Polyphase kinematics and geochronology of the late-Caledonian Kollstraumen detachment, north-central Norway

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The condensed tectonostratigraphic section from the Central Norway basement window, across the Devonian Kollstraumen detachment zone, and into the Helgeland Nappe Complex provides an excellent opportunity to assess the timing and kinematics of polyphase Caledonian deformation in central Norway. The Helgeland Nappe Complex, at present preserved in the hanging-wall of the Kollstraumen detachment zone (in the southwest) and the Nesna shear zone (north and east), provides evidence of Ordovician, Taconic deformation succeeded by emplacement of voluminous calc-alkaline plutons. These events pre-date the eastward thrusting of the Helgeland Nappe Complex across subjacent rock units during Scandian contractional deformation.

Structurally below the Kollstraumen detachment zone, Palaeoproterozoic orthogneisses and overlying supracrustal rocks of the Skjøtingen Nappe form the northern Central Norway Basement Window. During the Scandian event, these rocks were metamorphosed at medium to high grade and acquired a penetrative ductile fabric folded by roughly orogen-parallel, NE-SW-oriented regional folds. U-Pb dates on dykes of tonalite and granite that intruded supracrustal rocks of the Skjøtingen Nappe have yielded ages of 436 Ma and 430 Ma, respectively. Combining geochronological and structural data, we infer that the granite dykes may overlap in time with earliest Scandian contractional deformation. Later deformation of the dykes may have occurred during continued Scandian contraction as well as extension parallel to the regional fold axis. Titanite and monazite U-Pb dates from the dykes (c. 401-402 Ma) coincide in time with numerous pegmatites in central Norway and are interpreted to date metamorphism during latest Scandian exhumation of the Central Norway Basement Window. The contrasts in latest- to post-Scandian structural and metamorphic development suggests a major structural break between the Central Norway basement window and the Helgeland Nappe Complex, across which Middle and Upper Allochthonous units are excised along the Kollstraumen detachment zone.

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Introduction

The Scandinavian Caledonides consist of numerous composite thrust sheets derived either from Baltica, from outboard arcs and oceanic terranes, or from continental rocks exotic to the Baltica margin (e.g. Roberts & Gee 1985). The structural pattern observed in these rocks result from complex interactions of strain fields that developed successively during construction and collapse of the orogen. In central Norway, the present level of erosion provides a mid-crustal section through the orogen. These sections include tectonic windows where Precambrian crystalline rocks core structural culminations wrapped or overlain by allochthonous rock units assigned to the Middle, Upper and Uppermost Allochthons (Fig. 1).

One of these windows, the Central Norway Basement Window (CNBW, Braathen et al. 2000), is delimited by two regionally significant extensional shear zones, the Høybakken (Séranne 1992) and Kollstraumen detachments, to the southwest and northeast, respectively (Fig. 1). The Helgeland Nappe Complex (HNC), part of the Uppermost Allochthon and an exotic terrane relative to Baltica, structurally overlies the CNBW along the Kollstraumen detachment; this geometry was apparently achieved at the expense of intervening units of the Lower, Middle and parts of the Upper Allochthons.

In this paper, we describe the structural geology and kinematic history of the transition zone from the northern part of the CNBW, across the Kollstraumen detachment and into the basal parts of the Helgeland Nappe Complex. This highly attenuated section exhibits rocks that preserve elements of strain related to the major orogenic events in the central Caledonides and thus provides a condensed time/temporal section through the crust. In order to provide age control on

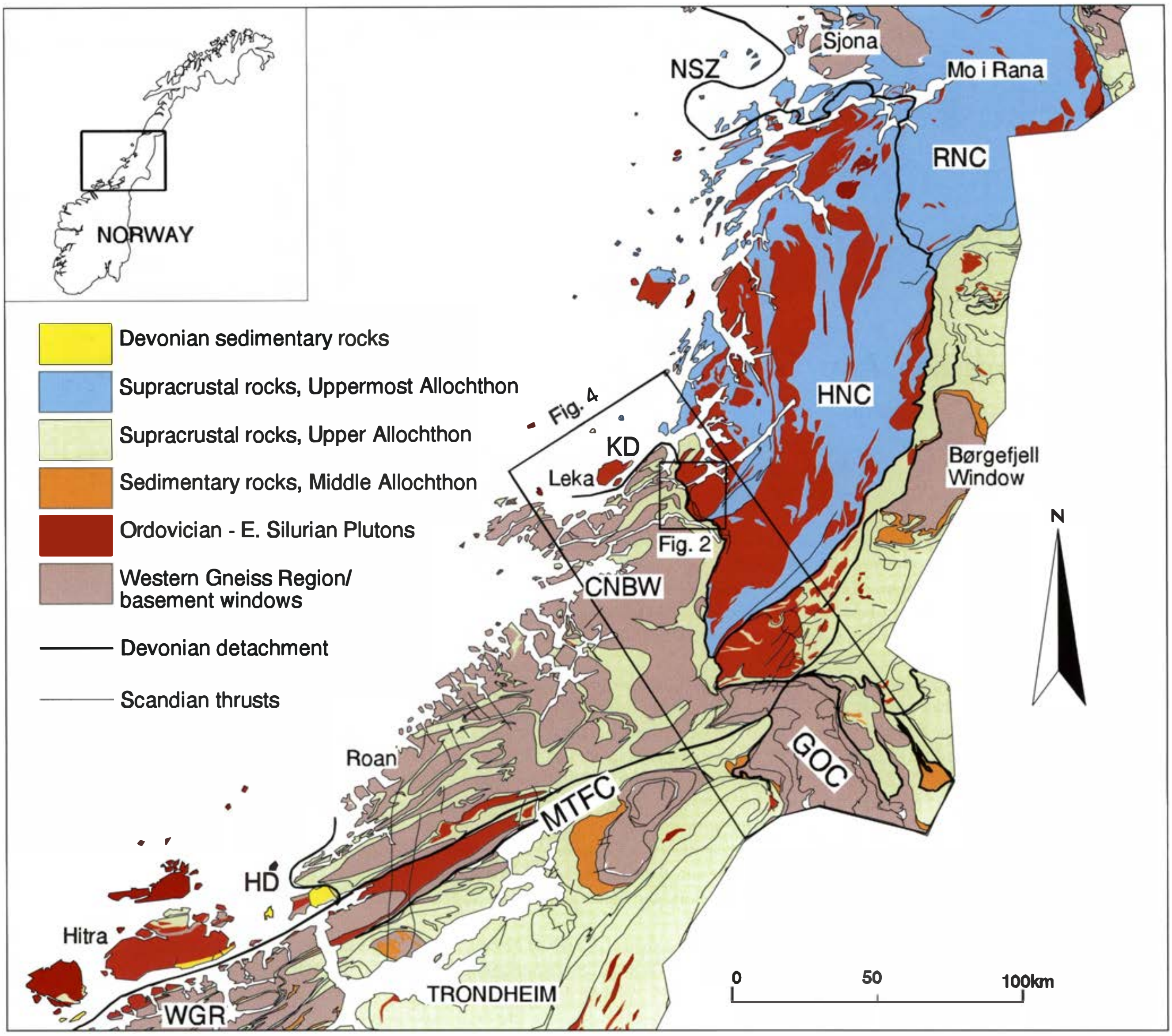

Fig. 1. Geological map of the central Scandinavian Caledonides in Norway showing the main tectonostratigraphic units and selected thrusts of Scandian origin. Major extensional shear zones and faults and Devonian supra-detachment basins are also shown. The Høybakken detachment (HD), the Kollstraumen detachment (KD), and the Møre-Trøndelag Fault Complex (MTFC) delimits the Central Norway Basement Window (CNBW), which is the northeast extension of the Western Gneiss Region to the southwest of Trondheim.
NSZ: Nesna Shear Zone; GOC: Grong-Olden Culmination; HNC: Helgeland Nappe Complex; RNC: Rødingsfjellet Nappe Complex; WGR: Western Gneiss Region. The map is based on Lundquist et al. (1996) and Koistinen et al. (2002).

the structural evolution in the study area, we also present new U-Pb ages on granitoid dykes cutting metasupracrustal rocks in the northern CNBW. By combining geochronological data with structural information in the CNBW-Kollstraumen-HNC section, we assess the effects of pre-Scandian and Scandian contractional events, as well as extensional deformation of the nappe pile. The regional Devonian evolution of the Caledonides in north-central Scandinavia is treated by Braathen et al. (2002), Eide et al. (2002) and Osmundsen et al. (2003); we review briefly below the regional setting as pertains to this study.

Regional setting

During the Silurian to Early Devonian Scandian event, the outboard allochthons were gradually accreted towards Baltica; the event culminated with continent-continent collision between Baltica and Laurentia, and final telescoping of the entire nappe pile across the autochthonous foreland (Roberts & Gee 1985, Pedersen et al. 1988, Stephens & Gee 1989, Greiling et al. 1998). The rocks of the Western Gneiss Region exhibit evidence of deep subduction of westernmost Baltica beneath Laurentia, and extreme crustal thickening led to extensional denudation and rapid exhumation of deeply subducted crust (Smith 1984, Dobrzhinetskaya et al. 1995, Wain 1997, Terry et al. 2000). In the Early to Mid Devonian, the nappe pile was thinned and modified along major extensional shear zones, and deposition of molasse took place in fault-controlled basins (Steel et al. 1985, Norton 1987, Séranne & Séguret 1987, Bøe et al. 1989, Séguret et al. 1989, Fossen 1992, Séranne 1992, Andersen 1998, Osmundsen et al. 1998. This was followed by renewed extension along localised shear zones and faults during the Late Palaeozoic and Mesozoic (e.g. Eide et al. 1997). The configuration of the basement windows and overlying allochthons in this setting may largely result from these late- to post-orogenic deformation episodes. Studies of extensional processes in the Scandinavian Caledonides have mainly focussed on western Norway. However, recent work has shown that a similar system of extensional shear zones and faults have considerably modified the Scandian nappe stack in central and north-central Norway (Braathen et al. 2002, Osmundsen et al. 2003, and references therein). Among these, the Kollstraumen detachment is exceptional in that it shows top-ENE movement, i.e. opposite to that of other major detachments in the region (Braathen et al. 2002). Below we provide a short description of the tectonostratigraphy and the main rock units of the study area.

