 ± 5.0		no good fit		n/a	n/a	n/a
H1601C2	hbl	0.01339	528.9 ± 1.8		no good fit		n/a	n/a	n/a
H1601E1	bio	0.01327	465.3 ± 3.0	477.9 ± 15	0.15	788 ± 809	466.6 ± 3.0	3–13/15	77
H1601E1	wm	0.01331	411.2 ± 1.2	406.5 ± 7.8	1.7	999 ± 922	412.2 ± 1.2	5–10/11	52
H1602A1	wm	0.01336	414.8 ± 3.1	415.0 ± 2.0	0.08	284.9 ± 1.8	414.9 ± 2.4	1–16/16	100
H1602D1	wm	0.01333	417.8 ± 2.4	441 ± 27	0.33	825 ± 526	413.9 ± 2.6	3–9/11	69
H1602C	hbl	0.01323	434.3 ± 1.4	422.9 ± 4.6	0.78	701 ± 81	433 ± 2	2–13/13	99
H1602E	hbl	0.01331	2162 ± 5.6	865 ± 197	0.38	6027 ± 888	n/a	4–12/20	24
H1602F2	hbl	0.01335	444 ± 3.6			no good fit; see text for interpretation			
H1602F3	wm	0.01329	418.1 ± 2.4	417.9 ± 2.0	0.28	174 ± 30	416.5 ± 2.4	1–11/11	100
H1603P1	wm	0.01137	401 ± 30	395 ± 34	0.79	347 ± 81	402 ± 25	2–10/10	97
H1603N4	wm	0.01334	415.4 ± 1.2	415.1 ± 2.0	0.44	289 ± 31	415.0 ± 1.2	3–11/11	90
H1603T3	hbl	0.01326	615.8 ± 1.8		no good fit		n/a	n/a	n/a
H1604E2	hbl	0.01339	570.6 ± 1.6	466 ± 28	0.15	6288	n/a	11–16/18	60
H1604E4	wm	0.01338	400.0 ± 1.2	397.5 ± 1.4	1.74	387 ± 14	398.7 ± 1.2	5–12/12	79
H1604J1	hbl	0.01336	671.1 ± 2.2		no good fit		n/a	n/a	n/a
H1604J3	wm	0.01338	405.1 ± 1.2	403.2 ± 3.2	0.77	342 ± 115	404.5 ± 1.2	4–10/12	88

Note: J—irradiation flux parameter; TFA—total fusion age (uncertainty reflects only analytical precision); IA—isochron age; MSWD—mean square weighted deviation (Wendt and Carl, 1991), which expresses the goodness of fit of the isochron (Roddick, 1978); WMPA—weighted mean plateau age (italics indicate a "weighted mean age," rather than plateau age, and the quoted uncertainty reflects our assessment of the spectrum quality, which generally encompasses the range in ages of nearly concordant steps); hbl—hornblende; bi—biotite; wm—K-white mica; IA and WMPA are based on *T* steps and fraction of ^{39}Ar listed in the last two columns. Preferred age is in boldface. Age uncertainties are ±2σ. Abbreviations: bio—biotite; hbl—hornblende; wm—white mica.

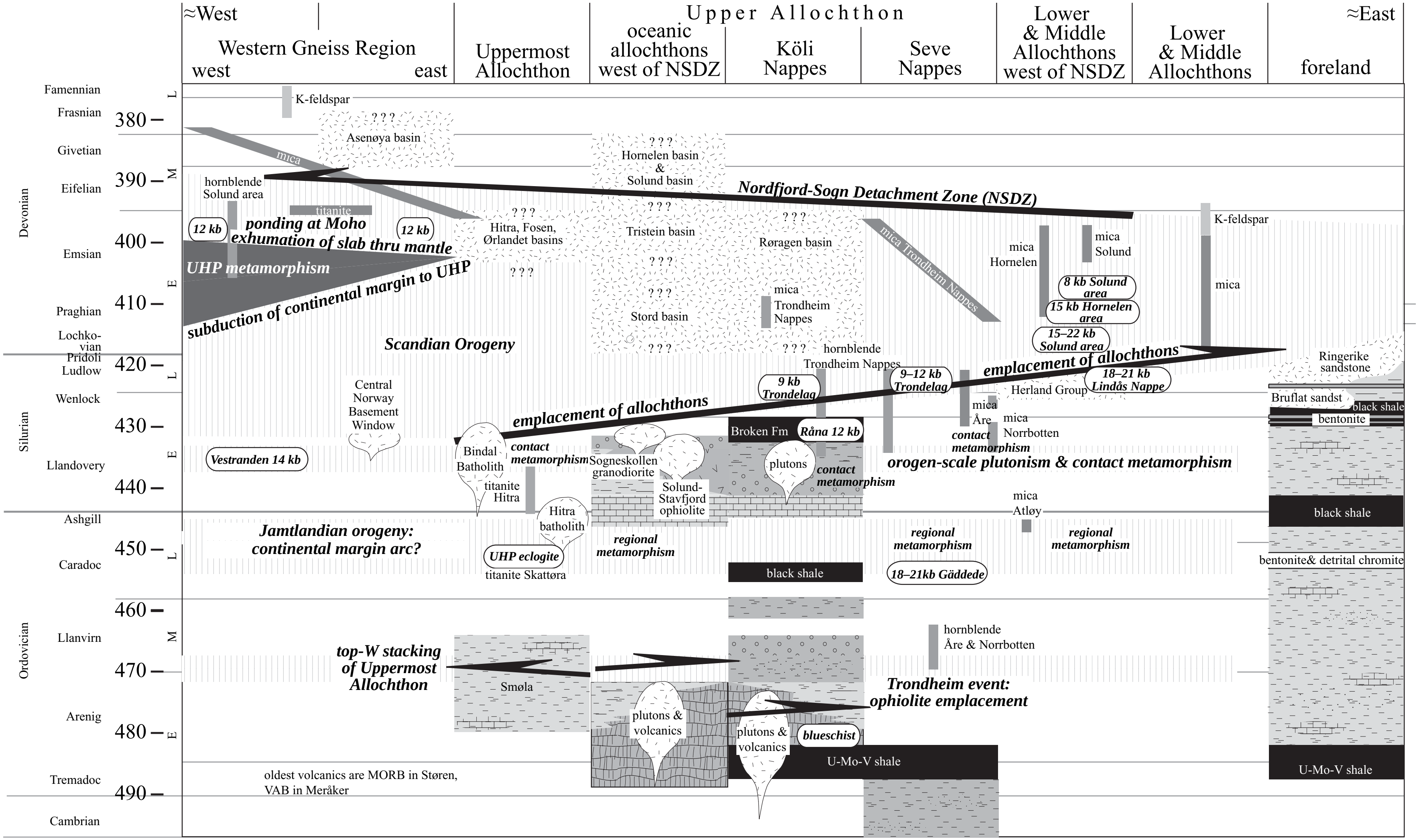

Figure 8. Tectonostratigraphic event diagram with E-W order of units at ca. 410 Ma. "Western Gneiss Region" includes the Western Gneiss Complex of the Lower Allochthon and overlying nappes of Middle and Upper Allochthon affinity, such as the Blåhø Nappe (Terry and Robinson, 2004). References to data are given in the text of this paper and in Hacker et al. (2003). "Titanite," "hornblende," "mica," and "K-feldspar" indicate U/Pb and $^{40}Ar/^{39}Ar$ age ranges. Ellipses indicate metamorphic pressures, and vertical ruling indicates regional metamorphic episodes. NSDZ—Nordfjord-Sogn Detachment Zone; UHP—ultrahigh-pressure; MORB—mid-oceanic-ridge basalt; VAB—volcanic arc basalts.

