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AN EARLY ORDOVICIAN (FINNMARKIAN?) FORELAND BASIN AND RELATED LITHOSPHERIC FLEXURE IN THE SCANDINAVIAN CALEDONIDES

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ABSTRACT. Early Ordovician (479 – 455 Ma) graywackes overlying Cambrian passive margin successions in the Baltica palaeocontinent-related Lower Allochthon of the Scandinavian Caledonides document early Caledonian tectonic activity. Such rocks occur from the Jämtland area (Sweden) northwards along the eastern Caledonian margin, and imply a wide regional extent of a foreland basin in Early Ordovician times. This foreland basin was subsequently incorporated into a fold-and-thrust belt during the final Caledonian, Scandian tectonic episode (c. 425 – 390 Ma). Based on published cross section data, this late deformation is restored. The results and other available information are compiled into a palaeogeographic map and sections on the geometry and evolution of the Early Ordovician foreland basin.

Graywacke/turbidite sedimentation (Föllinge Formation) started in western (internal) areas already in Early Arenig times with a main phase from Llanvirn to Late Caradoc (c. 472 – 461 Ma). There, the Föllinge Formation rests with an erosional unconformity on older beds. Towards east, however, it overlies successively younger beds related to a carbonate domain. It is suggested that the areas of the sub-turbidite erosional unconformity represent the early location of a flexural forebulge, which subsequently migrated eastwards towards the margin of the carbonate domain of palaeocontinent Baltica.

The restored foreland-basin geometry is compared with numerical models in order to derive some characteristics of the flexure of the foreland lithosphere. Time and lithospheric constraints make it possible to test the viability of the restoration and of foreland basin models. Relative to the available lithospheric strength data, the width of the basin is too large, the depth relatively small, and the large wavelength of the flexure is difficult to explain with simple orogenic loading.

Graywacke sedimentation occurred after Finnmarkian (515 – 475 Ma) HP metamorphism, perhaps as a consequence of exhumation and consequent loading of the Baltican margin. Graywacke sedimentation ended at the time of Jämtland phase (460 – 440 Ma) HP metamorphism and relatively deep water conditions. It is speculated that eclogitization of crustal material produced an additional load, which caused a relatively large down flexure of the lithosphere.

INTRODUCTION

Depending on the type of orogen, plate convergence and collision are processes that can last several tens to hundreds of Ma. Pre- or early-orogenic tectonic domains, such as passive, or active continental margins, exotic terranes, and even early foreland basins may be overprinted by subsequent deformation, metamorphism and magmatism. Examples can be found in the Palaeozoic orogens of eastern North America or the Cainozoic Alpine-Himalayan orogenic belt. Progressive orogenic shortening leads to an advance of orogenic loads over the continental forelands, which results in loading and formation of foreland basins. Their fill, derived from the orogen, records the character and timing of the interaction between orogen and foreland lithosphere. These basins are also likely to contain coal or hydrocarbons and other raw materials, which are important exploration targets. Therefore, the evolution in space and time of orogenic foreland basins may be of general importance.

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Understanding of orogenic processes was greatly advanced by the recent accumulation of a wealth of radiometric data on igneous and metamorphic episodes. In particular, such new age data together with new palaeomagnetic information led to new models for internal, metamorphic nappes, for example, the Upper and Uppermost thrust units in the Caledonian orogen. In contrast, there are only few radiometric data on external lower thrust units that often lack related igneous rocks and are generally only weakly metamorphosed. However, sedimentologic and biostratigraphic information provide clues for a tectonic interpretation of such lower thrust units. Taken together, these data from the Scandinavian Caledonides, allow a new approach to the tectonic evolution of the Baltican continental margin and its interaction with other terranes during the various Caledonian orogenic episodes. Therefore, it is timely to tie together these modern data, in order to apply and test modern models of lithospheric evolution during plate convergence and orogeny. The regional context is briefly presented, followed by stratigraphic and geometric data and, finally, models of the lithospheric flexure and a discussion of the results and their implications.

REGIONAL CONTEXT

The Caledonide Orogen, exposed on both sides of the North-Atlantic Ocean (fig. 1), is a classic example of a Wilson cycle and large-scale nappe transport towards the forelands. The western foreland is relatively well preserved in Eastern Greenland (Higgins and others, 2004), but elsewhere it is overprinted by subsequent deformation (for example, in the British Isles or the east coast of North America). In contrast, the eastern foreland, the Fennoscandian Shield, preserves most of the traces of Caledonian orogenic processes. Stratigraphic data in the foreland basin successions in southern Norway and western Sweden reveal its early Palaeozoic history (Gee and Kumpulainen, 1980; Bassett and others, 1982; Bockelie and Nystuen, 1985; Baarli, 1990; Karis, 1998), although it was subsequently incorporated into the Caledonian orogenic wedge, and it is now part of the Jämtland Nappes (for example, Gee and others, 1985a; Roberts and Stephens, 2000). These nappes represent the Caledonian Lower Allochthon (see table 1 and below) and originated during the final Caledonian, Scandian tectonic episode in Late Silurian – Early Devonian times.

The Caledonian Nappe Pile

Figures 2 and 3 show the present tectonic situation of the central parts of the Scandinavian Caledonides from just north of the Oslo area, including Lake Mjøsa, to the Bodø-Sulitjelma region in the north. The Caledonian nappes are lying on top of the foreland lithosphere, which is represented by the Fennoscandian Shield, and its Late Neoproterozoic to Cambro-Silurian cover rocks. Comprehensive reviews have recently been published (for example, Roberts and Stephens, 2000; Roberts, 2003; Hacker and Gans, 2005), and the reader is referred to the detailed references there. The Caledonian nappes are grouped conventionally in ascending order into the Lower, Middle, Upper, and Uppermost Allochthons. In table 1, a compilation of the relevant local and regional structural unit names attempts to provide a modern overview. Most important here is the distinction of different terranes, which are represented in the nappe units (for example, Stephens and Gee, 1989). Rocks of the Lower Allochthon are generally agreed to be derived from the Fennoscandian Shield or palaeocontinent Baltica. The restorations from the Oslo-Mjøsa area (Morley, 1986) show a continuous succession from the Autochthon and across the Lower Allochthon. Although the overlying nappes of the Middle Allochthon show similarities with the Lower Allochthon with regard to their sedimentary successions and their continental basement rocks (for example, Kumpulainen and Nystuen, 1985), it is not always clear whether these units were palaeogeographically contiguous with Baltica, or whether they were separated from Baltica by rifts or minor ocean basins. The same holds true for the Seve Nappe Complex of the Upper Allochthon, which contains crystalline