Central Norway basement window

The CNBW forms the northernmost extent of the Western Gneiss Region (Fig. 1). Its present setting between the Høybakken and Kollstraumen detachments resembles that of a metamorphic core complex (Braathen et al. 2000). The metamorphic grade related to the Scandian collision event varies, from high-P granulite facies in pyroxene-bearing gneiss of the Roan area (Fig. 1), to amphibolite facies in gneisses and in-folded supracrustal rocks (Möller 1988, Solli et al. 1997, Roberts 1998). The magnetic pattern of the rocks shows a distinct contrast between high- and low-magnetic rocks in the southwest and northeast, respectively (e.g. Skilbrei et al. 2002). This indicates that the rocks in the footwall of the Høybakken detachment were exhumed from deeper crustal levels than those in the northeast part of the window.

Palaeoproterozoic orthogneisses (1.80-1.85 Ga) with tonalitic to granitic compositions and local preservation of migmatitic structures (ca 1.6 Ga) in the northern CNBW, have tentatively been correlated with granitoids of the Svecofennian Province in Sweden (Johansson et al. 1986, Schouenborg et al. 1991). An Early Silurian generation of migmatitization has also been identified (Schouenborg et al. 1991). Supracrustal rocks including mica gneiss, garben schist, calc-silicate gneiss, marble and amphibolite have been strongly deformed and appear as tight synforms within the orthogneisses. Most of the supracrustal rocks are assigned to the Skjøtingen Nappe (a local equivalent of the Seve Nappe of the Upper Allochthon), but rocks from other tectonostratigraphic levels are also present (e.g. Johansson et al. 1987). In the Caledonides, the Seve Nappe forms a major thrust sheet of metamorphic rocks presumably derived from the outermost margin of Baltica (Gee 1975, Stephens & Gee 1985). These rocks were metamorphosed during the Scandian event, but have in places also been subjected to high-grade metamorphism with formation of eclogites in pre-Scandian time (e.g. Williams & Claesson 1987, Mørk et al. 1988, Gromet et al. 1996).

Helgeland Nappe Complex

The Helgeland Nappe Complex (HNC) is part of the Uppermost Allochthon. It consists of Neoproterozoic to Early Palaeozoic meta-sedimentary rocks including migmatitic paragneisses and thick marble units, as well as ophiolitic rocks with over-lying cover sequences of assumed Ordovician age (Kollung 1967, Gustavson 1975, 1978, Myrland 1972, Thorsnes & Løseth 1991, Trønnes & Sundvoll 1995, Heldal 2001). Mafic to ultramafic ophiolite slivers are assumed to be coeval with the Early Ordovician Leka Ophiolite Complex (Fig. 1) dated at 497 ± 2 Ma (Dunning & Pedersen 1988). An origin near the Laurentian margin or a microcontinental setting has been suggested (Stephens et al. 1985; Grenne et al. 1999). Recent structural, geochronological and stable isotope data from different parts of the Uppermost Allochthon support a Laurentian origin for the rocks and have shown that west-directed contractional deformation and granitoid magmatism occurred during an Ordovician Taconic event (Pedersen et al. 1999, Roberts et al. 2001, 2002, Melezhik et al. 2002, Yoshinobu et al. 2002). In the western HNC, voluminous crust-derived magmatism and migmatitisation at ca 477 – 466 Ma predate imbrication and assembly of the nappe complex along east-dipping, west-vergent shear zones. Intrusion of mafic to intermediate plutons and formation of contact migmatites was coincident with exhumation of the rocks at ca 448 – 445 Ma (Barnes & Prestvik 2000, Barnes et al. 2002, Yoshinobu et al. 2002). This event was followed by emplacement of a compositionally variable suite of predominantly calc-alkaline intrusive rocks, which took place in the Late Ordovician to Early Silurian (Nordgulen et al. 1993, Birkeland et al. 1993, Eide et al. 2002). Detailed mapping along the southwest margin of the HNC (Fig. 2) shows that one of these intrusions, the Heilhornet Pluton (444 ± 11 Ma), cuts a complex imbricate zone, providing evidence of pre-Scandian contractional deformation in the Uppermost Allochthon (Husmo & Nordgulen 1988, Nordgulen & Schouenborg 1990). Structural investigations along the southwest margin of the pluton show that it participated in younger deformation

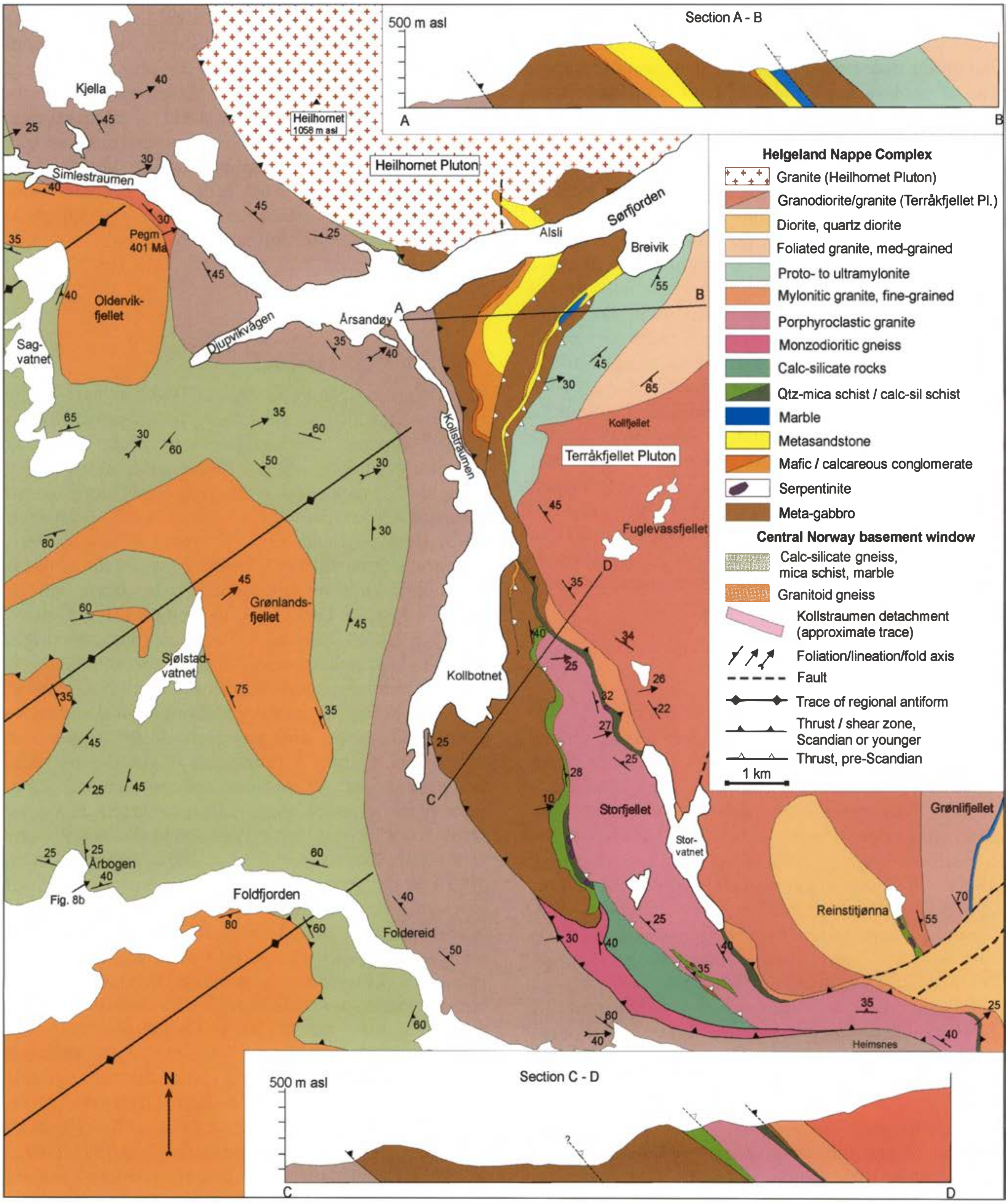

Fig. 2. Geological map of the northeastern part of the CNBW and the southwest HNC; see Fig. 1 for location. The approximate trace of highly strained rocks along the Kollstraumen detachment zone is schematically indicated below the base of the HNC (see text). Note how the NE-SW-oriented strike of the foliation in the CNBW changes progressively towards the detachment zone. Sections A-B and C-D illustrate the main features of a major duplex at the base of the HNC (see text). Also shown is the locality of the dated pegmatite (401 ± 3 Ma) from Simlestraumen (Schouenborg 1988). The dykes dated in this study were collected in the southeast limb of a regional synform, at Årbogen, north of Foldfjorden .

The CNBW - HNC contact

The Kollstraumen detachment partially follows and excises the contact between the CNBW and the HNC. This zone of highly strained rocks has been regarded as a major thrust formed prior to and during Scandian eastward translation of the HNC onto subjacent allochthons to the east (Gustavson 1981, Roberts et al. 1983, Dallmann 1986). Based on correlations to fossiliferous units in Sweden (Kulling 1933), this translation event is post-Wenlock in age (Gee 1975). However, initial accretion of nappe units in outboard terranes may have started in the Early Silurian.

Structural geology

This section describes critical field relations, the strain patterns, and kinematic interpretations from the study area. We focus on three distinguishable structural units (Figs. 2 and 3): (1) a basal unit of the CNBW gneisses and infolded supracrustal rocks, (2) the overlying Kollstraumen detachment zone characterised by polyphase shear events, and (3) a pre-Scandian, macroscopic duplex structure, in part affected by younger deformation, along the south-western boundary of the HNC. This subdivision is displayed in a schematic section (Fig. 3), where the approximate extent of the rocks in the middle unit, the Kollstraumen detachment zone, is outlined. Figure 3 also summarises the tectonostratigraphy and structural relationships based on detailed mapping and observations in the Foldfjorden-Sørfjorden area.