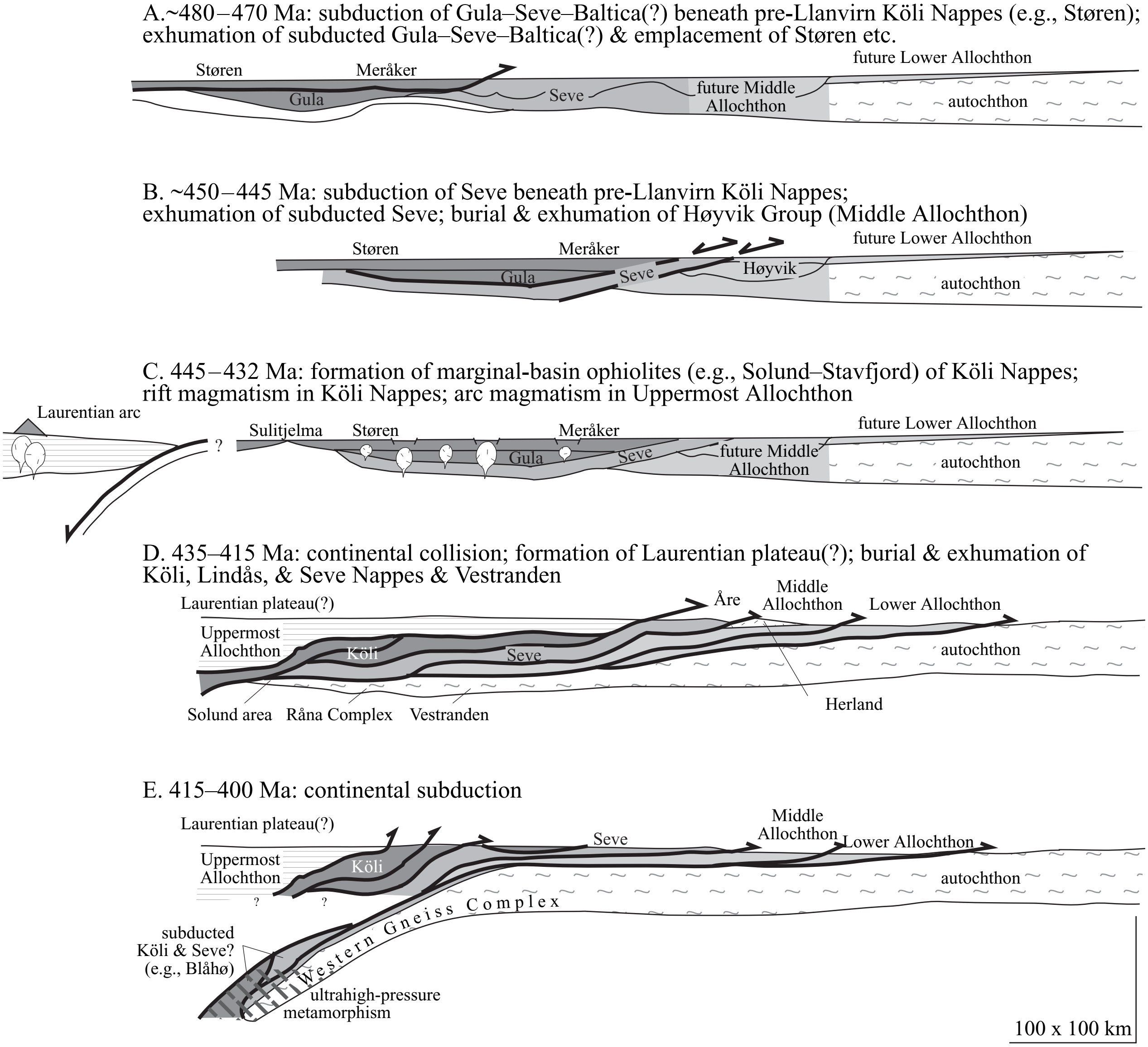

Figure 9. Tectonic history. (A) Subduction of the Gula Nappe (microcontinent?)–Seve Nappes–Baltica(?) composite beneath those parts of the Köli Nappes that existed prior to the Llanvirn (e.g., the Støren Nappe), exhumation of the subducted Gula-Seve-Baltica(?) rocks, and emplacement of the pre-Llanvirn portions of the Köli Nappes onto the Baltoscandian continental margin. (B) Subduction of the Seve Nappes beneath those parts of the Köli Nappes that existed prior to the Llanvirn, burial of the Høyvik Group (Middle Allochthon) beneath the Seve Nappes, and exhumation of the Seve Nappes and Høyvik Group. (C) Formation of marginal-basin ophiolites (e.g., the Solund–Stavfjord ophiolite) of the Köli Nappes, rift magmatism in the Köli Nappes, and arc magmatism in the Uppermost Allochthon. (D) Collision of the active margin of Laurentia, emplacement of the newly created arcs, marginal basins, and their basement onto the Seve Nappes, and telescoping of all structurally lower units; deep burial of parts of the continental margin in the Solund, Råna, and Vestranden areas. (E) Subduction of Baltica to ultrahigh-pressure depths. (Precontractional configuration of Baltica margin is modeled after modern Norwegian margin [Mosar, 2000].)

westward subduction of a Seve microcontinent (Brueckner and Roermund, 2004) beneath an older part of the Köli Nappes or to subduction of Seve Baltoscandian continental margin rocks beneath an unnamed arc (Dallmeyer and Gee, 1986; Roberts, 2003). Somewhat later, but prior to the late Arenig, Early Ordovician MORB-type ophiolitic rocks of the Köli Nappes were locally thrust onto Baltica(?) (e.g., the Otta area, Sturt et al., 1991) or onto a "Gula microcontinent" (Roberts and Stephens, 2000; Roberts et al., 2002b) during the Trondheim event (Fig. 9A). On the other side of Iapetus the Uppermost Allochthon was imbricated by top-W thrusting beginning at 477–468 Ma, perhaps during the Taconic orogeny (Roberts et al., 2001; Yoshinobu et al., 2002). Studies of well-known ophiolites, such as Oman (e.g., Hacker and Gnos, 1997), show that ophiolite emplacement onto the passive margin of one continent precedes subduction of both beneath another continent—a modern example is the imminent subduction beneath Iran of the Arabian passive margin with its cargo of the Oman ophiolite.

This ophiolite emplacement can lead to near-UHP metamorphism of the continental margin (Searle et al., 2001). Emplacement of the pre-Llanvirn ophiolites of the Köli Nappes onto the Gula Nappe microcontinent (the outboard Baltoscandian continental margin) before both were overrun by the Uppermost Allochthon (Laurentia) could reflect a similar tectonic setting, but high-pressure metamorphism has not been discovered in the Gula Nappe.

2. The Trondheim event was followed by another cryptic regional metamorphic/deformation event, the Jämtlandian orogeny, at ca. 450–445 Ma (Brueckner and Roermund, 2004) (Fig. 9B). The Caradoc black shales in the Köli Nappes provide an older bound to this event. Indicators of this Baltoscandian margin event include ca. 450 Ma eclogites and garnet peridotites in the Seve Nappes (Brueckner et al., 2004) and the 447 ± 4 Ma muscovite ages that postdate amphibolite-facies deformation and metamorphism in the outboard Middle Allochthon on Atløy (Høyvik Group; Andersen and Jamtveit, 1990; Andersen et al., 1998); coeval orogeny in Laurentia is indicated by 452 Ma eclogite (Corfu et al., 2002) and 456 Ma titanite (Selbekk et al., 2000) in Uppermost Allochthon arc rocks. The regional metamorphism in the Köli and Seve Nappes that predates the 445–432 Ma intrusive suite might also have occurred at this time. Together these features suggest westward subduction of the Seve Nappes beneath, perhaps, the Köli Nappes, followed by thickening, heating, and exhumation (Brueckner and Roermund, 2004), but the presence of high-pressure rocks in at least three major units—and no identified subduction-related magmatic arc—demonstrates an as-yet-unraveled, more complicated tectonic setting.