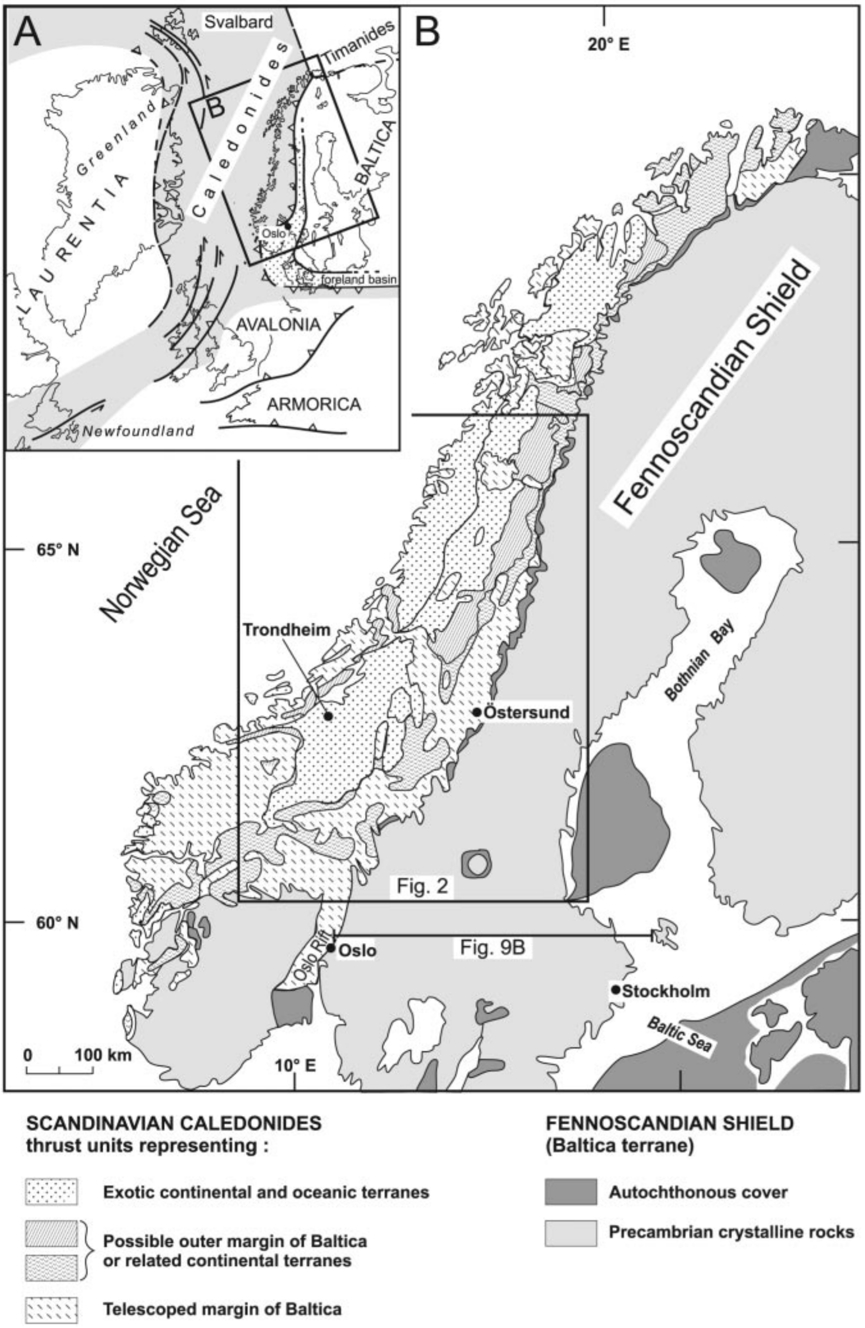


Fig. 1. (A) Sketch map of the North-Atlantic Caledonides at the time of final convergence and collision of the Laurentia, Baltica, and Avalonia continental terranes (c. mid-Silurian time). Due to the orogenic loading foreland basins developed on the continental foreland lithospheres. Their potential extent on SW Baltica is indicated schematically (dotted). Compiled from Soper and others (1992), Larson and others (1999), Katzung (2001), and Gee and Pease (2005). (B) Map of the major tectonic units of the Scandinavian Caledonides and their foreland. Also shown are the locations of figures 2 (box) and 9B (line).

TABLE 1

Major Caledonian structural units in SE Norway, W Sweden and adjacent areas compiled from Bockelie and Nystuen (1985), Gee and others (1985a, 1985b), and Zachrisson (1986)

Major unit	Major nappes	Subdivison	Local names	Major lithologies	Terranes, etc.
Uppermost Allochthon	**Helgeland Nappe Complex**				Laurentia-related (?)
Upper Allochthon	**Köli or Trondheim Nappe Complex**	Upper Köli		Ultramafic-mafic bodies, island-arc igneous rocks, related sedimentary sequences	Oceanic and island-arc terranes
		Middle Köli	Meråker Nappe		
		Lower Köli	Øyfjell Nappe Otta Nappe		intra-oceanic island-arc, Virisen terrane
	Seve Nappe Complex		Essandsjø Nappe	Medium to high-grade gneisses, ultramafics, amphibolites, metasediments	Baltica-related (?) continental terranes, Seve-Kalak super terrane Gula microcontinent
Middle Allochthon			Jotun Nappe Särv Nappe Valdres Nappe Kvitvola Nappe	Neoproterozoic to Ordovician, dominantly clastic cover sequences/ crystalline basement rocks	Baltica-related (?)
Lower Allochthon	**Jämtland Nappe Complex**		Synfjell Nappe Osen-Røa Nappe Olden Nappe	Neoproterozoic to Silurian, dominantly clastic cover sequences/ crystalline basement rocks	Baltica
Autochthon		Cover sequence		Cambro-Ordovician sandstones, shales, limestones	
		Crystalline basement		Granitoid to gabbroic plutons, minor metasediments	

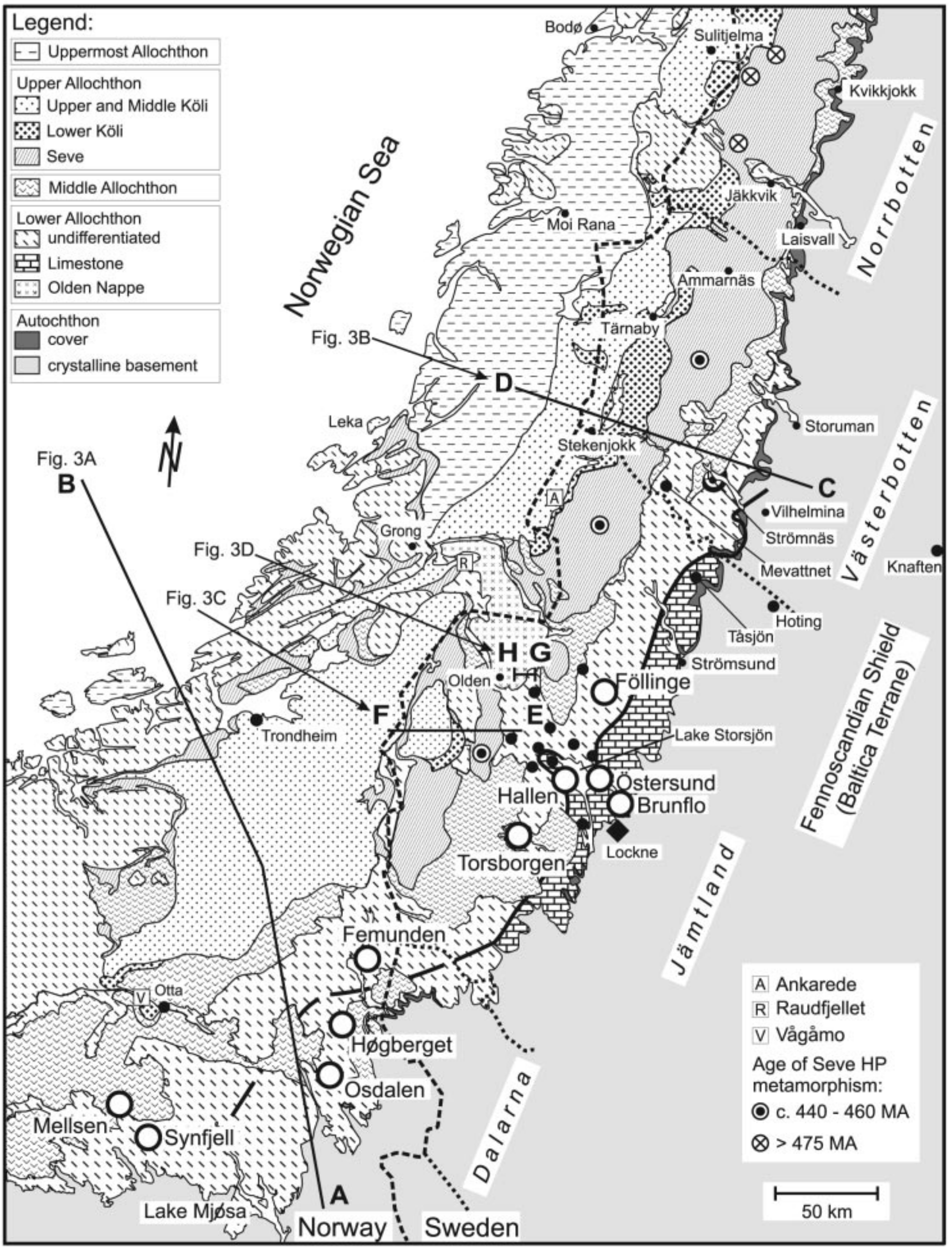


Fig. 2. Tectonic map of the central part of the Scandinavian Caledonides between the Oslo-Mjøsa and Bodø areas, simplified from Koistinen and others (2001). Details on locations and the carbonate facies belt in the early Ordovician sequences of the Lower Allochthon units are based on the reviews of Karis (1998) and Nystuen (1987). The thick line represents the boundary between carbonate sequences towards SE and shales and graywackes towards NW. See figure 5B for further details.