In order to assess the complex structural relationships of the area, we focus on two critical observations that clarify the structural chronology: (i) Within the Kollstraumen detachment zone (Simlestraumen-Djupvikvågen area, Fig. 2), a pegmatitic granite dyke has been dated to 401 ± 3 Ma (Schouenborg 1988), which is clearly younger than the Scandian thrusting event in the area. This dyke, as well as a number of neighbouring dykes of inferred similar age, constitute good strain markers since all of them participated in late, severe, top-ENE shear deformation. Locally, one can also document that this deformation is superimposed on older structural features of inferred Scandian age. The dykes are characteristically syn-tectonic (see below), suggesting that the late shear event affecting them is of Early Devonian age.
(ii) A large duplex in a gabbro-sedimentary cover sequence of the HNC is cut by the c. 444 ± 11 Ma Heilhornet and the adjacent Terråkfjellet Pluton (Figs. 2 and 3)(Nordgulen et al. 1993). This relationship documents that old, pre-Scandian thrust structures are present in the HNC. Besides, the plutons constitute good strain markers for the Scandian and/or Early Devonian events.

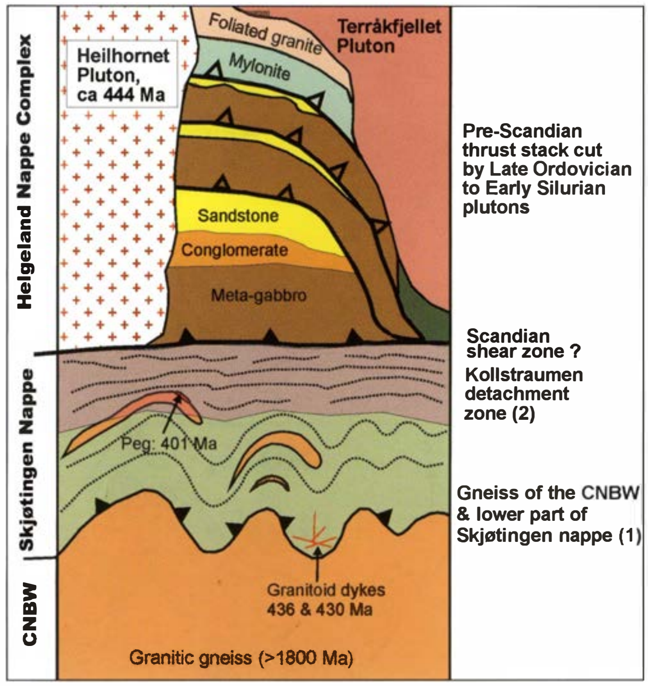

Fig. 3. Schematic section that outlines the main lithologies, tectonostratigraphic units and structural relationships across the northern Kollstraumen detachment zone (see map and legend in Fig. 2). In terms of structure, the section has been subdivided into three parts: 1) the upper gneisses of the CNBW and the overlying supracrustal rocks of the Skjøtingen Nappe; 2) the Kollstraumen detachment zone; and 3) the basal part of the HNC. See text for description. A composite box diagram illustrating the structural relationships across the entire CNBW is shown in Braathen et al. (2000).

CNBW – lower structural unit

The northern part of the CNBW (Figs. 2 & 3) consists of orthogneisses with infolded meta-supracrustal rocks of the Skjøtingen nappe, which host structural features interpreted to be of Scandian origin (e.g., Roberts 1998). In general, the rocks have a well-developed foliation parallel to lithological contacts, and a moderate to strong stretching lineation. The foliation is folded by and generally oriented parallel to the limbs of regional, NE-SW-oriented folds. Along the trace of down-folded supracrustal rocks within the orthogneisses, a lineation is locally the dominant structure, and the rocks can be classified as L-tectonites. Here, both regional and local fold axes, mineral lineation and mineral rodding have shallow east to northeast plunges (Fig. 4a, e). Approaching the Kollstraumen detachment zone, the regional foliation changes in attitude, and becomes approximately parallel with the strike of the detachment. At this level, large sheets of orthogneiss are present as concordant mega-lenses in supracrustal rocks (Figs. 2 and 3). They may represent decapitated antiforms, now occurring as sheets separated from the subjacent basement. Decapitation was either related to Scandian contraction or, alternatively, but less likely, to the Early Devonian extensional event.

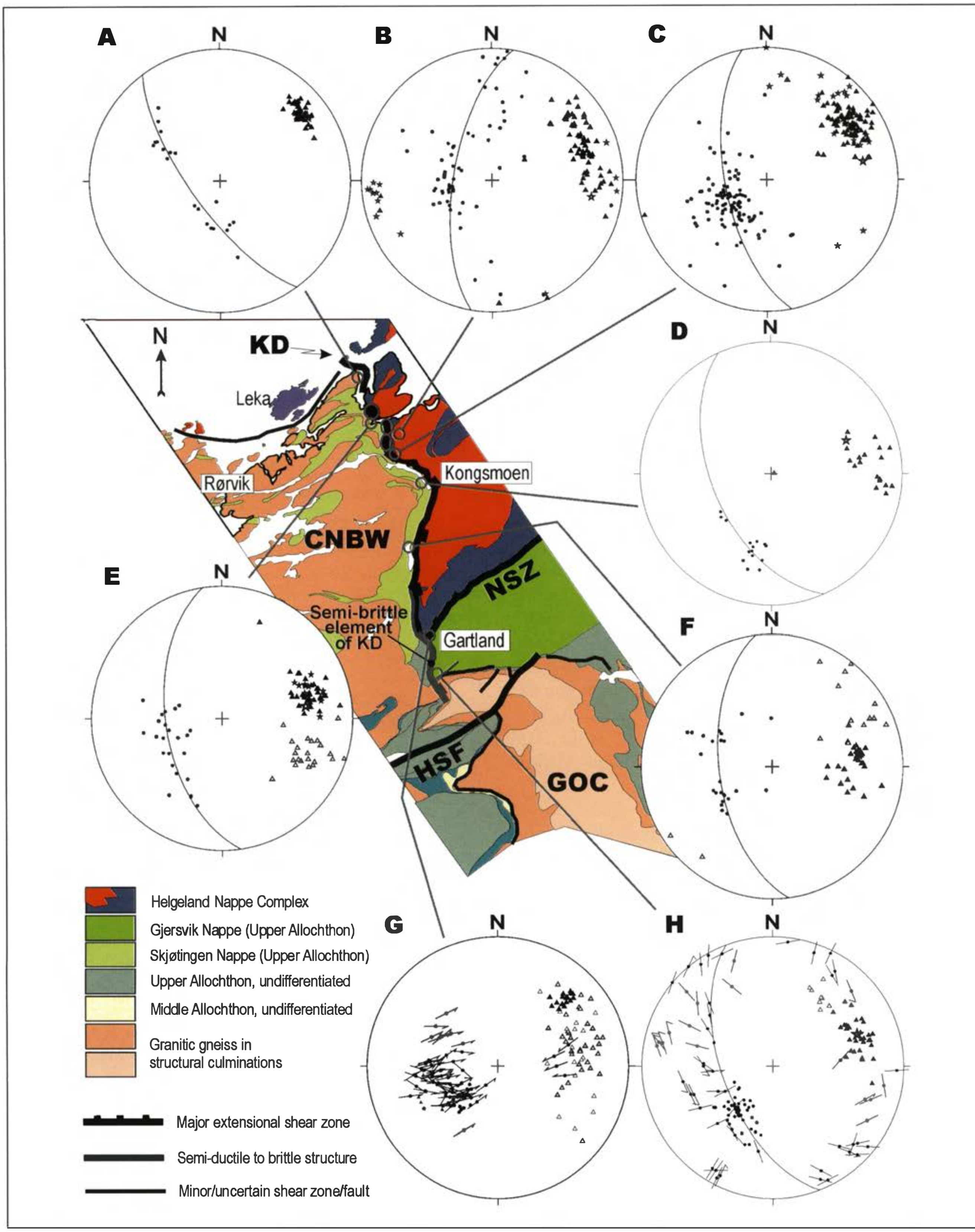

Fig. 4. Geological map simplified from Lundquist et al. (1996), showing sites and areas where structural data have been recorded. The data are summarized in the stereoplots A-H (equal area, lower hemisphere). See Fig. 1 for location.
Poles to fabric and faults are shown as dots; fold axes as stars. In plot A, B, C and D, stretching lineations are shown as filled triangles. In plot E, F, G and H, two generations of stretching lineation are shown as open triangles (older) and filled triangles (younger) (see text). Lines and arrows are slip-linear plots, which show the transport line of the hanging-wall block on the pole to the shear surface (method outlined in Braathen 1999). KD: Kollstraumen detachment; NSZ: Nesna shear zone; HSF: Hitra-Snåsa Fault. The Central Norway Basement Window (CNBW) is considered to be part of the Lower Allochthon and structurally overlies the Grong-Olden Culmination (GOC).

Within the lower structural unit (northern CNBW), the supracrustal rocks host a variety of granitic and pegmatitic dykes. In many cases, these are transformed into foliated sheets concordant with the foliation in the host rocks. However, in the hinge of regional synforms, for example at Årbogen (Fig. 2), numerous dykes having variable orientations are present. Some of these have intruded along the axial surface of the synform, whereas other dykes make small angles with the folded regional foliation. The structural pattern here suggests that dykes intruded during folding, but was subsequently mildly deformed, an observation of great importance for understanding the development of the regional fold system during the Scandian and subsequent events (see Geochronology).

When kinematic analysis (e.g. Hanmer & Passchier 1991) is applied to the lower structural unit, the overall kinematic pattern is that of NE to E and ESE-directed shear, as suggested by the stretching lineation in combination with asymmetric structures (Fig. 4a,e). However, the pattern is rather complex, with lineations rotating towards the pronounced stretching axis of the NE-SW-trending macroscopic folds.