3. Third was an areally extensive magmatic episode at ca. 445–432 Ma that included formation of significant new oceanic crust (e.g., the Solund–Stavfjord ophiolite; Dunning and Pedersen, 1988) and intrusion of plutons and dikes throughout the Uppermost Allochthon and Köli Nappes (Fig. 9C). This includes the plutons described above, plus others intruding the Köli Nappes such as the Sunnhordland batholith (Andersen and Jansen, 1987; Fossen and Austrheim, 1988), the Bremanger granitoid complex, the Gåsøy diorite (Hansen et al., 2002), and the Sogneskollen granodiorite (Skjerlie et al., 2000). Some of the plutons within the Köli Nappes were derived from melting of mantle in a continental-rift setting, and others were derived by melting of mafic crustal rocks at ~900 °C and 10–15 kbar (Dunning and Grenne, 2000; Pannemans and Roberts, 2000; Hansen et al., 2002; Nilsen et al., 2003); it is plausible that the seafloor-spreading, rift magmatism, and mafic crustal melts are all related. In contrast, the Bindal batholith intruding the Uppermost Allochthon formed in an arc setting (Nordgulen and Sundvoll, 1992). There are no known plutons of this age structurally beneath the Köli Nappes, implying that this magmatic event took place prior to the final emplacement of the Uppermost Allochthon and the Köli Nappes (except the Early Ordovician elements of the Köli Nappes, e.g., the Vågåmo ophiolite) onto the Seve Nappes and Baltica. In the Köli Nappes this intrusive event postdates Ashgill limestone and apparently predates the upper Llandovery Broken Formation. This rifting event marks a major interregnum in the contractional history of the orogen, implying that the Scandian UHP metamorphism that followed is unrelated to the pre-435 Ma contractional history.

4. The fourth major identifiable tectonic episode is the first that relates directly to the UHP event (Figs. 9D and 9E). Piecing together the evidence that defines this event is pivotal to reconstructing the origin of the UHP rocks. The evidence summarized in Figure 8 suggests that diachronous, eastward-propagating nappe emplacement began at ca. 437 Ma in the west and terminated by ca. 415 Ma in the east: *(a)* Regional metamorphism in the Vestranden gneiss (Fig. 1) (14 kbar at 435 Ma; Dallmeyer et al., 1992) and in the Råna complex of the Upper Allochthon (12 kbar at 432 Ma; Northrup, 1997) may reflect tectonic burial beneath the Uppermost Allochthon; hornblende in the Vestranden gneiss did not close to Ar loss until ca. 400 Ma (Dallmeyer et al., 1992). *(b)* The youngest fossiliferous rocks in the Upper Allochthon are upper Llandovery, and these are overlain by a thick turbiditic succession that may stretch into the Wenlock (Bassett, 1985), requiring that the faults bounding the Upper Allochthon are younger than late Llandovery (443–428 Ma). *(c)* The Wenlock Herland Group in the Middle Allochthon on Atløy was deposited during emplacement of the Upper Allochthon (Andersen et al., 1990). *(d)* Top-E thrusting of the Upper Allochthon after 434 Ma probably caused the 15–22 kbar metamorphism in the Solund area (Hacker et al., 2002) and may have caused the 423 Ma eclogite-facies, 18–21 kbar metamorphism in the Lindås Nappe (Bingen et al., 2003); the Solund area remained above hornblende closure to Ar until ca. 400 Ma (Chauvet and Dallmeyer, 1992). *(e)* The Gula Nappe was tectonically buried to 9 kbar and then cooled to hornblende closure by 423 Ma (Fig. 4). Isograds within the Gula Nappe cut lithologic boundaries (Dudek et al., 1973; Olesen et al., 1973; Lagerblad, 1984; McClellan, 1994) and also cross into the Meråker and Støren Nappes, requiring that these Nappes were juxtaposed prior to this regional metamorphism; muscovite ages indicate a pre-415 Ma age for this juxtaposition. *(f)* The compression + heating paths to ~12 kbar shown by the Seve Nappes (Fig. 4) likely formed in the footwall of the Köli Nappes. *(g)* Inverted metamorphic gradients indicate thrusting of the Lower Seve Nappe over the Middle Allochthon during regional metamorphism in the Åre, Handøl, and Norrbotten areas (Arnbom, 1980; Sjöström, 1984; Greiling and Kumpulainen, 1989); this must have happened after or during hornblende closure at 464–455 Ma and before mica closure at 429–427 Ma. *(h)* The youngest sedimentary rocks in the Lower Allochthon place a Wenlock (Bassett, 1985) bound on the end of thrusting of this allochthon. *(i)* The transition from marine carbonate platform to continental fluvial molasse sedimentation in the foreland in the latest Wenlock likely marks the easternmost effect of nappe emplacement. Active continental collisions, like the India–Asia collision, are typically associated with high topography—even plateaus—such that the Laurentia-Baltica collision could have been characterized by a high-altitude plateau. The overlying 35–45 km thick crustal column required to produce the 9–12 kbar metamorphism exhibited by the Vestranden gneiss, Råna intrusion, Seve Nappes, Gula Nappe, Lindås Nappe, and Solund area supports this idea.

Thus, an eastward-propagating sequence of nappe emplacements is permitted by diverse data that span the western to eastern edges of the orogen, corroborating the ideas of many earlier workers. This Scandian deformation began in the west with the emplacement of the Köli Nappes onto the Seve Nappes and the emplacement of the Uppermost Allochthon (Laurentia) onto the Köli-Seve-Baltica amalgam (although the stacking history is unclear); the combined Uppermost Allochthon–Upper Allochthon–Middle Allochthon–Lower Allochthon stack subsequently reached its easternmost thermal influence on the Baltica margin ca. 420 Ma. At that time, the peak of the UHP metamorphism was still 10 m.y. in the future. What, then, caused the UHP metamorphism? Why did the Western Gneiss Region sink so far into the mantle?

In general terms, continental crust can be driven to UHP depths if it (1) becomes denser than the mantle and sinks under its own weight, (2) is attached to sinking oceanic lithosphere, (3) is overlain by denser, sinking rocks that push it downward, or (4) is attached to sinking continental lithosphere. (1) The continental crust of the Western Gneiss Complex is too felsic to have reached greater-than-mantle densities at UHP conditions: Walsh and Hacker (2004) calculated maximum densities of 2.85–3.05 g/cm^3 for the predominantly quartzofeldspathic gneisses of the Western Gneiss Complex at 10–30 kbar. (2) The Western Gneiss Region cannot have been pulled deep into the mantle because it was attached to subducting, old oceanic lithosphere as the emplacement of ophiolitic and continental margin rocks onto the Baltica margin just 10–20 m.y. earlier requires large-scale thrusting between the two. (3) The Scandian thrust sheets reached pressures of 12–14 kbar (Fig. 8). At just a few kbar higher pressure, mafic allochthons overlying the Western Gneiss Complex would have become eclogites dense enough to sink into the mantle (e.g., Fig. 8 of Hacker and Abers, 2004) and depress the underlying Western Gneiss Complex continental crust. Perhaps the Blåhø Nappe, which is folded into the Western Gneiss Complex in the core of the orogen and consists of about half mafic rocks that are locally UHP eclogites (Terry and Robinson, 2004; Walsh and Hacker, 2004), is the record of this event. (4) Continental lithosphere capped by 20–30 km of crust with the 2.95–3.05 g/cm^3 density calculated above for the Western Gneiss Complex is negatively buoyant with respect to the asthenosphere (Cloos, 1993), implying that the Western Gneiss Complex could have sunk under its own weight if it transformed to high-pressure minerals and was depressed far enough into a sufficiently low-viscosity asthenosphere.