basement rocks of continental derivation, with abundant ultramafic and mafic rocks, and clastic and carbonate (meta-) sedimentary sequences. This rock association is strikingly similar to present passive continental margins and the continent-ocean

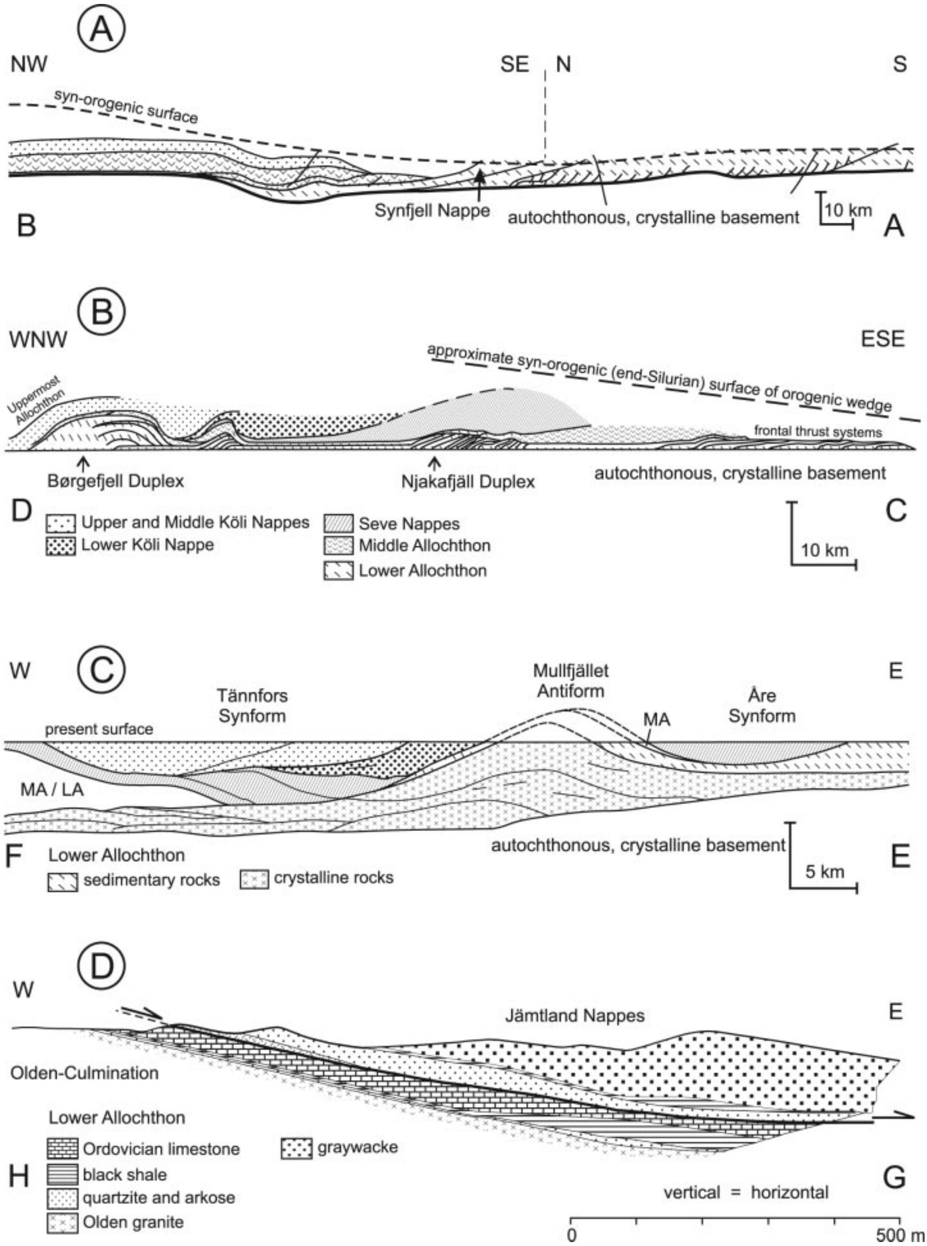


Fig. 3. (A-C) Regional sections across the central-southern Scandinavian Caledonides, based on Hossack (1985; A), Greiling and others (1998; B), and Hurich and others (1988; C), showing the thin-skinned character of the Caledonian fold-and-thrust belt and the succession of nappe units (see table 1 for details). (D) Section across the eastern margin of the Grong Culmination, redrawn from Strömberg (1998, fig. 24). Note Ordovician limestone in the cover sequence of the Olden unit and graywacke in the overlying thrust unit. For locations see figure 2.

transition (for example, Siedlecka and others, 2004). These rocks are found along most of the Scandinavian Caledonides and build up both the Seve and Kalak Nappes. Therefore, they were grouped into a Seve-Kalak superterrane (Andreasson and others, 1998). However, ages of HP metamorphism in different parts of this terrane range from more than 475 Ma in Norrbotten county (Mørk and others, 1988; Essex and others, 1997) to c. 440 to 460 Ma in Västerbotten and Jämtland counties (Williams and Claesson, 1987; Brueckner and van Roermund, 2004; see fig. 2). As a consequence, this superterrane may well be composed of distinct terranes, which were assembled only during the late Caledonian, Scandian tectonic episode. Based on these diachronous ages, it was also proposed that the Seve rocks were not always part of Baltica but formed a microcontinent of their own during early stages of Caledonian orogeny (for example, Roberts, 2003; Brueckner and van Roermund, 2004). It may be important to note that the graywacke sedimentation in the present Lower Allochthon started broadly at the end of the early HP episode and terminated at about the time of the later HP event in the Seve units. The overlying Köli Nappe Complex of the Upper Allochthon is mostly composed of oceanic and/or island arc terranes. Whilst there are indications that the Lower Köli terrane originated close to the Baltican margin, other Köli terranes are oceanic and may be more closely related to the terranes originally located offshore Avalonia and Laurentia (for example, Pickering and Smith, 1995; Harper, 1998, 2001). The Uppermost Allochthon represents a passive to active continental margin of Laurentian, North-American affinity (Grenne and others, 1999; Roberts and others, 2002; Yoshinobu and others, 2002).