Kollstraumen detachment zone – middle structural unit

The regional significance of the Kollstraumen detachment zone is discussed by Braathen et al. (2000, 2002). Here, we provide a detailed structural description based on studied localities along the detachment zone, focussing firstly on the northwestern area (northwest of Kongsmoen), and secondly on the southeastern extent of the detachment zone (near Gartland, Fig. 4).

Northwestern area. – The strain within the Kollstraumen detachment zone varies both through and along the zone, and there appears to be a gradual transition at the base and top towards rocks little affected by the detachment (Fig. 3). The central parts of the detachment zone reveal variably mylonitic, amphibolite-facies rocks, including marble, calc-silicate rocks, mica schist, minor amphibolite, and locally highly sheared megalenses of orthogneiss (Figs. 2 & 3). In some places, S-tectonites of inter-layered orthogneiss and schists are present with a well-preserved, amphibolite-facies foliation of inferred Scandian affinity. At some locations, this fabric is truncated by 10-cm to 1-m thick shear bands, which increase in intensity towards highly strained rocks where earlier fabrics are entirely transposed in mylonitic schist and schistose marble. In that the older fabric at most places is totally obliterated, one relies on key locations in order to separate old (Scandian?) deformation from the younger event (Early Devonian). The intensely deformed rocks have a well-developed stretching lineation (L>S-tectonites); L-tectonites are present in 10 to 20 m-thick zones.

A good example of the upper and lower transitional boundaries of the Kollstraumen detachment zone is found below the western contact of the Heilhornet Pluton (Fig. 2), underneath the HNC. In this section, ductile strain diminishes upward, and there is a change from mainly L>S- to S>L-tectonites. The detachment fabric becomes sub-penetrative with a declining number of apparently young, narrow shear-bands, and an inferred older foliation is discernible. The metamorphic facies of the rocks is similar to that of the underlying detachment zone, albeit the overall grain size is coarser in what is mainly a mylonitic schist. Along the top of the transition zone, at the east-dipping contact of the Heilhornet granite, an anastomosing pattern of 2-5m thick, fine-grained mylonite zones in the otherwise pristine granite shows the involvement of this granite in Scandian or younger deformation.

In general, the orientation of shear-sense indicators is linear structures in the Kollstraumen detachment zone are consistent with top-E to top-NE transport (Fig. 4). However, it is commonly difficult to separate structures that can confidently be assigned to Devonian extensional shear from those that may be related to Scandian or even older events. An exception is the mentioned area between Djupvikvågen and Simlestraumen (Fig. 2), where the presence of a strongly deformed pegmatite dated at 401 ± 3 Ma (Schouenborg 1988) shows that the shear deformation there post-dates the Scandian thrusting. There, the kinematics of the Devonian event can be established through nearby granititic and pegmatitic dykes, which include well-preserved sheets that truncate the foliation. When traced along strike, the sheets are locally tightly folded and sheared into blastomylonite, and/or transformed into sheath-folds plunging northeast parallel to the pronounced stretching lineation (Fig. 5a, b, c). Mutual truncation of and deformation along the foliation is consistent with syntectonic dyke injection. In the same area, one can also distinguish between an early E- to ESE-directed shear event expressed by an easterly-plunging lineation (Scandian), which is folded around L-tectonite lobes of the younger event (Fig. 5b). Kinematic indicators, common within the SL- and LS-tectonised rocks, and rare in the L-tectonites, include composite ductile shear fabrics, shear-related folds, winged porphyroclasts, and less commonly veins (e.g., Hamner & Passchier 1991). They support top-ENE shear along the Kollstraumen detachment zone during the Devonian event (Fig. 4e).

There is also evidence of younger activity along the northwestern part of the Kollstraumen detachment zone. This is revealed by truncating, brittle faults of the HNC (Fig. 2; Ihlen 1993), which strike either NE-SW or NNW-SSE, and are steeply inclined. Approaching the Kollstraumen detachment zone, some of the faults have listric geometry, becoming more gently dipping towards mylonitic marbles of the detachment zone.

This suggests that parts of the detachment zone were affected by low-grade reactivation. At higher levels, typical fault rocks of the generally 10 m wide fault zones are phyllonite and protocataclasite with characteristic red feldspar, and epidote-rich and greenish cataclasite, also seen as veining networks (Fig. 6a). Both types are succeeded by several generations of breccia, some being cemented by zeolites (see figure 10c of Braathen et al. 2002).

Southeastern area. – The southeast part of the Kollstraumen detachment zone is different from the areas in the northwest in that the dominant ductile fabric is less pronounced and strongly overprinted by semi-ductile and brittle structures. The characteristic medium-grade, ductile element of the detachment zone splays, with a prominent element linking with the N-S striking Nesna shear zone (Fig. 4), and a subordinate element continuing towards and along the northern contact of the Grong-Olden Culmination. In contrast, the predominantly semi-ductile to brittle deformation style can be traced continuously southeastward along a moderately NE-dipping fault zone, as shown in Fig. 4. Near Gartland, this fault zone is c. 200 m wide and characterised by down-ENE, semi-ductile shear bands, truncating the older fabric at a high angle. Farther southeast, this zone changes character, and is dominated by semi-brittle to brittle structures (Fig. 6b), which are superimposed on a minor ductile element. The architecture is that of approximately 10 m of retrograde, low-grade mylonite below at least 20 m of dark cataclasite to ultra-cataclasite, both truncated by 1-2 m of reddish, partly foliated, likely hydrous cataclasite. These fault rocks also appear as clasts in red, yellow and brown breccias, the former being cemented by carbonate, the latter two being unconsolidated. The youngest element is seen as steep, N-S to NE-SW striking faults, consisting of various 10-20 cm wide gouge and microbreccia zones, ranging from an older, brownish to a younger, light green type.

Kinematic data (e.g. Petite 1987) from the southeast Kollstraumen detachment show two patterns: Semi-ductile shear bands have the typical top-ENE transport direction, albeit slightly more to the NE (Fig. 4g). Within the south-easternmost part of the shear and fault

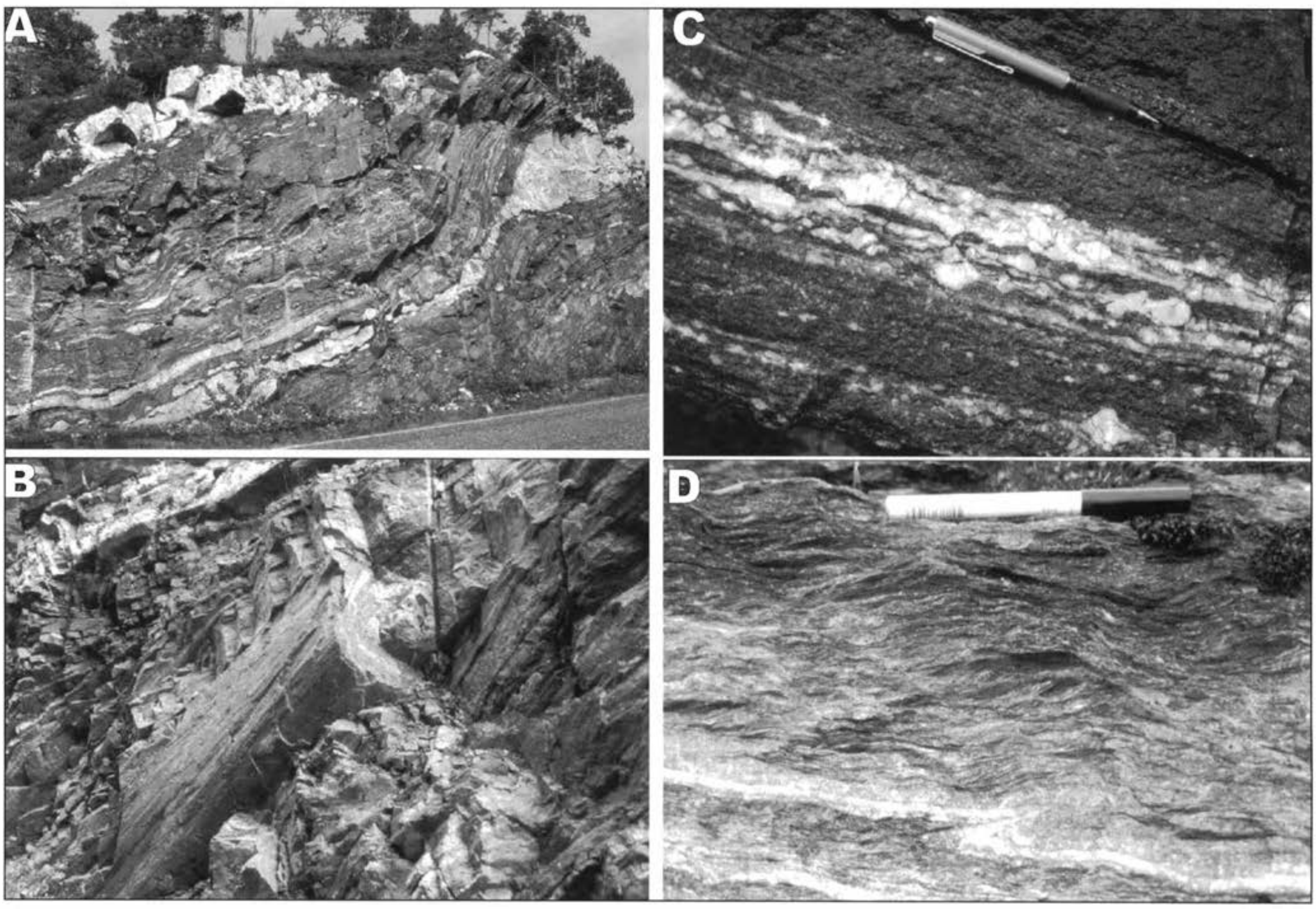

Fig. 5. Photographs of structures within the Kollstraumen detachment zone. A. Mylonitic schist and highly strained slightly discordant granitic dyke. View is to the north. B. L-tectonised mylonitic schist with a sheath-folded granitic dyke plunging down the ENE-trending stretching lineation. In places an older, folded lineation can be recognized (folded around sheath fold), which in general plunges to the ESE. C. Mylonitic schist with a highly sheared, mylonitic granitic dyke. View is to the northeast. D. Mylonitic schist near the intersection between then Nesna shear zone and the Kollstraumen detachment zone. Semi-ductile, top-NE shear bands truncate and partly rejuvenates the older fabric.

zone, south of Gartland, an ENE-plunging stretching lineation is observed in the low-grade mylonite, and the pattern of faulting is complex (Fig. 4h). The faults appear in two main populations, either top-ENE normal faults, or N-S to NE-SW striking oblique-slip and strike-slip faults with dominantly sinistral slip. Abundant, near transport-parallel faults may reflect the intersection between the detachment zone and the CNBW/Grong Olden Culmination, with deformation progressively becoming localised along the margin of the CNBW, or alternatively, influenced by the Hitra-Snåsa Fault system (cf. Séranne 1992, Heim 1997).