CONCLUSIONS

The UHP rocks in the Western Gneiss Region of Norway were produced during the latest stages of the Scandian continental collision. Ophiolite emplacement beginning at 435 Ma produced high-pressure metamorphism of the continental margin, but was complete 10–20 m.y. before the peak ultrahigh-pressure event. The early stages of continental collision produced widespread 9–12 kbar metamorphism—and possibly a Tibet-style continental plateau—that was finished by 415–400 Ma. The UHP metamorphism occurred at 410–400 Ma during the closing stages of the continental collision, with no simple relationship to earlier orogenic processes.

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Table 4. Electron probe data (electronic repository).
"<" indicates below detection.
core and rim compositions are given separately unless phase is unzoned.

H1531B1	g core	g rim	bi core	bi rim	fsp core	fsp rim	st
SiO2	36.79	36.86	35.71	35.49	57.56	60.20	26.71
TiO2	0.04	<	1.70	1.63	<	0.09	0.39
Al2O3	21.50	21.59	18.86	19.23	26.33	24.48	53.49
Cr2O3	<	0.04	0.10	0.13	<	<	0.06
Fe2O3	2.07	2.19	0.34	1.70	0.10	0.34	<
FeO	27.51	29.12	14.19	13.42	<	<	13.14
MnO	5.09	1.96	<	0.08	<	<	0.29
MgO	5.14	3.77	13.43	13.19	<	<	2.36
CaO	1.72	4.85	<	0.05	7.99	6.10	<
Na2O	<	<	0.33	0.37	7.02	8.00	0.18
K2O	<	<	9.01	8.38	<	0.11	<
Totals	99.86	100.38	93.67	93.67	99.00	99.32	96.62
Oxygens	12	12	11	11	8	8	46
Si	2.93	2.92	2.69	2.67	2.60	2.70	7.51
Ti	0.00	<	0.10	0.09	<	0.00	0.08
Al	2.02	2.02	1.68	1.71	1.40	1.29	17.73
Cr	<	0.00	0.01	0.01	<	<	0.01
Fe3	0.12	0.13	0.02	0.10	0.00	0.01	<
Fe2	1.83	1.93	0.90	0.85	<	<	3.09
Mn	0.34	0.13	<	0.01	<	<	0.07
Mg	0.61	0.45	1.51	1.48	<	<	0.99
Ca	0.15	0.41	<	0.00	0.39	0.29	<
Na	<	<	0.05	0.05	0.62	0.70	0.10
K	<	<	0.87	0.81	<	0.01	<
Sum	8.00	8.00	7.82	7.76	5.01	5.00	29.59

H1601C1	g core	g rim	bi core	bi rim	am core	am rim	fsp core	fsp rim	mu
SiO2	38.10	38.60	36.90	37.50	43.40	42.00	60.70	62.70	48.10
TiO2	0.05	0.07	1.65	1.44	0.36	0.40	<	<	0.50
Al2O3	21.50	21.70	17.90	19.90	16.90	18.10	25.40	24.00	33.50
Cr2O3	<	<	0.07	<	<	0.04	<	<	0.07

Fe2O3	0.04	<	<	<	3.09	2.61	0.11	0.11	<
FeO	30.06	30.10	15.80	15.10	11.92	12.65	<	<	1.20
MnO	2.10	1.39	0.04	0.04	0.14	0.10	<	<	<
MgO	2.80	3.20	12.70	11.80	9.30	8.60	<	<	1.30
CaO	6.50	6.40	<	0.10	10.30	10.80	6.70	5.20	<
Na2O	<	<	0.15	0.19	1.93	1.78	7.77	8.62	0.91
K2O	<	0.06	9.03	9.26	0.39	0.46	0.05	0.08	9.83
Totals	101.15	101.52	94.24	95.33	97.73	97.54	100.73	100.71	95.41
Oxygens	12	12	11	11	23	23	8	8	11
Si	3.00	3.01	2.78	2.77	6.33	6.17	2.68	2.76	3.18
Ti	0.00	0.00	0.09	0.08	0.04	0.04	<	<	0.03
Al	2.00	2.00	1.59	1.73	2.90	3.13	1.32	1.24	2.61
Cr	<	<	0.00	<	<	0.01	<	<	0.00
Fe3	0.00	<	<	<	0.34	0.29	0.00	0.00	<
Fe2	1.98	1.97	1.00	0.93	1.45	1.55	<	<	0.07
Mn	0.14	0.09	0.00	0.00	0.02	0.01	<	<	<
Mg	0.33	0.37	1.43	1.30	2.02	1.88	<	<	0.13
Ca	0.55	0.54	<	0.01	1.61	1.70	0.32	0.25	<
Na	<	<	0.02	0.03	0.55	0.51	0.67	0.74	0.12
K	<	0.01	0.87	0.87	0.07	0.09	0.00	0.00	0.83
Sum	8.00	7.99	7.78	7.73	15.32	15.37	4.99	4.99	6.96

H1601D1	g core	g rim	bi core	bi rim	mu core	mu rim	fsp core	fsp rim	am core	am rim
SiO2	36.57	36.10	33.55	34.23	45.55	45.86	55.57	60.04	34.60	37.40
TiO2	0.06	0.12	2.73	2.10	0.55	0.58	<	<	1.24	0.11
Al2O3	20.71	21.06	17.95	18.63	34.91	34.43	27.57	25.61	17.80	17.50
Cr2O3	0.09	0.05	0.27	0.19	0.20	0.06	<	<	0.05	0.00
Fe2O3	1.80	2.00	<	<	<	<	0.11	0.39	4.29	2.31
FeO	36.30	33.12	23.30	22.24	1.62	2.13	<	<	21.34	21.32
MnO	1.30	0.56	0.13	0.08	<	<	<	<	0.24	0.23
MgO	1.99	1.32	6.92	7.91	0.69	0.74	<	<	2.30	3.00
CaO	2.04	5.62	<	<	<	<	9.64	6.97	10.47	10.85
Na2O	<	<	0.11	0.12	0.57	0.66	6.10	7.52	1.77	1.75
K2O	<	<	9.36	9.44	10.62	10.42	0.05	0.14	1.70	1.10
Totals	100.86	99.95	94.32	94.94	94.71	94.88	99.04	100.67	95.80	95.57