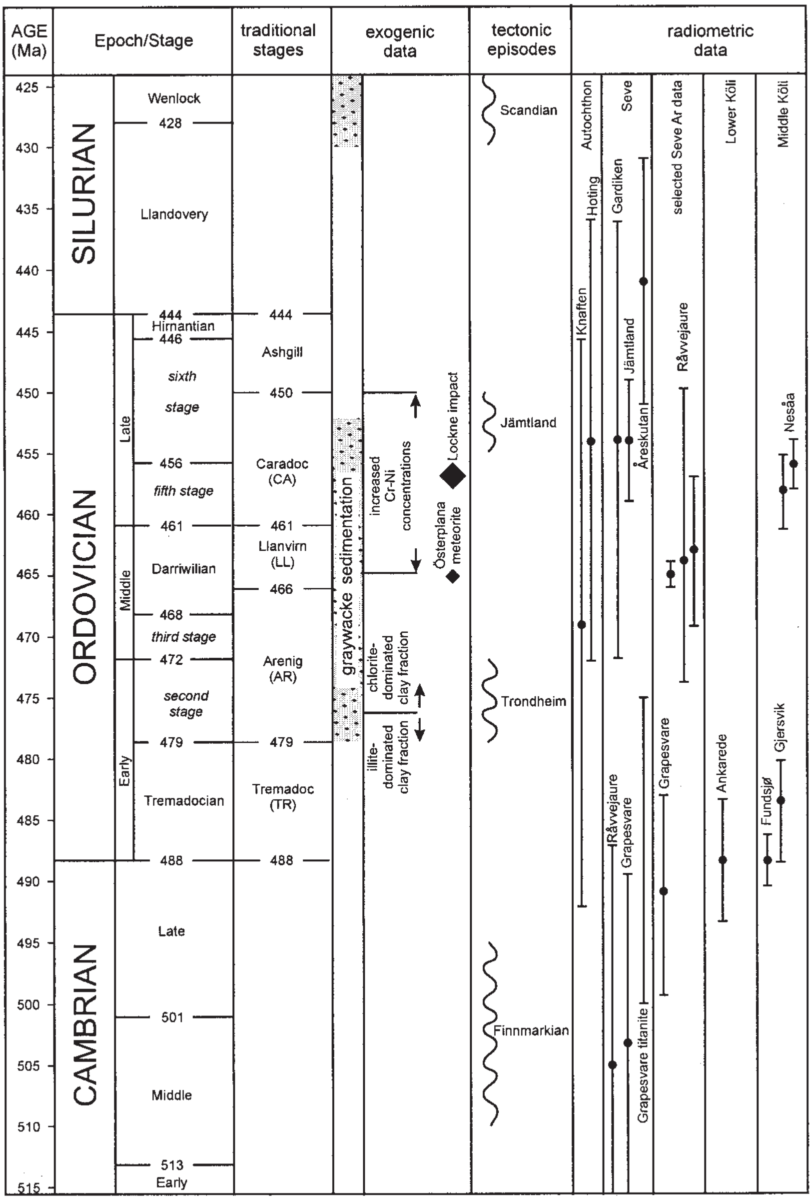
Tectonic Evolution

The present pile of allochthonous units (table 1) is the product of the Scandian phase of the Caledonian orogeny. The sedimentary record in the Lower Allochthon shows a relatively complete sequence of Neoproterozoic to Mid-Silurian age, indicating no major structural disturbances prior to the Late Silurian – Early Devonian, Scandian deformation. Tectonically, these sediments imply that late Neoproterozoic rifting is followed by a Cambrian passive margin evolution (Greiling and others, 1999) and subsequent synorogenic sedimentation. The Scandian deformation at this level is characterized by the formation of thrust systems under very low to low-grade metamorphic conditions. In most nappes of the Middle Allochthon the sedimentary succession ends with early Cambrian sandstones. In the Valdres and Kvitvola Nappes Lower Ordovician shallow marine shales and feldspathic sandstones are the highest beds preserved (Bockelie and Nystuen, 1985). Similar to the evolution in the Lower Allochthon sequence, a transition from early rifting to a subsequent Cambrian passive margin can be interpreted. Deformation in the Middle Allochthon is dominated by ductile shearing and polyphase deformation under low to amphibolite grade metamorphic conditions. In the overlying Seve Nappe Complex of the Upper Allochthon radiometric data indicate a polyphase metamorphic and structural evolution. Metamorphism occurred during at least three episodes: an early, Finnmarkian phase (Sturt and others, 1978) prior to c. 475 Ma (Essex and others, 1997), the Jämtland phase at c. 440 to 460 Ma ago (Brueckner and van Roermund, 2004), and the Scandian phase after c. 430 Ma (Gee, 1975).

In contrast, more or less complete Ordovician to Early Silurian successions in the Lower Köli Nappes of the Upper Allochthon (for example, Stephens and Gee, 1985) indicate relatively quiet conditions in between the Finnmarkian tectonic episode, which may have been terminated by eclogite exhumation and ophiolite obduction, and the Scandian phase. However, in the higher Köli units, a Trondheim event at c. 475 Ma has been observed (table 2). A somewhat later, Taconian event is restricted to the highest Köli units and the Uppermost Allochthon (Roberts, 2003). Fragmented obducted ophiolites have been found in two of the Köli nappes within the Trondheim Nappe Complex (Sturt and Roberts, 1991; Roberts and others, 2002; Nilsson and others, 2005; for example Raudfjellet, fig. 2), as well as at the base of the Lower Köli Otta Nappe farther to the south (Sturt and Ramsay, 1999; Vågåmo, fig. 2). The ophiolites overlie continental crystalline rocks, which, at this time, were either still

Table 2

Compilation of data relevant for the early Caledonian orogenic evolution at the (present) western margin of the Baltica continental terrane



The first three columns are based on Gradstein and others (2004); stratigraphic ages of graywacke sedimentation on Karis (1998), Dahlqvist (2004), and Dahlqvist and Calner (2004); clay and Cr-Ni data from Bjørlykke (1974); Österplana meteorite from Nyström and others (1988); Lockne impact from Lindström and others (1996); tectonic episodes from Roberts (2003). Ages determined biostratigraphically are "recalculated" according to the time-scale of Gradstein and others (2004). Radiometric U/Pb data from Knaften: Wasström (1993), Hoting: Hellström and Larson (2003), Råvvejaure, Grapesvare: Mørk and others (1988), Grapesvare Titanite: Essex and others (1997), Gardiken and Åreskutan: Williams and Claesson (1987), Jämtland: Brueckner and van Roermund (2004), Ankarede: Claesson and others (1983), Fundsjø: Bjerkgård and Bjørlykke (1994), Gjersvik: Kullerud and others (1988), Nesåa: Roberts and Tucker (1991), Meyer and others (2003); $^{40}Ar/^{39}Ar$ data from Råvvejaure: Dallmeyer and Stephens (1991), Grapesvare: Dallmeyer and Gee (1986).

contiguous with the Baltican continent or belonged to a nearby microcontinent (for example, Roberts, 2003; Brueckner and van Roermund, 2004). In the first case, the ophiolites may represent an orogenic load on top of the Baltican lithosphere which caused a flexure of the continental lithosphere and produced a foreland basin. Unfortunately, emplacement ages are not available from these ophiolites. In the Lower Köli unit of northern Jämtland, a sequence containing ultramafic rocks and detrital serpentinites, which may be remnants of obducted ophiolites, is overlain by the Ankarede volcanite formation (see fig. 2), which was dated as c. 488 Ma old (Claesson and others, 1983). This date gives an upper age limit for the emplacement of the ultramafic rocks (and possibly ophiolites) and is distinctly older than the onset of graywacke sedimentation in the Lower Allochthon.

The Scandian tectonic evolution overprinted many earlier Caledonian features, but during the last few decades evidence of early events became available. Early to mid-Ordovician graywackes indicate such early tectonic activity. In the county of Jämtland, comprehensive lithologic and biostratigraphic data for Late Cambrian and Early Ordovician times led to a classic model of facies belts along the Baltica palaeocontinental margin towards the Caledonian orogenic belt. Proceeding from the continent with carbonate sedimentation, there extends a shale belt, followed by graywackes in the deepest part of the basin (Jaanusson, 1973). Karis (1998, p. 165) interpreted the clastic sequence as "general infill of a perimontane trough". The features of such a basin can be examined on the basis of a new time-scale (Gradstein and others, 2004), which facilitates correlation of new biostratigraphic data (for example, Karis, 1998) with metamorphic data, and by taking into account quantitative data on the Scandian shortening of the Lower Allochthon, which provide the possibility to restore the geometry of the Ordovician foreland basin (Hossack and others, 1985; Morley, 1986; Gayer and Greiling, 1989). These data can be integrated with models of foreland basins (Garfunkel and Greiling, 1998). Therefore, it is attempted here to summarize these data and use them as a base for discussing the early Caledonian foreland basin. This makes it possible to examine questions such as whether the Lower Köli terrane qualifies as an orogenic load on top of the Baltica lithosphere or whether a larger, or later, orogenic load is required to explain the observed Ordovician foreland basin.

CAMBRO-ORDOVICIAN STRATIGRAPHY IN THE LOWER ALLOCHTHON

The sedimentary record of the Lower Allochthon is best preserved in the Jämtland region and the adjacent areas. There, the occurrence and distribution in space and time of Early Ordovician graywackes, deposited as turbidites, indicate the filling of a foreland basin (for example, Stephens, 1988) from source areas in the SW, W, and NW (see below). In order to characterize the geometry and evolution of this foreland basin, the distribution of the graywackes is summarized here, starting from SE Norway and proceeding towards NE, into Jämtland and Västerbotten. Figure 2 shows the relevant locations in the Lower Allochthon. The corresponding stratigraphic columns are compiled in figure 4, the local formation names in table 3.