HNC – upper structural unit

The southwestern portion of the HNC consists of meta-gabbro with an overlying, unconformable cover sequence of conglomerate with mafic and calcareous clasts, meta-sandstone, mica schist, calcareous schist and marble (Fig. 2). Similar meta-gabbros are also present to the north and east of the Heilhornet Pluton, where they are associated with ultramafic rocks and locally pillow lava. This rock association is interpreted to be a dismembered ophiolite similar to those described elsewhere in the HNC (cf. Thorsnes & Løseth 1991, Heldal 2001). Other rock units include orthogneiss and grey, fine-grained mylonites and ultramylonites of partly uncertain origin.

South of Sørfjorden, the gabbro-cover unit is repeated in what appears to be a contractional duplex structure, consisting of three thrust sheets, which at present are tilted towards the east (Figs. 2 & 3). The approximately 20 to 50 m-wide shear zones of the duplex reveal strain gradients, as seen from a footwall to hanging-wall position. They start with well-preserved, albeit foliated, conglomerate, in places showing a well-developed clast lineation, followed by 10-20 m of protomylonitic conglomerate; the latter is succeeded by up to 20 m of mylonite and thin layers of ultramylonite, topped by a few metres of protomylonitic gabbro. The northern part of this megascopic duplex structure is clearly truncated by the Heilhornet granite, dated at 444 ± 10 Ma (Husmo & Nordgulen 1988, Nordgulen & Schouenborg 1990).

Further to the south, in the area between Kollbotnet and Storvatnet (Fig. 2), the duplex consists of meta-gabbro and porphyroclastic granite gneiss overlain by quartz schist, mica schist, and calc-silicate schist and gneiss. Locally, small lensoid bodies of serpentinised dunite and meta-gabbro are present in the supracrustal units (Fig. 2). The top of the duplex towards the Terråkfjell Pluton is marked by fine-grained, mylonitic granite. The medium-grained granodiorite of the Terråkfjell Pluton generally has a moderate mineral orientation of igneous origin. Although there is evidence of strong ductile deformation in its western part, the pluton clearly cuts mylonites in the upper part of the duplex structure (e.g. at Kollfjellet, Fig. 2). A large inclusion consisting of quartz schist and serpentinites similar to the rocks present in the duplex structure occurs south of Reinstitjønna (Fig. 2). The granodiorite of the Terråkfjellet Pluton is geochemically and petrographically similar to the Kråkfjellet Pluton (Nordgulen 1992), dated to 443 ± 7 Ma (Nordgulen et al. 1993). Assuming a similar age for the Terråkfjell Pluton, the data provide further evidence for pre-Scandian contractional deformation within the HNC and show that the duplex must be pre-Scandian in age.

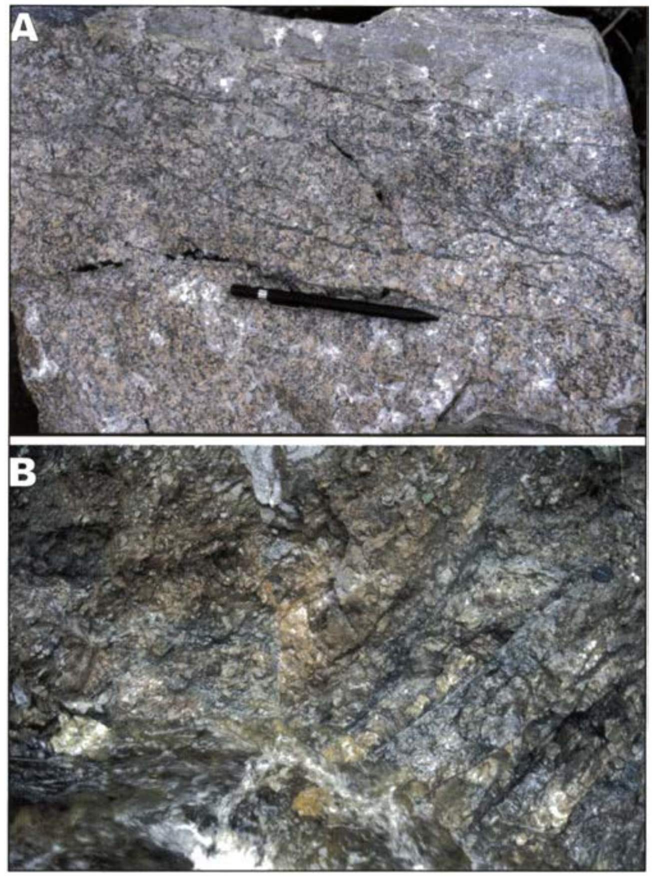

Fig. 6 A. Photograph of fault rocks characteristic for the late, truncating faults in the Helgeland Nappe Complex (see Fig. 2). Silicified, semi-ductile shear bands (upper parts) are superseded by a protocataclasite with distinct reddish staining of feldspar from the granodioritic host rock. The youngest fault rock is a veining breccia grading into a protobreccia with epidote as cement and fracture filling.
B. Brittle faults of the southeast part of the Kollstraumen detachment zone. Reddish, partly foliated, cataclasite is incorporated as clasts and blocks in red-grey, yellow and brown breccias. The first generation of breccia is cemented by carbonate, the two latter ones are nonconsolidated. These fault rocks are cut by steep, N-S- to NE-SW-oriented gouge and micro-breccia zones, seen as an older, brownish and younger, light-green type.

In more detail, the pre-Scandian deformation history of the rocks within the duplex can be further subdivided. In the meta-gabbros, structures include a foliation that is open to tightly folded and truncated by a fold-related axial plane cleavage. These structures are cut by an angular unconformity at the base of the overlying sedimentary cover sequence. Above, and in some areas along this contact zone, the meta-sedimentary rocks and the meta-gabbro share a common, younger SL- to S-type foliation, which is parallel to the shear zones related to the megascopic duplex structure. In places, the meta-gabbros host swarms of granitoid dykes commonly oriented at a high angle to, and cut by, the shear zones in the duplex structure. The relationships outlined above clarify that structures in the meta-gabbro predate formation of the duplex and are probably related to deformation prior to or during exhumation of the gabbros. This deformation preceded deposition of the cover sequences. A similar situation has been described from meta-gabbros and ultramafic serpentinites elsewhere in the HNC (Thorsnes & Løseth 1991; Heldal 2001).

The cross-cutting relationship between Scandian(?) and pre-Scandian deformation is well displayed towards the duplex north of Storvatnet (Fig. 2). There, the granodiorite of the Terråkfjellet Pluton has acquired a progressively stronger, penetrative tectonic fabric that is parallel to the mylonitic fabric in the fine-grained granite in the upper part of the duplex. In addition, a number of evenly spaced, north-dipping, narrow shear zones cut the granodiorite and gradually curve into the zone of strong ductile strain in the duplex. Since the Terråkfjellet Pluton cuts the pre-Scandian duplex (Fig. 2), the ductile high-strain zone in the pluton is consistent with a Scandian(?) shear zone. This zone, which extends between northern Kollbotnet and Storvatnet (Fig. 2), truncates both the duplex and the pluton. While the age of this shear event is not independently constrained, the shear zone appears to continue towards Kongsmoen (Fig. 4) and link up with a major top-east shear zone suggested to be Scandian in age (Roberts et al. 1983). Thus, the rocks in the hangingwall of the Kollstraumen detachment zone exhibit evidence for both pre-Scandian and Scandian contractional deformation.

The well-constrained structural character and chronology of the southern HNC forms a good framework for a kinematic analysis. In the contractional duplex of the southwestern HNC, consistent shear-sense indicators and recorded stretching lineations indicate that the nappe transport was towards east to northeast (Fig. 4b). A significant spread in the orientation of the lineation and mylonitic foliation reflects the presence of small, superimposed folds with an E-W axis. This axis is near the transport direction of the underlying Kollstraumen detachment zone. The detachment thus appears to have affected the hangingwall, a conclusion supported by the fact that intervening nappes have been excised, and the HNC itself truncated. In this context, the Kollstraumen detachment zone would act as a root or sole structure above the CNBW (cf. Braathen et al. 2002). In contrast, the Scandian shear zone(s) within the HNC and partly distinguishable within the Kollstraumen detachment zone, influenced overlying rocks to a lesser degree. This is probably consistent with a Scandian shear zone that acted as a basal décollement, below the Uppermost Allochthon.

U-Pb geochronology

In order to enable us to distinguish between the effects of different deformation events, we have dated two granitoid dykes occupying a structural position below the Kollstraumen detachment zone. The dated samples were collected in a road cut at Årbogen, north of Foldfjorden (UTM 36130-720795) (Fig. 2). The detailed geological setting and strain-age patterns are treated here.