Oxygens	12	12	11	11	11	11	8	8	23	23
Si	2.95	2.93	2.65	2.66	3.06	3.08	2.52	2.66	5.57	5.93
Ti	0.00	0.01	0.16	0.12	0.03	0.03	<	<	0.15	0.01
Al	1.97	2.01	1.67	1.71	2.77	2.73	1.48	1.34	3.38	3.27
Cr	0.01	0.00	0.02	0.01	0.01	0.00	<	<	0.01	0.00
Fe3	0.11	0.12	<	<	<	<	0.00	0.01	0.52	0.28
Fe2	2.45	2.24	1.54	1.45	0.09	0.12	<	<	2.87	2.83
Mn	0.09	0.04	0.01	0.01	<	<	<	<	0.03	0.03
Mg	0.24	0.16	0.82	0.92	0.07	0.07	<	<	0.55	0.71
Ca	0.18	0.49	<	<	<	<	0.47	0.33	1.81	1.84
Na	<	<	0.02	0.02	0.07	0.09	0.54	0.65	0.55	0.54
K	<	<	0.94	0.94	0.91	0.89	0.00	0.01	0.35	0.22
Sum	8.00	8.00	7.82	7.83	7.01	7.02	5.01	4.99	15.78	15.66

H1601E2	g core	g rim	bi	mu	am core	am rim	fsp core	fsp rim
SiO2	37.50	37.50	36.80	46.40	42.00	43.30	64.40	63.80
TiO2	0.09	0.06	1.58	0.51	0.43	0.41	<	<
Al2O3	21.20	21.60	16.90	33.30	17.00	16.20	22.40	22.80
Cr2O3	<	0.05	<	0.08	0.16	0.06	<	<
Fe2O3	0.99	1.65	2.22	<	2.11	1.90	0.11	0.11
FeO	28.81	27.81	15.10	1.70	12.70	12.39	<	<
MnO	1.95	0.69	0.05	0.04	0.10	0.08	<	<
MgO	2.40	3.80	13.20	1.70	9.20	9.70	<	<
CaO	7.60	7.50	<	<	11.00	10.90	3.40	3.90
Na2O	<	<	0.10	1.40	2.06	2.00	9.72	9.40
K2O	<	<	9.00	9.30	0.45	0.44	0.05	0.05
Totals	100.54	100.66	94.95	94.43	97.21	97.38	100.08	100.06

Oxygens	12	12	11	11	23	23	8	8
Si	2.98	2.95	2.76	3.12	6.20	6.35	2.84	2.81
Ti	0.01	0.00	0.09	0.03	0.05	0.05	<	<
Al	1.98	2.00	1.50	2.64	2.96	2.80	1.16	1.19
Cr	<	0.00	<	0.00	0.02	0.01	<	<
Fe3	0.06	0.10	0.13	<	0.24	0.21	0.00	0.00
Fe2	1.91	1.83	0.95	0.10	1.57	1.52	<	<

Mn	0.13	0.05	0.00	0.00	0.01	0.01	<	<
Mg	0.28	0.45	1.48	0.17	2.02	2.12	<	<
Ca	0.65	0.63	<	<	1.74	1.71	0.16	0.18
Na	<	<	0.02	0.18	0.59	0.57	0.83	0.80
K	<	<	0.86	0.80	0.09	0.08	0.00	0.00
Sum	8.00	8.00	7.78	7.03	15.48	15.42	5.00	5.00

H1602A1	g rim	bi core	bi rim	mu	fsp core	fsp rim
SiO2	36.63	35.20	35.28	45.60	69.98	68.20
TiO2	<	1.46	0.98	0.62	<	<
Al2O3	20.77	18.20	18.08	35.30	19.70	19.60
Cr2O3	<	<	<	<	<	<
Fe2O3	0.03	0.03	0.03	0.03	0.03	0.03
FeO	32.91	18.60	20.17	1.30	<	<
MnO	7.06	0.09	0.33	0.06	0.04	<
MgO	2.51	10.70	10.43	0.80	<	<
CaO	0.43	<	0.04	<	0.21	0.10
Na2O	<	0.25	0.10	1.42	11.94	11.44
K2O	<	9.42	8.88	9.45	<	0.06
Totals	100.34	93.95	94.32	94.58	101.90	99.43
Oxygens	12	11	11	11	8	8
Si	2.98	2.71	2.72	3.05	3.00	2.99
Ti	<	0.09	0.06	0.03	<	<
Al	1.99	1.66	1.65	2.79	1.00	1.01
Cr	<	<	<	<	<	<
Fe3	0.00	0.00	0.00	0.00	0.00	0.00
Fe2	2.24	1.20	1.30	0.07	<	<
Mn	0.49	0.01	0.02	0.00	0.00	<
Mg	0.30	1.23	1.20	0.08	<	<
Ca	0.04	<	0.00	<	0.01	0.01
Na	<	0.04	0.02	0.18	0.99	0.97
K	<	0.93	0.88	0.81	<	0.00
Sum	8.03	7.86	7.84	7.02	5.00	4.99

H1602B1	g core	g rim	bi core	bi rim	mu	fsp core	fsp rim	st

SiO2	36.30	37.10	35.90	36.40	45.20	59.00	61.50	27.10
TiO2	0.04	0.05	1.38	1.38	0.44	0.10	<	0.71
Al2O3	21.10	21.30	19.80	19.10	35.90	24.20	23.30	53.70
Cr2O3	<	0.09	0.06	0.04	<	<	<	0.05
Fe2O3	1.18	1.96	0.68	0.73	<	0.22	0.11	<
FeO	31.90	31.14	14.99	15.84	1.00	<	<	13.30
MnO	4.07	0.83	0.04	<	<	<	<	<
MgO	3.70	3.50	12.50	12.30	0.80	<	<	2.00
CaO	2.39	4.76	<	<	<	5.82	4.58	<
Na2O	<	<	0.38	0.37	1.83	7.99	8.91	0.24
K2O	<	<	8.50	8.45	8.46	0.09	0.06	<
Totals	100.68	100.73	94.23	94.61	93.63	97.42	98.46	97.10
Oxygens	12	12	11	11	11	8	8	46
Si	2.91	2.94	2.69	2.73	3.04	2.69	2.77	7.57
Ti	0.00	0.00	0.08	0.08	0.02	0.00	<	0.15
Al	2.00	1.99	1.75	1.69	2.84	1.30	1.24	17.69
Cr	<	0.01	0.00	0.00	<	<	<	0.01
Fe3	0.07	0.12	0.04	0.04	<	0.01	0.00	<
Fe2	2.14	2.07	0.94	0.99	0.06	<	<	3.11
Mn	0.28	0.06	0.00	<	<	<	<	<
Mg	0.44	0.41	1.40	1.37	0.08	<	<	0.83
Ca	0.21	0.40	<	<	<	0.29	0.22	<
Na	<	<	0.06	0.05	0.24	0.71	0.78	0.13
K	<	<	0.81	0.81	0.73	0.01	0.00	<
Sum	8.05	8.00	7.77	7.76	7.00	5.00	5.01	29.50

H1602D1	g core	g rim	am core	am rim	bi	mu	fsp core	fsp rim	st core	st rim
SiO2	35.99	35.95	42.40	41.60	37.12	47.19	59.30	63.20	27.70	28.00
TiO2	0.12	0.05	0.39	0.36	1.42	0.42	<	<	0.58	0.57
Al2O3	21.27	20.81	17.20	17.22	18.64	35.86	25.20	23.90	53.46	53.62
Cr2O3	<	<	<	<	<	0.05	<	0.04	<	0.01
Fe2O3	2.84	3.32	3.18	3.68	<	<	0.08	<	<	0.00
FeO	26.71	29.38	12.34	12.27	15.41	1.01	<	<	12.84	12.70
MnO	3.05	0.87	0.07	0.07	<	<	<	<	<	0.05
MgO	2.33	3.54	8.90	8.76	13.15	0.83	<	<	2.16	2.04