SE Norway

SE Norway, and the Oslo-Mjøsa region in particular, contain some of the classic Cambro-Silurian stratigraphic sections of Scandinavia (for example, Bockelie and Nystuen, 1985; Owen and others, 1990). Ordovician sedimentary sequences in the Oslo area are about 200 to 300 m thick and dominated by limestones and shales. Graywackes are absent. However, there is a significant change in clay mineral composition and trace element contents (Englund, 1973; Bjørlykke, 1974). An increase in chlorite content occurred in Early Arenig times (Bjørlykke, 1974), which is about the same time as graywacke sedimentation started in western parts of the Jämtland region (Karis, 1998; see fig. 4, table 2). Cr and Ni contents increased after Arenig time, with a

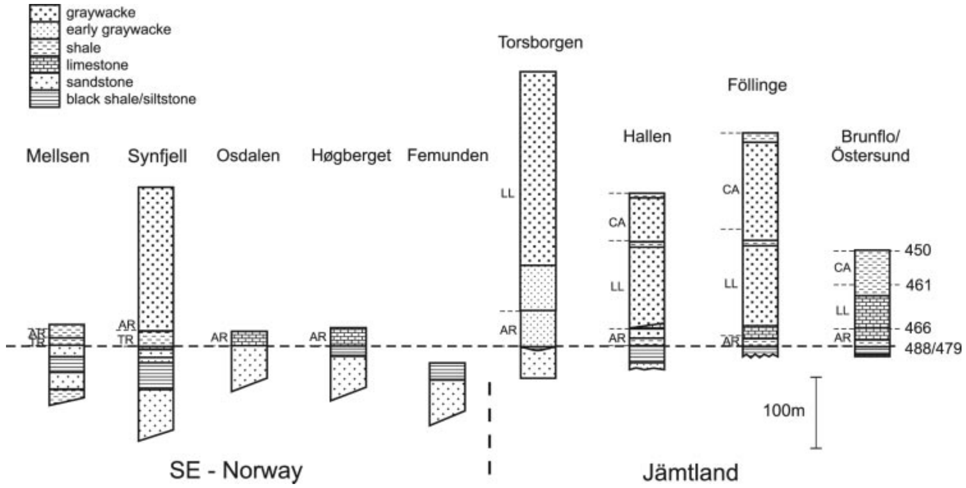


Fig. 4. Stratigraphic columns covering the lithologic succession in the lower tectonic units in SE Norway and W Sweden, from late Cambrian to Ordovician times, redrawn from Nickelsen and others (1985, Mellsen, Synfjell), Nystuen (1987, Osdalen to Femunden), and Karis (1998, Jämtland) with the Cambrian-Ordovician boundary as a horizontal datum. For locations see figure 2, for stages and time-scale table 2.

peak at the end of the Caradoc (Bjørlykke, 1974). To the northeast of the Oslo-Mjøsa region, two columns from the Lower Allochthon at Osdalen and Høgberget, respectively, show a stratigraphic gap beneath Arenig-age limestones, which rest on Cambrian beds (Nystuen, 1987). Stratigraphically higher parts of the sequence have not been recorded there. Only in the higher units of the Lower Allochthon, which overlie the successions of the Oslo area towards the north, have graywackes been observed (for example Nickelsen and others, 1985). There, the Synfjell section shows several hundred metres of graywackes of probable Arenig age (fig. 4). Since these graywackes are relatively strongly deformed, primary textures and contact relationships are not well preserved. Furthermore, there is no evidence available as to whether the primary contact towards the underlying Tremadoc age shales was conformable or an angular

Table 3

Stratigraphic nomenclature of Baltica palaeocontinent-related Ordovician graywackes and underlying Formations in SW Scandinavia

SE-Norway Synfjell Nappe	South and central Jämtland	Jämtland-Västerbotten	Norrbotten
Strondafjord Formation	Föllinge Formation (with Andersön Shale)	Norråker Formation	Mierkenis Group
Ørnberget Formation	Isön Limestone Formation		
	Tøyen Shale Formation		
	Latorp Limestone Formation		
	Kläppe Shale Formation	Fjällbränna Formation	

Compiled from Nickelsen and others (1985), Karis (1998), Gee and others (1974, 1978, 1990), and Kulling (1982). The Föllinge Formation is contiguous with graywackes of the Norråker Formation and the correlation between the two is well established. However, correlation with graywackes of the Strondafjord Formation and the Mierkenis Group, respectively, is less certain.

unconformity. Finally, the stratigraphic range of the graywackes can no longer be precisely determined, since no fossils have been found in them and overlying beds have been removed by Scandian nappe stacking processes. No graywackes have been reported from the early Ordovician section at Mellsen, representing the Kvitvola Nappe of the overlying Middle Allochthon.

Sweden

In Sweden, Ordovician graywackes in the Lower Allochthon are distributed along the Caledonian margin in the county of Jämtland, where they represent the Föllinge Formation. In northern Jämtland and farther north, in Västerbotten county, they form part of the time-equivalent Norråker Formation (for example, Gee and others, 1974, 1990). At the base of the graywackes the sections show a substantial stratigraphic break in eastern areas of the Jämtland region, generally between the Late Cambrian zone with *Peltura minor* and the Early Ordovician Latorp limestone in the Arenig series (Karis, 1998, p. 142). Only in the Hallen area (see figs. 2 and 3) a few meters of Tremadocian shales and limestones are preserved. The Latorp limestone is successively overlain by the Töyen shale, and the Isö and equivalent limestones towards the east (table 3), which represent a carbonate facies on the Baltica craton (for example, Jaanuson, 1973; Gee and others, 1974; Karis, 1998). Whilst this eastern facies is dominated by limestones throughout the Ordovician, western areas of Jämtland are characterized by facies belts with, successively, shales and graywackes of the Föllinge Formation. Jaanuson (1973) established a classic facies belt model with a carbonate domain in the east, a graywacke basin in the west and an intermediate belt with shales. All of these belts are assumed to be broadly parallel with the Caledonian mountain chain. However, there is evidence of carbonate deposits farther west, within the graywacke belt, in the Olden area (Geological Survey of Sweden, 1984; Strömberg, 1998), and farther north in Västerbotten county (Strömnäs, Zachrisson and Greiling, 1996).

Sedimentologic data make it possible to distinguish two different clastic facies types (Heuwinkel, ms, 1986; Lindström and Heuwinkel, 2006; Lindström, 2006, personal communication): a basin plain mud, and lithic graywackes with, inter alia, feldspar and detrital carbonate clasts, respectively. Sedimentary textures indicate a sediment transport from southwesterly directions in southern Jämtland and from nortwesterly directions in western Jämtland (Schenk, 1975; Heuwinkel, ms, 1986; Lindström and Heuwinkel, 2006). As summarized by Karis (1998), turbidite sedimentation started already in Early Arenig time (479 Ma) in western areas. The main phase of turbidite deposition covered the time from Llanvirn to Caradoc (466 – 455 Ma) with a subsequent transition to silt and shale, followed by a regression in late Ashgill times, linked to the Hirnantian glaciation (Karis, 1998; Dahlqvist, 2004). In the southwest of the Jämtland region, the Föllinge Formation rests with an erosional unconformity on older strata, mostly Lower Cambrian sandstones (Vemdal) or Middle to Upper Cambrian shales (Kläppe). Towards the east, however, it overlies successively younger beds, the Latorp limestone, the Töyen shale, and the Isö limestone, respectively. It is remarkable that there is no erosional unconformity in the east but a transition and interfingering relationship. In the westernmost areas, the Lower Llanvirn Isö limestone is characterized by a reduced thickness, although representing the same time span as relatively thicker sequences in the east.

Whilst the roof thrust of the Lower Allochthon in central Jämtland is cutting across Silurian beds, it is cutting downwards along strike, towards south and north, approximately normal to the Scandian thrust transport direction. As a consequence, the sections in SE Norway shown in figure 4 are delimited by the roof thrust of the Lower Allochthon. Similarly, in southern Västerbotten, the roof thrust is cutting across the graywacke sequence, or even at a level stratigraphically beneath them. However, farther north, in the Laisvall-Jäkkvik area of Norrbotten