Field relations

The Årbogen area provides a road section through calc-silicate gneisses in the hinge zone of a regional, upright, NE-SW-oriented synform (Fig. 2). Small-scale parasitic folds observed along the profile through the hinge of the major fold are consistently NW-verging; however, the regional significance of this has not been clarified. A number of different granitoid dykes cut the amphibolite-facies foliation in the calc-silicate gneisses. The dykes are variably oriented including some that are dipping steeply and are sub-parallel to the axial surface of the regional fold. In more detail, ductile deformation has affected the dykes, and depending on their initial orientation, the dykes have been folded and boudinaged. The field relations show that the dykes have been subjected to sub-vertical flattening and a NE-trending, shallow-plunging lineation occurs along their margins (Fig 7a, b).

At the locality sampled for geochronological work, three generations of dykes cut the NE-dipping (30-40 degrees) foliation on the southeast limb of the synform. Based on cross-cutting relationships, the following sequence of intrusion has been established (Fig. 7b).

1. Grey, medium to fine-grained biotite tonalite (dated sample N00-33); the rock is metaluminous with high Na_2O and relatively high Sr contents.
2. Weakly peraluminous, medium-grained biotite+muscovite±garnet granite, partly pegmatitic (not dated);
3. Weakly peraluminous, medium-grained biotite+muscovite±garnet granite locally grading into fine-grained granite, aplite and pegmatite (dated sample N00-34).

Towards the northwest from the sampled locality, the late granite dykes can be observed along a profile through the hinge of the regional synform. The consis-

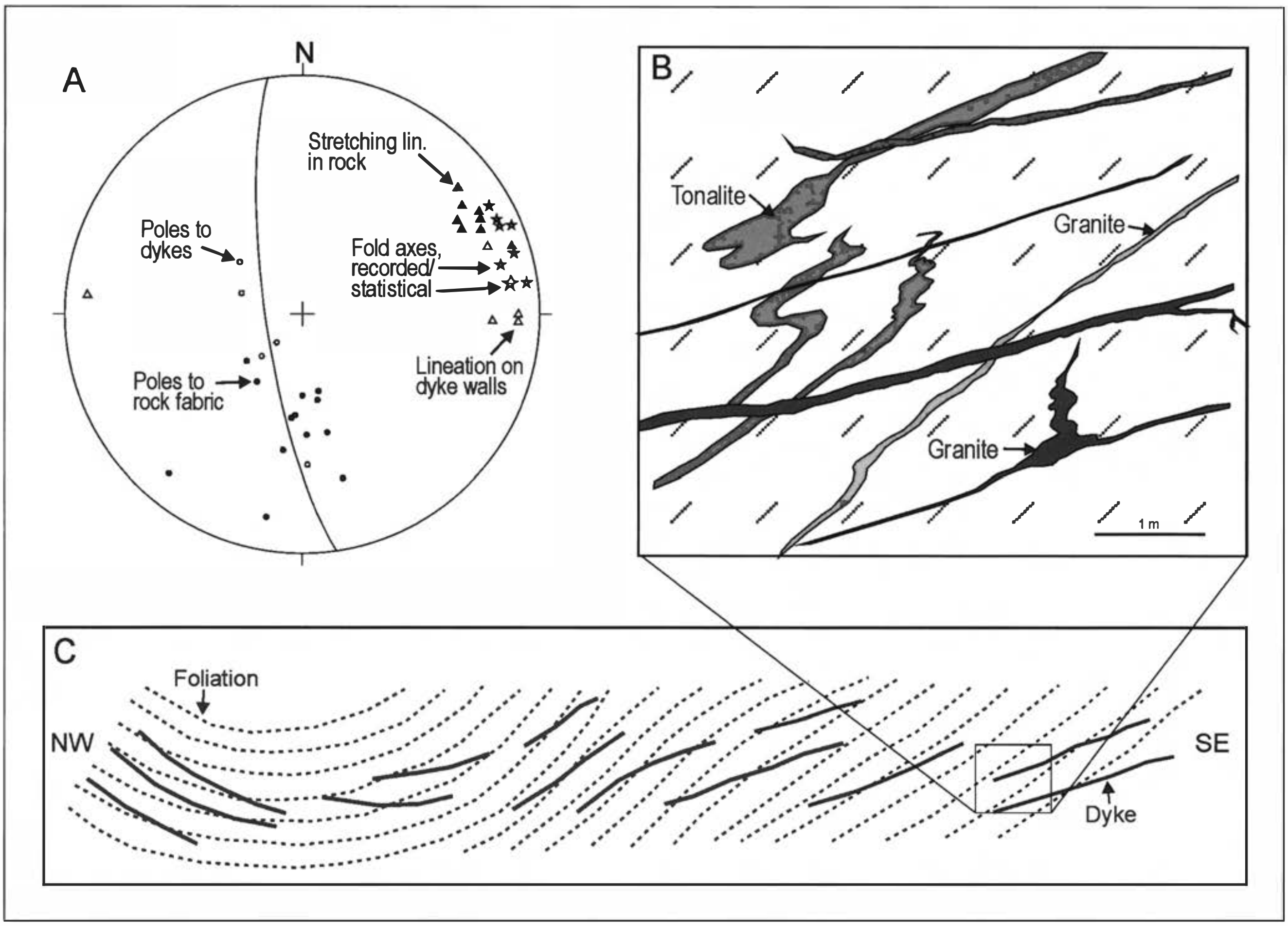

Fig. 7. The Årbogen locality (see Fig. 2 for location), with foliated calc-silicate gneisses that are exposed along a profile through the hinge of a regional, NE-SW-oriented synform. A. Structural data obtained along a SE-NW profile through the hinge of the synform. Note that both the foliation and dykes are affected by the folding. B. Schematic drawing of the field relationships at the locality sampled for geochronology. Different types of dykes cut the foliation (stippled) in calc-silicate gneiss. Grey: tonalite dated at 436 ± 2 Ma (oldest); pale grey: granite (not dated); dark grey: granite/pegmatite dated at 430 ± 4 Ma (youngest). C. Schematic profile (approximately 250 m) along the road showing the attitude of the foliation in the calc-silicate schists (stippled). The closure of the regional synform is to the northwest. Note the presence of prominent granitic dykes that cut the foliation at a low angle, but are rotated during further tightening of the fold.

tent angular relationships between the foliation and late granite dykes that have a relatively small angle with the foliation (Fig 7a), illustrate that the dykes cut a folded foliation. Furthermore, the dykes are openly folded, hence they have been affected by late tightening of the regional fold (Fig. 7c).

Analytical techniques

The U-Pb analyses were carried out by isotope dilution thermal ionization mass spectrometry (TIMS) using a $^{205}Pb/^{235}U$ spike. Following mineral separation, zircon, monazite and titanite were picked under a binocular microscope, abraded (Krogh 1982), and dissolved at 185°C in teflon bombs (zircon) or on a hotplate in Savillex vials (monazite and titanite). Zircon fractions smaller than 4 µg were measured without any specific purification whereas U and Pb were separated from the other solution using anion exchange resin with HCl for zircon and monazite and a combination of HBr, HCl and HNO_3 for titanite. Details of the measurement procedure are given in Corfu and Evins (2002). Blank correction was 2 pg Pb and 0.1 pg U for zircon and monazite, and 10 pg Pb and 0.3 pg U for titanite, and initial Pb was corrected using Pb compositions calculated with the Stacey & Kramers (1975) model. The results were plotted and regressed using the software of Ludwig (1999). The decay constants are those of Jaffey et al. (1971). Uncertainties in the isotopic ratios and the ages represent 2σ.

Results

N00-33 (tonalite) – This sample contains a relatively scarce zircon population, which also shows a wide variety of zircon types including grains that are sub-rounded or exhibit core - overgrowth relationships. Xenocrystic grains dominate the population whereas zircons of probable magmatic origin are rare. Two of the most promising crystals were chosen for analysis, one was a

Table 1. U-Pb data

Mineral, characteristics	Weight	U	Th/U	Pbc		$^{206}Pb/^{204}Pb$	$^{207}Pb/^{235}U$	2σ	$^{206}Pb/^{238}U$	2σ	rho	$^{207}Pb/^{206}Pb$	2σ	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$
	[mg]	[ppm]		[ppm]	[pg]			[abs]		[abs]			[abs]		[Ma]	
(1)	(1)	(2)	(3)	(4)	(4)	(5)	(6)	(6)	(6)	(6)		(6)	(6)	(6)	(6)	(6)
N00-34 granitic dyke																
Z eu tip [2]	<1	>1563	0,11		1,8	3858	0,5568	25	0,07099	27	0,86	0,05689	13	442,1	449,4	487,2
Z eu lp fr [1]	1	625	0,09		1,1	2492	0,5412	25	0,07009	23	0,74	0,05600	17	436,7	439,2	452,3
Z eu lp fr [6]	<1	>810	0,13		1,6	2283	0,5361	30	0,06970	27	0,72	0,05578	22	434,4	435,9	443,8
Z tip [1]	1	4195	0,05		1,8	10338	0,5247	23	0,06879	28	0,93	0,05532	9	428,8	428,3	425,2
Z eu flat [1]	1	1575	0,10		19	376	0,5217	49	0,06852	27	0,48	0,05522	46	427,2	426,3	421,1
Z eu flat [2]	<1	>821	0,01		0,8	4242	0,5217	22	0,06840	23	0,88	0,05531	11	426,5	426,3	424,8
M eu eq NA [1]	5	4694	6,29		13	7119	0,4848	12	0,06421	16	0,84	0,05475	8	401,2	401,3	402,2
M eu eq NA [1] a	36{	628	7,42		5,0	18171	0,4846	14	0,06429	17	0,87	0,05467	8	401,7	401,2	398,8
		630	7,42		4,4	20746	0,4837	10	0,06417	12	0,90	0,05467	5	400,9	400,6	398,8
N00-33 tonalitic dyke																
Z eu lp fr [1]	3	879	0,05		1,0	11400	0,5363	22	0,06989	28	0,97	0,05565	5	435,5	436,0	438,4
Z eu lp [1]	8	91	0,28		34	112	0,5296	166	0,06994	36	0,16	0,05491	169	435,8	431,5	408,7
T br-rd [14]	289	391	0,34	2,0		808	0,5096	25	0,06697	17	0,56	0,05519	22	417,9	418,2	419,9
T br-rd	136	406	0,24	2,3		714	0,5042	25	0,06619	15	0,48	0,05525	24	413,2	414,5	422,2
T pale-br	112	57	0,27	2,8		98	0,5007	180	0,06492	32	0,07	0,05594	201	405,4	412,2	450,1
T pale-br	182	180	0,21	1,8		405	0,4912	110	0,06441	47	0,42	0,05530	11	402,4	405,7	424,5