CaO	6.99	4.90	10.46	10.51	0.05	<	6.70	4.90	<	0.00
Na2O	0.05	<	1.82	1.68	0.41	1.79	7.85	8.94	0.46	0.47
K2O	<	0.06	0.40	0.37	8.58	8.63	<	0.07	<	0.01
Totals	99.35	98.88	97.16	96.52	94.78	95.78	99.13	101.05	97.20	97.47
Oxygens	12	12	23	23	11	11	8	8	46	46
Si	2.90	2.91	6.24	6.18	2.76	3.09	2.66	2.77	7.71	7.77
Ti	0.01	0.00	0.04	0.04	0.08	0.02	<	<	0.12	0.12
Al	2.02	1.98	2.98	3.02	1.64	2.77	1.34	1.23	17.55	17.53
Cr	<	<	<	<	<	0.00	<	0.00	<	0.00
Fe3	0.17	0.20	0.35	0.41	<	<	0.00	<	<	0.00
Fe2	1.80	1.99	1.52	1.52	0.96	0.06	<	<	2.99	2.95
Mn	0.21	0.06	0.01	0.01	<	<	<	<	<	0.01
Mg	0.28	0.43	1.95	1.94	1.46	0.08	<	<	0.90	0.84
Ca	0.60	0.43	1.65	1.67	0.00	<	0.32	0.23	<	0.00
Na	0.01	<	0.52	0.48	0.06	0.23	0.68	0.76	0.25	0.25
K	<	0.01	0.08	0.07	0.82	0.72	<	0.00	<	0.00
Sum	8.00	8.00	15.35	15.35	7.78	6.97	5.01	5.00	29.52	29.48

H1602F3	g core	g rim	bi	mu	fsp core	fsp rim
SiO2	36.80	37.50	35.60	45.80	65.80	67.00
TiO2	0.09	0.04	1.54	0.34	<	<
Al2O3	20.80	21.40	17.70	34.90	22.10	21.10
Cr2O3	0.04	<	0.04	0.06	<	<
Fe2O3	1.74	1.51	<	<	0.22	0.11
FeO	31.23	34.74	19.20	2.00	<	<
MnO	5.84	0.11	<	<	<	<
MgO	2.10	3.10	10.10	0.90	<	<
CaO	2.42	3.33	<	<	2.86	1.85
Na2O	<	<	0.19	1.27	10.23	10.76
K2O	<	<	8.92	9.49	0.04	0.07
Totals	101.06	101.73	93.29	94.76	101.25	100.89
Oxygens	12	12	11	11	8	8
Si	2.96	2.96	2.76	3.07	2.86	2.92
Ti	0.01	0.00	0.09	0.02	<	<

Al	1.97	1.99	1.62	2.76	1.13	1.08
Cr	0.00	<	0.00	0.00	<	<
Fe3	0.11	0.09	<	<	0.01	0.00
Fe2	2.10	2.29	1.25	0.11	<	<
Mn	0.40	0.01	<	<	<	<
Mg	0.25	0.37	1.17	0.09	<	<
Ca	0.21	0.28	<	<	0.13	0.09
Na	<	<	0.03	0.17	0.86	0.91
K	<	<	0.88	0.81	0.00	0.00
Sum	8.00	8.00	7.80	7.02	5.00	5.00

H1602F4	g core	g rim	fsp core	fsp rim	mu	pa	bi	st core	st rim
SiO2	36.88	37.14	62.79	63.70	46.10	45.30	35.26	26.77	27.73
TiO2	0.04	0.05	<	<	0.49	0.15	1.82	0.47	0.44
Al2O3	21.19	21.47	22.76	22.30	34.69	39.70	17.74	52.80	52.86
Cr2O3	<	<	<	<	<	0.09	<	0.05	0.05
Fe2O3	1.42	2.43	<	0.16	<	<	<	<	<
FeO	31.32	31.08	<	<	1.19	0.70	18.34	12.60	12.06
MnO	4.95	0.13	<	<	<	<	<	0.04	<
MgO	2.51	3.67	<	<	1.13	0.10	10.92	1.70	2.14
CaO	2.45	4.93	4.05	3.28	<	0.60	0.07	<	<
Na2O	<	0.05	9.40	9.79	2.05	6.90	0.24	0.99	0.84
K2O	<	0.05	0.06	0.05	8.69	1.40	8.85	<	<
Totals	100.76	101.00	99.06	99.28	94.34	94.94	93.24	95.42	96.12
Oxygens	12	12	8	8	11	11	11	46	46
Si	2.96	2.93	2.80	2.83	3.08	2.93	2.73	7.61	7.79
Ti	0.00	0.00	<	<	0.03	0.01	0.11	0.10	0.09
Al	2.00	2.00	1.20	1.17	2.73	3.03	1.62	17.70	17.50
Cr	<	<	<	<	<	0.01	<	0.01	0.01
Fe3	0.09	0.15	<	0.01	<	<	<	<	<
Fe2	2.10	2.05	<	<	0.07	0.04	1.19	3.00	2.83
Mn	0.34	0.01	<	<	<	<	<	0.01	<
Mg	0.30	0.43	<	<	0.11	0.01	1.26	0.72	0.90
Ca	0.21	0.42	0.19	0.16	<	0.04	0.01	<	<
Na	<	0.01	0.81	0.84	0.27	0.87	0.04	0.55	0.46

K	<	0.01	0.00	0.00	0.74	0.12	0.87	<	<
Sum	8.00	8.00	5.01	5.01	7.03	7.04	7.81	29.70	29.59

H1603M1	g core	g rim	fsp core	fsp rim	mu	par	bi	st
SiO2	37.00	35.80	62.20	61.60	45.90	46.00	36.38	26.27
TiO2	<	<	<	<	0.41	0.22	1.71	0.61
Al2O3	21.20	21.46	23.60	24.30	36.00	39.80	19.80	53.01
Cr2O3	0.06	0.08	<	0.04	0.09	0.05	0.13	0.16
Fe2O3	2.15	2.29	0.21	0.37	<	<	<	<
FeO	30.88	29.40	<	<	0.97	0.39	15.05	13.07
MnO	4.29	0.94	<	<	<	<	0.04	0.16
MgO	3.89	4.18	<	<	0.67	0.11	12.46	2.21
CaO	2.60	3.90	4.90	5.70	<	0.60	0.05	<
Na2O	<	<	8.80	8.46	2.14	5.90	0.41	0.10
K2O	<	<	0.07	0.04	8.33	1.99	8.55	<
Totals	102.07	98.05	99.78	100.51	94.51	95.06	94.58	95.59
Oxygens	12	12	8	8	11	11	11	46
Si	2.92	2.90	2.76	2.72	3.05	2.96	2.71	7.47
Ti	<	<	<	<	0.02	0.01	0.10	0.13
Al	1.97	2.05	1.24	1.27	2.82	3.02	1.74	17.76
Cr	0.00	0.01	<	0.00	0.01	0.00	0.01	0.04
Fe3	0.13	0.14	0.01	0.01	<	<	<	<
Fe2	2.04	1.99	<	<	0.05	0.02	0.94	3.11
Mn	0.29	0.07	<	<	<	<	0.00	0.04
Mg	0.46	0.51	<	<	0.07	0.01	1.38	0.94
Ca	0.22	0.34	0.23	0.27	<	0.04	0.00	<
Na	<	<	0.76	0.73	0.28	0.74	0.06	0.06
K	<	<	0.00	0.00	0.71	0.16	0.81	<
Sum	8.03	8.00	5.00	5.00	7.01	6.97	7.76	29.53