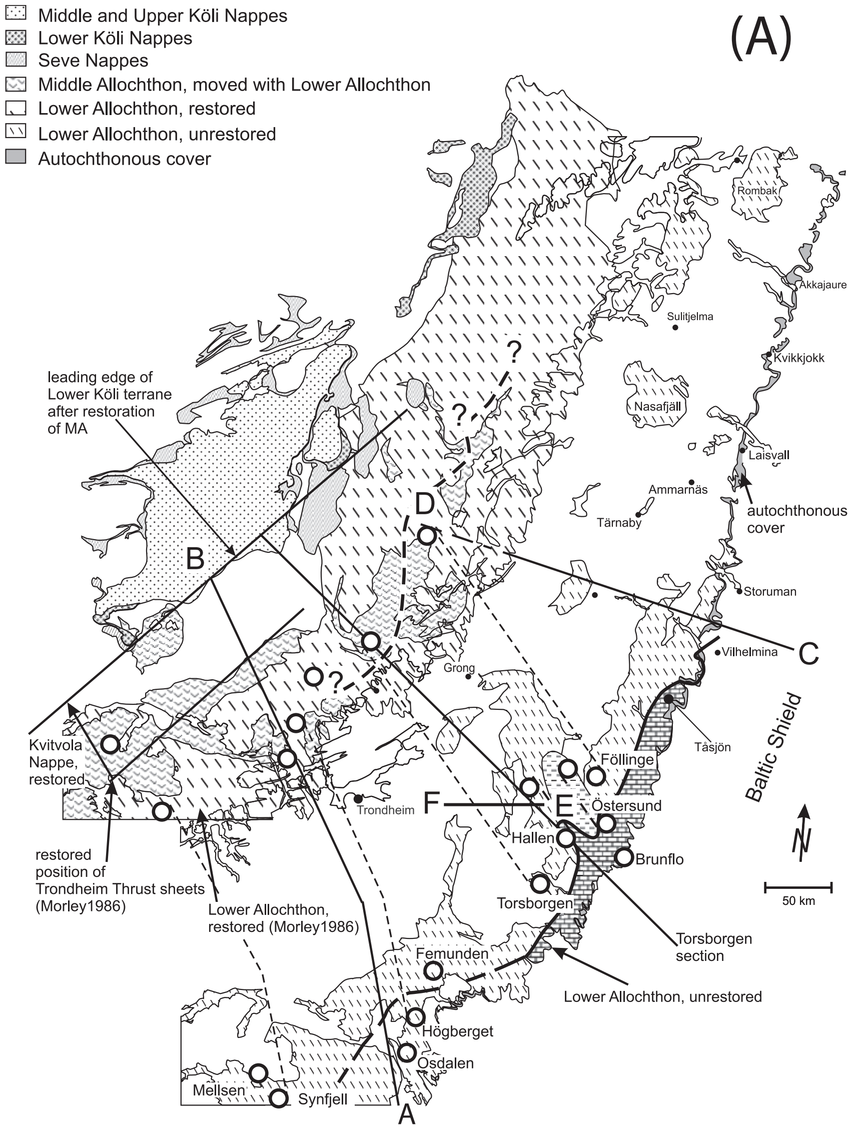


Fig. 5. (A) Tectonic map as of figure 2 with restoration of the allochthonous units, based on balanced sections by Morley (1986) and further information (Gee and others, 1978; Hossack, 1985; Gayer and Greiling, 1989; Strömberg, 1998). Tie lines (thin dashed lines) connect unrestored and restored positions, respectively, of stratigraphic columns shown on figure 4. Carbonate rocks at the Caledonian front are shown unrestored, as in figure 2. Section line A-B is the same as on figure 2. The Torsborgen section is added (see figs. 6 and 7), as are leading branch lines of higher nappes at the base of the Upper Allochthon. The thick dashed line delimits the area of an erosional unconformity in the west from that of a broadly conformable sequence (albeit with a hiatus in Tremadocian time) in the east.

county, Ordovician graywackes are again preserved beneath the roof thrust (for example, Albrecht, ms, 2000; see fig. 5).

RESTORING THE EARLY ORDOVICIAN PALAEOGEOGRAPHY

In order to determine the exact geometry of the Early Ordovician foreland basin, the effects of subsequent, Scandian deformation have to be removed by restoration of

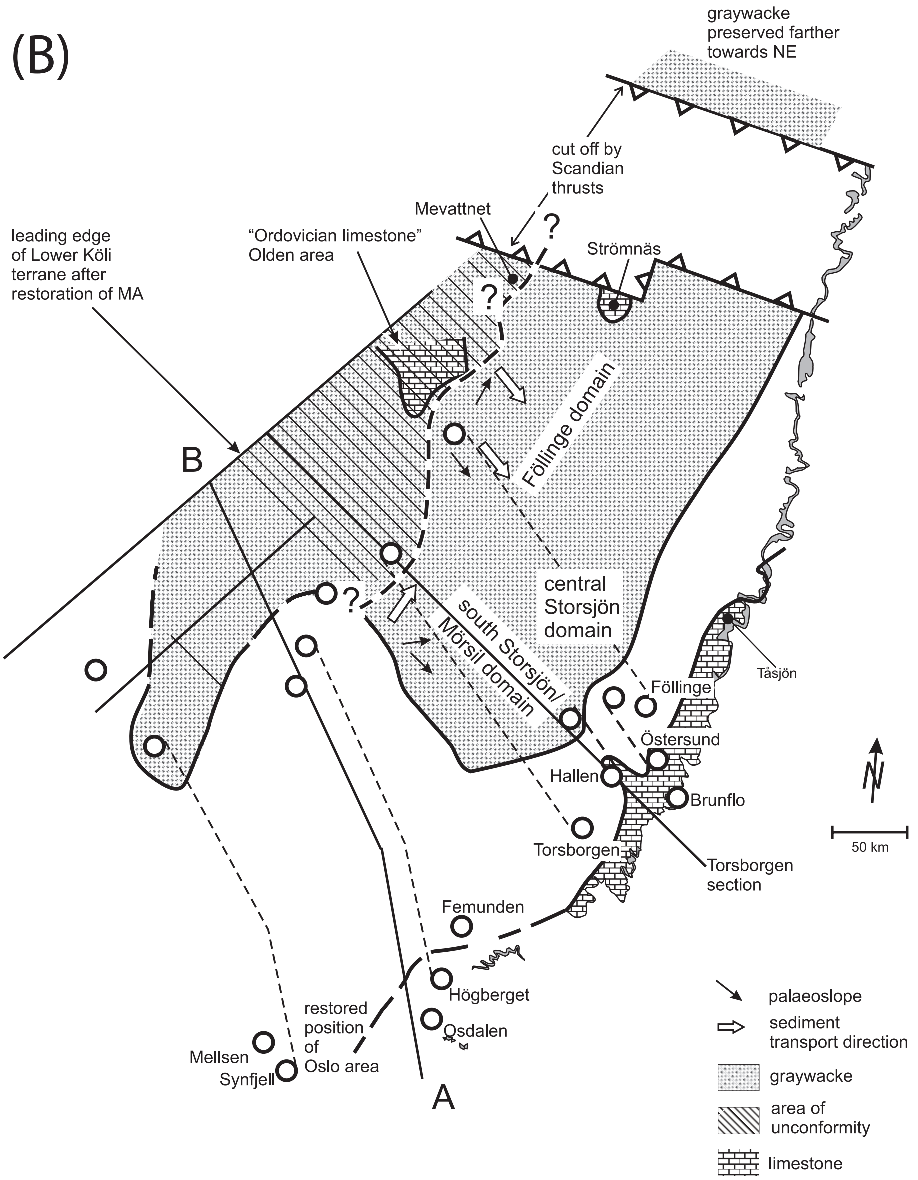


Fig. 5 (continued). (B) The same map area with details relevant for the restoration and early Ordovician palaeogeography. The thick dashed line is also taken from A, the distribution of graywackes, after restoration, is shown by the dotted pattern. The graywacke distribution shows the extent of the early Ordovician foreland basin, which can be traced for at least 500 km in NNE-SSW-direction with a width of 200 to 300 km. See text for further details.