1.) Z = zircon; M = monazite; T = titanite; eu = euhedral; eq = equant; lp = long prismatic (l/w >4); fr = fragment; br = brown; rd = red; a = aliquot; NA = non-abraded, all the others abraded; [n] = number of grains (no indication means >40) 2,4.) weight and concentrations are known to better than 10%. 3.) Th/U model ratio inferred from 208/206 ratio and age of sample. 4.) Pbc = total common Pb in sample (initial +blank). 5.) raw data corrected for fractionation and blank. 6.) corrected for fractionation, spike, blank and initial common Pb (calculated with Stacey and Kramers (1975) model; the errors were calculated by propagating the main sources of uncertainty; errors indicate the last significant digits of the values.

long euhedral needle and the second a broken piece of a crystal with a euhedral pyramid. Although one of the analyses yielded a high common Pb content (Table 1) resulting in a large error ellipse, the two analyses overlap and define an age of 436 ± 2 Ma (Fig. 8).

Titanite is the other characteristic component of this sample, occurring as a mixture of dark brown and very pale-brown fragments and flat ovoidal grains. Two pairs of analyses for the dark and pale titanite varieties yield data that are respectively concordant, but correspond to statistically different ages. The oldest brown titanite fraction defines a minimum age of 418 ± 2 Ma for crystallization of this older generation, whereas the pale-brown generation formed at or after 402 ± 3 Ma. The latter population was generated by new growth of titanite, or by recrystallization of the older component. We interpret the age of 436 ± 2 Ma to date magmatic emplacement and crystallization of the euhedral zircons analysed. The 418 ± 2 Ma titanite age represents a minimum age for intrusion, but may be also be related to a tectonometamorphic event. Subsequent titanite growth at 402 ± 3 Ma probably reflects renewed tectonic activity, probably related to open folding of the dated dykes (see Discussion).

N00-34 (granite) - The granitic dyke N00-34 contains a population of zircons comparable to that of the tonalitic dyke, but with a higher proportion of zircons of probable magmatic origin The analyses were focussed on crystals and parts of crystals that had the highest probability of being of magmatic origin and free of xenocrystic components. The zircon data plot into two groups: one group of three slightly discordant analyses defines a short discordia line projecting to an upper intercept age of ca. 1720 Ma and a lower intercept age of 433 ± 2 Ma. These three analyses were obtained from selections of euhedral tips and of broken pieces of euhedral long-prismatic crystals. A second group of analyses, obtained from one tip and from very flat euhedral zircon crystals overlaps on the Concordia curve indicating an age of about 427 ± 1 Ma.

Monazite is very abundant in this dyke and two euhedral grains were analysed. One of them was split after dissolution, but before chemistry, and processed separately to verify the reproducibility of the analyses. All three data points overlap at an age of 401 ±1 Ma (average $^{207}Pb/^{235}U$ age identical to the Concordia age).

The euhedral morphology and low Th/U ratio of the analysed zircon crystals are characteristic of zircon grown in water-rich granitic melts, and it thus appears justified to conclude that they formed during crystallization of the granitic dyke, in which case the monazite age of 401 ± 1 Ma must be dating a superimposed metamorphic event (see Discussion). The distinction of the zircon data into age groups can have two possible explanations: First, because of the morphology (thin crystals and tips) and high U-content (over 800 - 4700 ppm), it is possible that the 427 Ma group of zircons may have lost some Pb and hence yield a too low apparent age. In this case, the 433 ± 2 Ma age of the upper group would represent the more reliable estimate for the time of intrusion of the dyke. An alternative explanation is that the zircons of the upper group may be xenocrystic, having been picked up from the country rock in the final stages of emplacement without undergoing any significant resorption or overgrowth, in which case the age of 427 ± 1 Ma would likely be the more reliable one. We prefer the first alternative age of 433 ± 2 Ma, but cannot completely exclude the second alternative. Although the two ages are nearly similar within uncertainty, we choose a conservative mean value of 430 ± 4 Ma in subsequent discussion of crystallisation of this sample.

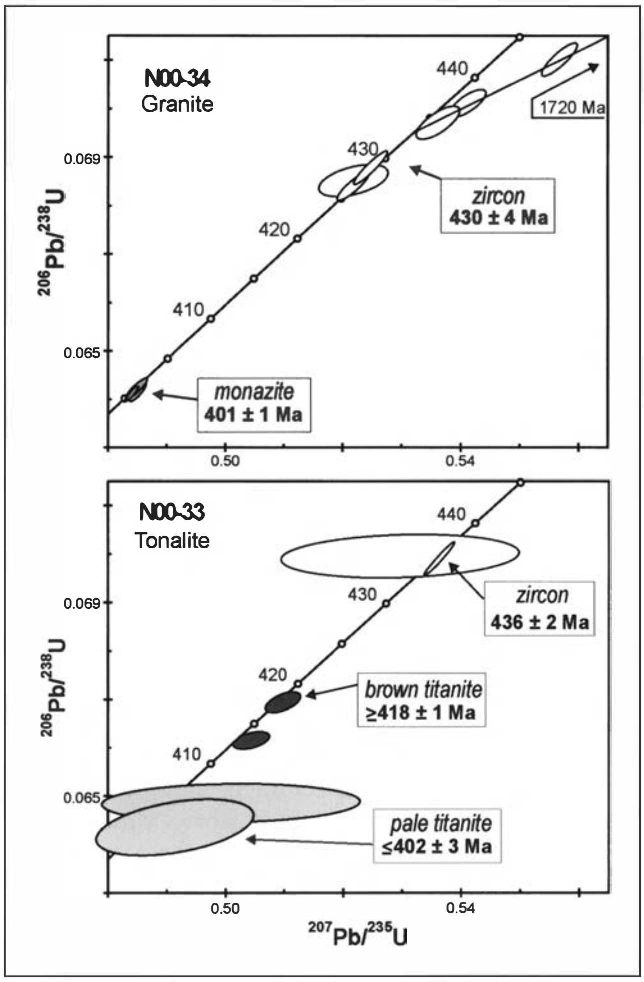

Fig. 8. U-Pb isotope data for zircon and titanite in sample N00-33 (tonalite); and for zircon and monazite in sample N00-34 (granite).

Discussion

Structural evolution

Above the Kollstraumen detachment, the principal structural pattern of the HNC reflects Ordovician amalgamation of the nappe complex, which took place prior to Late Ordovician to Early Silurian plutonism and the subsequent Scandian nappe translation (Nordgulen et al. 1990, 1993). In the western HNC, Yoshinobu et al. (2002) have suggested that west-vergent nappe transport took place in the Mid Ordovician. They correlated this event with Taconian deformation in Laurentia. Westward-verging structures pre-dating Scandian thrusting have also been documented farther north in the Uppermost Allochthon (Roberts et al. 2001, 2002). Our kinematic analysis of the major imbricate duplex east of Kollbotnet (Fig. 3) shows that the preserved structures are indicative of eastward contractional deformation (Fig. 4b). If the observed structures relate to initial Taconian assembly of the duplex zone, the transport direction would be the opposite of that of the western HNC. However, it is possible that top-northeast displacement during Scandian thrusting of the HNC, and subsequent development of the Kollstraumen detachment zone, may have obliterated the evidence of earlier top-west movement. The foliation in highly strained rocks of the duplex zone is locally folded around E-W axes; we interpret these folds to relate to subordinate reactivation mainly during the development of the Devonain Kollstraumen detachment zone.

During Scandian contractional deformation, the major nappe units of the Caledonian mountain belt were thrust onto the margin of Baltica (Gee 1975, Roberts & Gee 1985). Below the Kollstraumen detachment zone, the structures preserved in the CNBW are to a considerable extent the result of Scandian deformation. The igneous protoliths of the CNBW were transformed into banded, migmatitic orthogneisses with locally preserved lensoid bodies of less strained rocks. Also, the predominant NE-SW-oriented ductile fabric in the rocks of the CNBW probably relate to this event (Möller 1988, Solli et al. 1997). The Skjøtingen Nappe was thrust onto the subjacent gneisses, and in the eastern CNBW, there is evidence that the gneisses of the CNBW were thrust eastward onto the western margin of the Grong-Olden culmination (Fig. 4). Other nappe units of the Upper Allochthon were probably also present above the CNBW, and are at present locally preserved in synformal cores (e.g. Johansson et al. 1986). Thrusting of the HNC across subjacent nappes also took place during the Scandian event, as shown by shear zones and thick mylonites developed along the base of the HNC (e.g. Roberts et al. 1983, Dallmann 1986).

Implicitly, prior to late- to post-Scandian extension and unroofing along the Kollstraumen and Høybakken detachments, the entire CNBW was covered by a thick sequence of nappes. The plutonic and metasedimentary rocks above the Høybakken detachment, including the Smøla-Hitra Batholith (Gautneb & Roberts 1989, Nordgulen et al. 1995) are similar in age and may be correlated with those of the HNC. Thus, although their original extent prior to extension and faulting remains uncertain, rocks of the HNC and correlative units of the Uppermost Allochthon formed a contiguous nappe stack covering a large area from Hitra northwards to Mo i Rana (Fig. 1) and beyond. The preservation of low-grade rocks in several places, for example on Smøla (Roberts 1980) and Leka (Sturt et al. 1985), and in Helgeland (Gustavson 1975), shows that during the Scandian collision, this tectonic unit remained at relatively shallow crustal levels and was separated from the high-grade rocks at deeper levels by intervening nappes. Juxtaposition with rocks at lower tectonostratigraphic levels was achieved during late-Scandian extensional denudation of the nappe stack, as discussed by Braathen et al. (2002) and Osmundsen et al. (2003).