H1603N3	g core	g rim	mu core	mu rim	bi core	bi rim	fsp core	fsp rim	st
SiO2	36.20	35.76	45.53	45.03	35.99	35.85	58.92	60.63	26.33
TiO2	<	<	0.48	0.23	1.42	1.38	<	<	0.52
Al2O3	21.39	20.59	35.84	36.59	19.37	18.61	24.74	24.52	54.11
Cr2O3	0.05	<	0.17	0.08	0.06	0.08	<	<	0.07

Fe2O3	2.41	2.70	<	<	0.57	1.42	0.04	0.21	<
FeO	26.69	28.43	0.87	0.82	14.20	13.97	<	<	12.73
MnO	4.59	5.26	<	<	0.09	0.08	<	<	0.24
MgO	3.79	3.24	0.72	0.54	13.16	13.02	<	<	2.53
CaO	4.07	2.47	<	<	<	<	6.17	5.68	<
Na2O	<	<	1.74	1.92	0.36	0.40	7.90	8.16	0.11
K2O	<	<	8.74	8.41	8.67	8.34	0.05	0.09	<
Totals	99.19	98.45	94.09	93.62	93.89	93.15	97.82	99.29	96.64
Oxygens	12	12	11	11	11	11	8	8	46
Si	2.91	2.92	3.05	3.02	2.70	2.72	2.68	2.71	7.39
Ti	<	<	0.02	0.01	0.08	0.08	<	<	0.11
Al	2.03	1.99	2.83	2.89	1.71	1.66	1.33	1.29	17.90
Cr	0.00	<	0.01	0.00	0.00	0.01	<	<	0.02
Fe3	0.15	0.17	<	<	0.03	0.08	0.00	0.01	<
Fe2	1.79	1.94	0.05	0.05	0.89	0.89	<	<	2.99
Mn	0.31	0.36	<	<	0.01	0.01	<	<	0.06
Mg	0.45	0.40	0.07	0.05	1.47	1.47	<	<	1.06
Ca	0.35	0.22	<	<	<	<	0.30	0.27	<
Na	<	<	0.23	0.25	0.05	0.06	0.70	0.71	0.06
K	<	<	0.75	0.72	0.83	0.81	0.00	0.01	<
Sum	8.00	8.00	7.00	7.00	7.79	7.77	5.01	5.00	29.58

H1603P1	g core	g rim	bi core	bi rim	mu core	mu rim	fsp core	fsp rim
SiO2	36.83	35.90	35.41	35.30	50.00	46.36	63.04	66.56
TiO2	<	0.06	1.68	1.38	0.32	0.29	<	<
Al2O3	20.55	20.70	18.08	17.10	29.74	36.18	23.25	21.22
Cr2O3	<	<	0.06	0.07	0.05	<	<	<
Fe2O3	1.63	2.51	<	0.94	<	<	0.13	0.14
FeO	35.63	34.64	21.73	20.95	2.32	1.41	<	<
MnO	1.69	1.30	0.10	0.07	<	<	<	0.04
MgO	2.38	2.50	8.61	9.00	2.14	0.52	<	<
CaO	1.80	1.67	<	<	<	<	4.47	1.95
Na2O	<	<	0.05	0.07	0.62	1.85	9.29	10.79
K2O	0.05	0.11	8.92	8.74	9.97	8.66	0.09	0.07
Totals	100.56	99.39	94.64	93.62	95.16	95.27	100.27	100.77

Oxygens	12	12	11	11	11	11	8	8
Si	2.97	2.93	2.74	2.76	3.33	3.06	2.78	2.90
Ti	<	0.00	0.10	0.08	0.02	0.01	<	<
Al	1.96	1.99	1.65	1.58	2.33	2.82	1.21	1.09
Cr	<	<	0.00	0.00	0.00	<	<	<
Fe3	0.10	0.15	<	0.06	<	<	0.00	0.01
Fe2	2.41	2.36	1.41	1.37	0.13	0.08	<	<
Mn	0.12	0.09	0.01	0.01	<	<	<	0.00
Mg	0.29	0.30	0.99	1.05	0.21	0.05	<	<
Ca	0.16	0.15	<	<	<	<	0.21	0.09
Na	<	<	0.01	0.01	0.08	0.24	0.80	0.91
K	0.01	0.01	0.88	0.87	0.85	0.73	0.01	0.00
Sum	8.00	8.00	7.78	7.78	6.95	7.00	5.01	5.01

H1603S1	g core	g rim	bi	mu core	mu rim	fsp core	fsp rim
SiO2	37.58	39.09	38.47	48.06	47.44	59.70	61.70
TiO2	<	<	1.26	1.01	0.58	<	0.05
Al2O3	21.28	22.35	17.94	33.42	34.32	24.40	22.70
Cr2O3	0.06	<	0.06	0.06	0.08	<	<
Fe2O3	1.67	<	<	<	<	<	<
FeO	30.39	28.47	13.44	1.10	1.12	<	<
MnO	2.37	0.05	<	0.04	<	<	<
MgO	4.82	6.84	14.44	1.77	1.43	<	<
CaO	2.80	4.29	0.05	<	<	5.84	4.20
Na2O	<	<	0.20	1.24	1.52	8.19	9.07
K2O	<	0.04	8.70	9.50	8.97	0.08	0.09
Totals	100.97	101.13	94.56	96.20	95.46	98.21	97.81

Oxygens	12	12	11	11	11	8	8
Si	2.96	3.00	2.84	3.15	3.13	2.70	2.79
Ti	<	<	0.07	0.05	0.03	<	0.00
Al	1.98	2.02	1.56	2.59	2.67	1.30	1.21
Cr	0.00	<	0.00	0.00	0.00	<	<
Fe3	0.10	<	<	<	<	<	<
Fe2	2.00	1.83	0.83	0.06	0.06	<	<

Mn	0.16	0.00	<	0.00	<	<	<
Mg	0.57	0.78	1.59	0.17	0.14	<	<
Ca	0.24	0.35	0.00	<	<	0.28	0.20
Na	<	<	0.03	0.16	0.19	0.72	0.80
K	<	0.00	0.82	0.80	0.76	0.01	0.01
Sum	8.00	7.99	7.74	6.98	6.98	5.01	5.00

H1603T1	g core	g rim	bi core	bi rim	mu	fsp core	fsp rim
SiO2	37.56	38.87	30.79	38.02	47.88	59.53	63.11
TiO2	0.05	<	0.78	1.09	0.87	<	<
Al2O3	21.44	22.10	19.84	18.37	32.51	25.16	23.01
Cr2O3	<	0.05	0.09	<	0.23	<	<
Fe2O3	1.38	0.97	2.94	<	<	0.03	0.10
FeO	28.64	28.21	14.98	13.36	1.39	<	<
MnO	2.91	0.25	0.04	0.05	<	<	<
MgO	4.35	7.24	17.60	14.69	2.09	<	<
CaO	4.33	3.99	<	<	<	7.14	4.61
Na2O	<	<	0.06	0.14	1.08	7.67	9.12
K2O	<	<	3.80	9.34	9.66	0.06	0.04
Totals	100.66	101.68	90.92	95.06	95.71	99.59	99.99
Oxygens	12	12	11	11	11	8	8
Si	2.96	2.97	2.38	2.80	3.17	2.67	2.79
Ti	0.00	<	0.05	0.06	0.04	<	<
Al	1.99	1.99	1.81	1.59	2.54	1.33	1.20
Cr	<	0.00	0.01	<	0.01	<	<
Fe3	0.08	0.06	0.17	<	<	0.00	0.00
Fe2	1.89	1.81	0.97	0.82	0.08	<	<
Mn	0.19	0.02	0.00	0.00	<	<	<
Mg	0.51	0.83	2.02	1.61	0.21	<	<
Ca	0.37	0.33	<	<	<	0.34	0.22
Na	<	<	0.01	0.02	0.14	0.67	0.78
K	<	<	0.37	0.88	0.82	0.00	0.00
Sum	8.00	8.00	7.78	7.79	6.99	5.01	5.00