the nappe units into their pre-deformational positions. From the areas in the south, in SE Norway, quantitative data on shortening and nappe transport distance are available (Hossack and others, 1985; Morley, 1986). There are also some data from the very north of Jämtland (Gee and others, 1978) and the adjacent areas farther to the north, in Västerbotten county (for example, Gayer and Greiling, 1989; Zachrisson, 1996, 1997). The restored section of Morley (1986), shown as section A-B in figure 2, is drawn parallel to the recorded transport direction of the Lower Allochthon nappe units in this area. Structural data show that the nappe transport direction is not constant along the strike of the orogen (for example, Soper and others, 1992). Therefore, a restoration at the northern margin of the Jämtland region used a different direction, which is parallel with the nappe transport direction recorded there (Gayer and Greiling, 1989). The restored section of Gayer and Greiling (1989) is marked as C-D in figure 2. Both these sections rely on the restoration of horses in thrust systems, which are well developed in the Neoproterozoic to Middle Cambrian successions, and are dominated by competent quartz-rich arkoses, quartzites, and siltstones. Relatively thin, incompetent levels such as the Late Neoproterozoic tillite-carbonate succession and the Middle Cambrian to earliest Ordovician alum shales provide detachment horizons for floor and roof thrusts, respectively. Both sections, A-B and C-D, document a shortening in the order of c. 50 percent (Morley, 1986; Gayer and Greiling, 1989). The Jämtland Nappes in between these sections are built up mostly of relatively incompetent limestones, shales, and generally fine-grained graywackes of Ordovician and Silurian age. There, deformation is dominated by more ductile features such as folds, and shortening led to intense cleavage formation, as documented extensively by Karis (1998). Wherever the stratigraphically underlying, competent levels are exposed, thrust systems can be observed (Walser, 1980; Strömberg, 1998), for example around the Olden Culmination (see Olden Nappe in figs. 2 and 3D). Since there is no obvious break between the thrust-dominated domains and the fold-cleavage-dominated domains, it is assumed here that the amount of shortening in the Jämtland Nappes is similar to the amount of shortening as documented along the balanced sections A-B and C-D (fig. 2). Accordingly, the inferred original locations in the Jämtland Nappes, shown in figure 2, were restored assuming 50 percent shortening.

Based on this information, it is attempted here to restore the basin geometry of the Föllinge turbidite basin and to calculate the related flexure of the Baltican lithosphere. Figure 5 shows a tectonic map, covering the area of figure 2, and applying the information from the restored sections. Accordingly, the restoration of the stratigraphic column locations is shown schematically using 'tie lines' between the present and the restored positions. From these data, a representative section is compiled here (fig. 6), named the Torsborgen section after the westernmost column from the Jämtland region (fig. 5). It forms the base for a tectonic interpretation shown in figure 7 and discussed below.

Reliability, Local Complexities, and Results

In the south of the area covered by figure 2, the restoration relies on the balanced sections by Morley (1986), which are based on detailed maps from a relatively well exposed region (section A-B on figs. 2, 3, and 5). Subsequent work has shown some potential, structural overprint by late Scandian extension (for example, Norton and others, 1987; Braathen and others, 2002; Eide, 2002). However, most of these extensional faults are located to the W/NW of the area and are, therefore, not very important for the present problem. More important is the fact that Morley (1986) grouped the Upper Allochthon (Trondheim Nappe Complex) with the Middle Allochthon. In order to establish the pre-shortening position of the Synfjell section, the Kvitvola Nappe of the Middle Allochthon is restored here so that its area does no longer overlie the Lower Allochthon (fig. 5A). Shortening within the Kvitvola Nappe is not restored. As a consequence, the amount of restoration is somewhat low, and the restored width of the thrust units is probably too conservative. In order to make the map, figure 5A, easily readable, this restoration is only shown by the trailing branch line of the Kvitvola Nappe and the Middle Allochthon still appears as if overlying the Lower Allochthon. Similarly, the internal geometry of the Lower Allochthon is left unchanged.

A particular problem had been the Olden Nappe farther north, which was interpreted earlier both as the most internal or the most external unit of the Jämtland

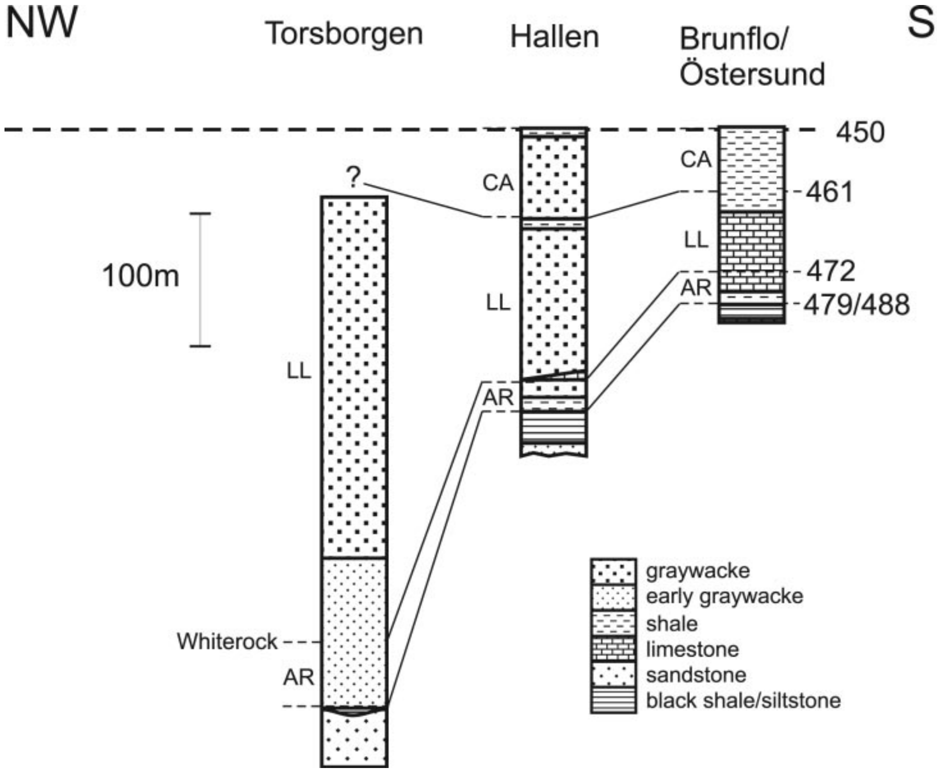


Fig. 6. Stratigraphic columns from the preserved part of the foreland basin in late Cambrian and Ordovician times along the Torsborgen section (see fig. 5 for location). Redrawn from figure 4, using the 450 Ma time line as a horizontal datum. For stages and time-scale see table 2.

Nappes. As is clear from the section, figure 3D, the Olden unit is overlain by Ordovician limestones. The restoration (along section C-D) shows that these limestones are not contiguous with the Baltica carbonate domain, but represent an isolated realm. Seismic sections from the Östersund-Trondheim area clearly show a basal sole thrust (Hurich and others, 1988; Palm and others, 1991) so that an autochthonous position of the Olden unit can be ruled out. To the south of section C-D (fig. 2), extensive drilling has documented a basal sole thrust and a transport of the Lower Allochthon towards the foreland with a minimum distance of 40 km (Gee and others, 1978). In the nearby Västerbotten region, balanced section restoration showed shortening of about 50 percent (Gayer and Greiling, 1989). Subsequent mapping (for example, Zachrisson, 1996, 1997) showed further shortening (see also Greiling and others, 1998; Grimmer and Greiling, 2004). These results imply that also the restoration of section C – D is on the conservative side.

A combination of these section restorations and sedimentologic data from the central Jämtland (Storsjön-Föllinge) region (Heuwinkel, ms, 1986; Karis, 1998; Lindström and Heuwinkel, 2006) provides important new information on the basin geometry. Accordingly, there are two domains of proximal graywackes, which are separated by an area of distal graywackes. Following Karis (1998) and Lindström and Heuwinkel (2006), the distal graywacke belt is called here central Storsjön domain with the south Storsjön/Mörsil domain and the Föllinge domain of proximal graywackes to the southwest and north, respectively (see fig. 5B). Sedimentologic data show a palaeoslope at the SW-margin of the Mörsil domain towards NE directions, normal to