The latest-Scandian Kollstraumen detachment zone exhibits ductile, medium-grained fabrics characterised by top-ENE shear. It is evident from the map pattern that the shear zone was involved in the folding of the underlying CNBW. This is also well displayed in plots of the foliation, which define great circles consistent with ENE-plunging fold axes (Fig. 4 c, d, e, f, h). In along-strike sections, these folds are open and also appear to be thicker in the synforms. This relationship may reflect either fold decapitation or synchronous shear and folding (Braathen et al. 2000, 2002). In the CNBW, similar folds have higher amplitudes; synforms of supracrustal rocks are tight to isoclinal. When the trend of these folds is compared to the stretching axis of the bounding Kollstraumen and Høybakken detachment zones (Fig. 1, cf. Séranne 1992, Braathen et al. 2000), it is clear that the folds are near parallel to the stretching direction, and besides, approximately normal to the overall SSE-directed Caledonian thrusting direction. Such kinematics and interaction suggest that extensional and contractional tectonics overlapped in the middle crust during latest-Scandian deformation in the central Scandinavian Caledonides (Braathen et al. 2002, Eide et al. 2002). A similar situation may obtain in the Møre region, to the southwest of the study area, where Terry et al. (2000) proposed Early Devonian contractional tectonics in the lower crust that may have coincided with upper crustal extension.

Timing of tectonic events

The U-Pb zircon dates of tonalite (436 ± 2 Ma) and granite (430 ± 4 Ma) are interpreted as crystallization ages and show that the dykes intruded the calc-silicate gneisses at Årbogen in the Early Silurian (Fig. 8). The dykes cut a folded metamorphic fabric in calc-silicate rocks of the Skjøtingen nappe; the fabric must therefore be related to pre-Scandian deformation of the supracrustal rocks. Age determinations from strongly deformed granitoids occurring within the Skjøtingen nappe in the northern CNBW (Fig. 2) indicate intrusion ages of 450 - 500 Ma (Schouenborg et al. 1991). Although precise ages were not obtained, the data provide a minimum age for the host rocks and suggest that the granitoids intruded in the same time period as the Early to Mid Ordovician magmatism documented elsewhere in the Upper Allochthon (Stephens et al. 1993), and recently also from the western HNC (Pedersen et al. 1999, Yoshinobu et al. 2002). The intrusion age of the dated dykes fits the pattern of late Ordovician to Wenlock granitoid magmatism in various units of the Upper (e.g. Stephens et al. 1993, Hansen et al. 2002) and Uppermost Allochthons (Nordgulen et al. 1993, Eide et al. 2002) in a setting outboard of the margins of Laurentia or Baltica.

Based on our studies at Årbogen (Fig. 7), we propose that the initiation of folding of the foliation in the Skjøtingen Nappe pre-date intrusion of the dated tonalite and granite dykes. Regional evidence suggests that Scandian thrusting of nappes on to Baltica took place in the Wenlock (Kulling 1933, Gee 1975, Greiling et al. 1998). However, initial Scandian accretion in outboard terranes may have begun in the Early Silurian. The Skjøtingen (Seve) rocks show evidence of Ordovician polyphase structural events that are not easily distinguished from strain related to early Scandian deformation and thrusting. Thus, the folds may either have a pre-Scandian origin, or alternatively, relate to the early stages of Scandian deformation with accretion of the supracrustal Skjøtingen (Seve) nappe rocks along the outermost margin of Baltica. The dykes were deformed during tightening of the synform and in addition show evidence of sub-vertical flattening and NE-SW-oriented extension. This extension trend is parallel to the regional fold axes and to the extension trend of the Kollstraumen detachment zone. Since the general pattern of in-folded supracrustal units in subjacent gneiss was accentuated on a regional scale during deformation also affecting Devonian basins in central Norway (Roberts 1983, Robinson 1985, Bøe et al. 1989, Séranne 1992, Braathen et al. 2000), we relate this combined contraction-extension pattern to latest-Scandian deformation. In conclusion, the regional folds of the CNBW appear to have developed over a long period of time and may bridge the transition from Scandian contractional, to latest-Scandian, orogen-parallel extension.

Scandian thrusting culminated with continent-continent collision and deep subduction causing high- and ultra-high-P metamorphism in the Western Gneiss

Region. In the CNBW, high-pressure granulite-facies rocks from the Roan area yielded a Sm/Nd age of 432 ± 6 Ma (Dallmeyer et al. 1992), and migmatitic leucosomes from Rørvik (Fig. 4) yielded a U-Pb zircon age of 434 ± 24 Ma (Schouenborg et al. 1991), indicating high-grade metamorphism in the Silurian. The titanite fractions (ca 414 - 418 Ma) from the tonalite dated in this study (Fig. 8) also support tectonometamorphic events related to thrusting and collision in the latest Silurian to Early Devonian (time scale of Tucker et al. 1997). However, recent studies in the Western Gneiss Region suggest that the high-pressure event took place at c. 410-400 Ma, followed by rapid exhumation of subducted rock units (Tucker et al. 1987, 1991, Terry et al. 2000). New U-Pb and Ar-Ar data from the Sjona window (Fig. 1) and adjacent areas in central Nordland provide further evidence of Late Silurian contractional deformation followed by Early Devonian unroofing (Larsen et al. 2002, Eide et al. 2002). Collision and high-pressure metamorphism in the late Early Devonian is also in agreement with Devonian regional cooling of the CNBW as indicated by $^{40}Ar/^{39}Ar$ data on hornblende (414-393 Ma) and muscovite (395-390 Ma) (Dallmeyer et al. 1992). We conclude that although the age of Scandian collision in the CNBW remains to be more precisely established, the local evidence combined with regional data from other parts of the mountain belt are consistent with Late Silurian to Early Devonian thrusting and collision.

The geochronological studies of dykes at Årbogen show that growth of young titanite in the tonalite (402 ± 3 Ma) overlaps with the age of monazite (401 ± 1 Ma) in the granite (Fig. 9); this age is similar to a zircon U-Pb date obtained on a highly strained granite pegmatite in the Kollstraumen detachment zone. Pegmatites yielding Early Devonian ages are fairly widespread in the CNBW, and also in the Western Gneiss Region and in basement windows in Nordland (Schouenborg et al. 1991, Tucker et al. 1991, Larsen et al. 2002). Their formation results from decompression melting, possibly enhanced by increased fluid activity during exhumation immediately following collision of a considerable portion of the central Caledonides. Given the structural and geochronological data available at present, we suggest that these titanite and monazite ages reflect the metamorphic conditions during latest Scandian folding and related exhumation of the CNBW.

Unroofing of the CNBW took place during latest-Scandian, orogen-parallel, extension along the Kollstraumen and Høybakken detachment zones (Braathen et al. 2000). Recent work shows that the Kollstraumen detachment belongs to a regionally developed system of extensional shear zones and faults in north-central Norway (Braathen et al. 2002; Osmundsen et al. 2003). Ar-Ar geochronology on rocks across the northern part of the Nesna shear zone shows that top-WSW extension took place at c. 398 Ma and continued into the Late Devonian (Eide et al. 2002). The strongly deformed, ca. 400 million-year-old granite pegmatite in the Kollstraumen detachment zone shows that ductile top-NE deformation along the detachment there occurred in the late Early Devonian. Taking the thermo-chronological data into account, we conclude that major exhumation of the CNBW took place by thinning and removal of the overlying Scandian nappe stack in the late Early to Mid Devonian.

Conclusions

Structural studies and geochronology of dykes in the northern CNBW support the notion of a major, latest- to post-Scandian structural break between the CNBW and the HNC. The southern HNC has a prolonged history of pre-Scandian deformation and magmatism predating eastward thrusting during the Scandian event. Medium-grade fabrics recorded along the base of the HNC affected granitoids of Late Ordovician to Early Silurian age and may be related to Scandian thrusting. These structures are overprinted by shear along the Kollstraumen detachment zone.

In the northern CNBW, granitoid dykes cutting medium-grade, foliated supracrustal rocks of the Skjøtingen Nappe yield early Silurian ages which overlap in time with incipient Scandian contractional deformation. Deformation of the dykes reflects continued, Scandian to latest-Scandian contraction and tightening of regional NE-SW-oriented folds, as well as elongation parallel to the fold axes. Titanite and monazite ages of 401-402 Ma probably date tectonometamorphic activity during latest- to post-Scandian exhumation of the CNBW.

Our data suggest that an Early Devonian structural and thermal event affected the CNBW and overlying detachments. This is broadly similar to the situation that obtains in the Western Gneiss Region and in basement windows in central Nordland (e.g., Tucker et al. 1987, 1991, Terry et al. 2000, Larsen et al. 2002). Evidence for an Early to Mid Devonian event has not been detected in the HNC above the Kollstraumen detachment, indicating that the HNC remained at relatively high crustal levels after cessation of plutonism and metamorphism in the Early Silurian (430 - 425 Ma). Thus, contrasts in latest- to post-Scandian structural and metamorphic development suggest a major structural break between the CNBW and the HNC, across which Middle and Upper Allochthonous units are excised along the Kollstraumen detachment zone.

The Kollstraumen and Høybakken detachments, as well as the Nesna shear zone, can be traced offshore using combined potential field data (Olesen et al. 2002). Brittle faults are common in the HNC and show a complex history of multiple faulting events. This is expressed by a variety of deformation products consistent with the nappe rocks occupying a progressively shallower crustal level during successive development of the faults (Braathen et al. 2002). The faults are mainly oriented NE-SW and NNW-SSE and have orientations similar to that of basin-bounding, pre-Mid Triassic faults under the Trøndelag platform (Osmundsen et al. 2002). Therefore, the latest- to post-Scandian structural features present at deep levels offshore central Norway have exposed counterparts that can be studied in the adjacent land areas.

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