H1603T7	g rim	g core	bi	mu	fsp core	fsp rim	st

SiO2	36.40	37.55	36.34	46.60	59.00	61.70	27.73
TiO2	0.04	<	1.24	0.94	<	<	0.45
Al2O3	21.62	22.13	18.35	33.50	26.10	24.10	55.45
Cr2O3	<	0.04	0.06	0.07	<	<	0.10
Fe2O3	1.25	1.25	1.25	1.25	1.25	1.25	1.25
FeO	31.20	26.60	12.90	1.12	0.09	<	11.07
MnO	1.26	0.67	0.07	<	<	<	0.14
MgO	6.09	6.18	14.94	1.65	<	<	1.62
CaO	2.13	6.68	0.06	<	7.90	5.60	<
Na2O	<	<	0.44	1.11	7.19	8.46	0.25
K2O	<	0.04	8.93	9.65	0.05	0.08	<
Totals	99.99	101.14	94.58	95.89	101.58	101.19	98.06
Oxygens	12	12	11	11	8	8	46
Si	2.89	2.91	2.71	3.09	2.61	2.72	7.60
Ti	0.00	<	0.07	0.05	<	<	0.09
Al	2.03	2.02	1.61	2.62	1.36	1.25	17.92
Cr	<	0.00	0.00	0.00	<	<	0.02
Fe3	0.08	0.07	0.07	0.06	0.04	0.04	0.26
Fe2	2.07	1.72	0.80	0.06	0.00	<	2.54
Mn	0.09	0.04	0.00	<	<	<	0.03
Mg	0.72	0.71	1.66	0.16	<	<	0.66
Ca	0.18	0.55	0.01	<	0.37	0.26	<
Na	<	<	0.06	0.14	0.62	0.72	0.13
K	<	0.00	0.85	0.82	0.00	0.00	<
Sum	8.06	8.04	7.84	7.00	5.00	5.00	29.27

H1604E1	g core	g rim	am core	am rim	fsp core	fsp rim
SiO2	37.40	37.63	45.00	43.19	64.99	60.12
TiO2	0.16	<	0.78	0.69	<	<
Al2O3	20.90	21.12	13.00	15.08	22.35	25.68
Cr2O3	<	<	0.04	<	<	<
Fe2O3	1.30	0.92	3.06	2.65	0.08	0.14
FeO	27.53	29.20	12.64	14.01	<	<
MnO	2.54	<	<	0.05	<	<
MgO	1.50	2.75	10.60	8.93	<	<

CaO	9.40	8.49	10.90	11.17	3.25	7.26
Na2O	<	<	1.27	1.18	9.99	7.69
K2O	<	<	0.70	0.62	0.05	0.08
Totals	100.73	100.11	97.99	97.57	100.71	100.97
Oxygens	12	12	23	23	8	8
Si	2.97	2.98	6.58	6.38	2.84	2.66
Ti	0.01	<	0.09	0.08	<	<
Al	1.96	1.98	2.24	2.63	1.15	1.34
Cr	<	<	0.01	<	<	<
Fe3	0.08	0.06	0.34	0.29	0.00	0.01
Fe2	1.83	1.94	1.55	1.73	<	<
Mn	0.17	<	<	0.01	<	<
Mg	0.18	0.33	2.31	1.97	<	<
Ca	0.80	0.72	1.71	1.77	0.15	0.34
Na	<	<	0.36	0.34	0.85	0.66
K	<	<	0.13	0.12	0.00	0.00
Sum	8.00	8.00	15.29	15.31	5.00	5.01

H1604E4	g core	g rim	mu core	mu rim	bi	fsp core	fsp rim
SiO2	36.16	37.32	49.10	47.24	35.39	62.88	66.58
TiO2	0.06	0.04	0.75	0.59	1.58	<	<
Al2O3	20.83	21.08	31.04	33.46	18.11	23.85	21.71
Cr2O3	<	<	<	0.04	<	<	<
Fe2O3	2.09	1.04	<	<	<	<	0.07
FeO	32.86	34.14	2.36	2.69	22.15	<	<
MnO	2.38	1.04	0.04	<	0.18	<	<
MgO	1.57	2.82	1.85	1.25	8.12	<	<
CaO	3.69	3.34	<	<	0.04	5.31	2.61
Na2O	0.11	<	0.56	0.69	0.06	9.00	10.30
K2O	<	<	10.29	10.47	9.53	0.10	0.07
Totals	99.75	100.82	95.99	96.43	95.16	101.14	101.34
Oxygens	12	12	11	11	11	8	8
Si	2.94	2.98	3.25	3.13	2.74	2.76	2.89
Ti	0.00	0.00	0.04	0.03	0.09	<	<

Al	2.00	1.98	2.42	2.61	1.65	1.23	1.11
Cr	<	<	<	0.00	<	<	<
Fe3	0.13	0.06	<	<	<	<	0.00
Fe2	2.24	2.28	0.13	0.15	1.43	<	<
Mn	0.16	0.07	0.00	<	0.01	<	<
Mg	0.19	0.34	0.18	0.12	0.94	<	<
Ca	0.32	0.29	<	<	0.00	0.25	0.12
Na	0.02	<	0.07	0.09	0.01	0.77	0.87
K	<	<	0.87	0.89	0.94	0.01	0.00
Sum	8.00	8.00	6.97	7.02	7.82	5.01	4.99

H1604J2	g core	g rim	bi	fsp core	fsp rim	mu	st
SiO2	36.85	35.30	33.22	62.07	60.90	46.56	27.79
TiO2	<	0.04	1.03	<	<	0.31	0.57
Al2O3	21.35	20.80	19.51	24.61	24.90	35.40	53.32
Cr2O3	<	<	<	<	<	<	0.09
Fe2O3	2.25	3.65	2.86	0.11	0.11	<	<
FeO	31.55	30.55	14.56	<	<	0.95	12.63
MnO	1.47	0.50	0.05	<	<	<	0.06
MgO	4.15	3.13	12.06	<	<	0.87	1.96
CaO	2.77	4.26	0.10	5.88	6.14	0.07	<
Na2O	<	<	0.56	8.52	8.09	1.65	0.09
K2O	<	<	8.51	0.04	0.05	9.07	<
Totals	100.39	98.23	92.46	101.23	100.19	94.88	96.51
Oxygens	12	12	11	8	8	11	46
Si	2.93	2.89	2.57	2.72	2.70	3.09	7.77
Ti	<	0.00	0.06	<	<	0.02	0.12
Al	2.00	2.00	1.78	1.27	1.30	2.77	17.58
Cr	<	<	<	<	<	<	0.02
Fe3	0.14	0.22	0.17	0.00	0.00	<	<
Fe2	2.10	2.09	0.94	<	<	0.05	2.95
Mn	0.10	0.04	0.00	<	<	<	0.01
Mg	0.49	0.38	1.39	<	<	0.09	0.82
Ca	0.24	0.37	0.01	0.28	0.29	0.01	<
Na	<	<	0.08	0.73	0.70	0.21	0.05

K	<	<	0.84	0.00	0.00	0.77	<
Sum	8.00	8.00	7.86	5.00	5.00	7.00	29.33