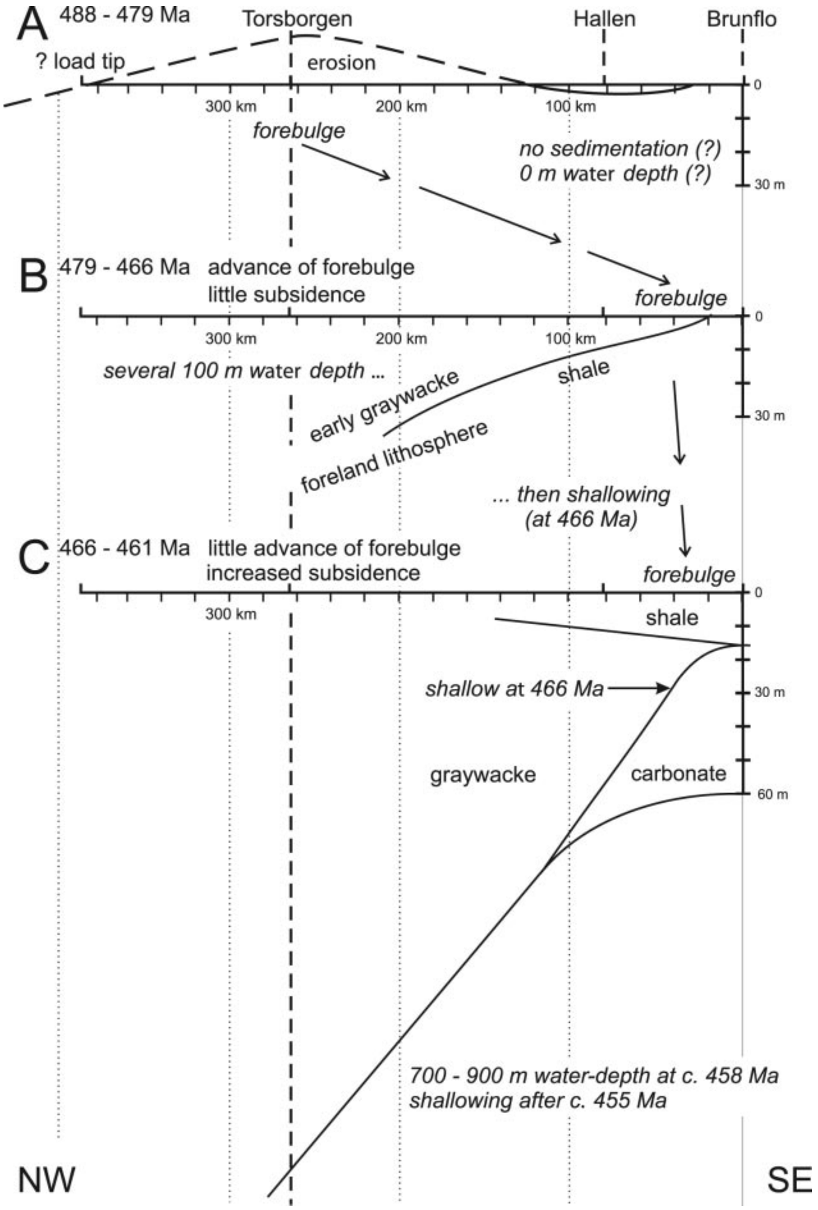


Fig. 7. Tectonic interpretation of the sedimentary record as shown in figure 6 along the Torsborgen section (see fig. 5 for location; times according to Gradstein and others, 2004). The thickness of sediments for the respective time intervals is drawn from the horizontal axis (section line) downwards. Topographic or seafloor relief is not shown (see text). (A) Early Ordovician situation with forebulge at Torsborgen (erosion). (B) Subsequent stage with (little) subsidence and early graywacke deposition. (C). Final stage of major subsidence. Water-depth is considerably higher than the column of sedimentary rocks (Ormö and others, 2002, see text).

the SW basin margin as deduced after the restoration. Data from the Föllinge domain show a sediment transport from the NW (fig. 5B). The Mörsil domain (Olden trough of Heuwinkel, ms) is characterized by quartz wackes with mostly quartz and quartzite fragments. In contrast, the Föllinge domain is dominated by lithic graywackes with abundant carbonate clasts (Heuwinkel, ms, 1986). According to the restoration, the source area to the NW of the Föllinge domain is covered by the Ordovician limestones of the Olden Nappe. Together with observations by Strömberg (1998) that the limestones are, in places, directly overlain by graywackes, this situation gives independent support for the restoration of the Olden Nappe to an area farther west/northwest than the overlying Lower Allochthon nappe units.

As a consequence, two traditional views have to be modified. The simple basin model of Jaanuson (1973) of a SE-NW-succession of limestone-mudstone-graywacke facies belts is no longer tenable. Instead, further limestone domains to the west of, and isolated from, the main Baltica limestone domain are present. Whereas the Olden Nappe may contain the largest of these limestone areas, there is a smaller one in southern Västerbotten, where further Lower Ordovician limestones are exposed, which are surrounded by graywacke sequences without limestone members (figs. 2 and 5, Zachrisson and Greiling, 1996). The second implication is that the Olden Nappe can now be regarded as palaeogeographically situated to the NW of the present Föllinge domain. Earlier restorations, based on the facies belt model of Jaanuson (1973) suggested that the units of the Jämtland Nappes which are situated structurally above the Olden Nappe, were derived from W of the Olden Nappe and were transported over the Olden Nappe, prior to thrusting of the Olden Nappe. However, with the present information, a more simple thrust sequence of the Jämtland Nappes can be assumed with a normal sequence of thrusts propagating from NW towards SE.

FORELAND BASIN GEOMETRY AND EARLY TO MID-ORDOVICIAN EVOLUTION

Figure 5 shows the facies distribution between the rocks of the carbonate domain in the east and the clastic sequences in the west in the present, unrestored situation (figs. 2 and 5). The margin of the carbonate domain continues towards SW, and is running between the Synfjell location in the north and the Oslo region in the south. Further details of the limits and distribution of the different facies are shown on the maps, figures 5A and 5B, and in the sections on figures 6 and 7. There, the positions of the stratigraphic columns are restored to a pre-Scandian situation, before the incorporation of the Lower and Middle Allochthons into the Caledonian orogenic wedge. Based on this restoration, the basin geometry and the areal extent of the erosional unconformity beneath the graywackes and the distribution of the graywackes themselves can be shown in their pre-deformational situation (fig. 5B). The western margin of the Baltoscandian carbonate domain represents the external margin of the foreland basin. It is remarkable that the margin of the carbonate facies belt is slightly oblique to the present erosional margin of the Caledonides.

The general axial trend of the foreland basin can be assumed to be broadly NE-SW, since additional Ordovician graywacke occurrences can be found along the present external part of the Caledonides in Sweden and into northern Norway. Therefore, the Torsborgen section is drawn NW-SE, broadly normal to the general orientation of the foreland basin. The basin geometry is complicated by limestone areas in the Olden area and at Stromnäs, and by NW-SE trending domains or troughs of different graywacke facies. Proximal facies are found in the south Storsjön/Mörsil domain and the Föllinge domain, which are subdivided by the central Storjön domain, which is characterized by distal facies (Heuwinkel, ms, 1986; Karis, 1998; see fig. 5B). Together with the graywacke occurrences in the Synfjell Nappe, the graywacke areas in SW Jämtland and SE Norway constitute the southern margin or lateral end of the Finnmarkian foreland basin in this part of the Scandinavian Caledonides (fig. 5B).

From the restored foreland-basin geometry, some characteristics of the lithospheric flexure can be derived (figs. 6 and 7). Figure 7 shows the interpreted evolution in three steps. The earlier Tremadoc stage of the evolution is not documented, since deposits of this age are only locally preserved. The erosional unconformity at Torsborgen (Strömberg, 1998) may point to a major phase of erosion. Tectonically, the uplift that made erosion possible is considered to have occurred as a forebulge at the external margin of the foreland basin. Subsequently, graywacke sedimentation, starting at c. 479 Ma, documents subsidence. Subsidence ended at c. 466 Ma, when a shallowing can be observed across the section area. During the same time, the forebulge can be seen to migrate towards the foreland. Renewed subsidence led to further deepening of the foreland basin but little advance of the forebulge. Since, until c. 461 Ma, sedimentation was still occurring at Torsborgen, the tip of the load cannot yet have reached this area at the time. Therefore, the distance from the forebulge to the load tip must have exceeded 260 km (fig. 7C). This value gives a minimum figure for the width of the foreland basin and, by inference, on the strength of the lithosphere. Going back in time (figs. 7B and 7A), the forebulge was even farther NW in the foreland basin at 479 Ma. As a consequence, the load tip was still farther to the NW.

Whilst the sediment fill of the basin is relatively small, not exceeding 500 m (fig. 7), the marine character of the sediments indicates that the basin was also partly filled by water. A general increase of water depth can be assumed from the carbonate domain towards the basin. However, absolute data are difficult to gauge. During the time interval 479 to 466 Ma, several hundred m of water-depth were reached in between shallow intervals (Karis, 1998). A similar evolution occurred between c. 466 and 455 Ma, with considerable water-depth at the time of the Lockne impact (see fig. 2 for location) at the western margin of the carbonate domain, which occurred at c. 458 Ma ago (Lindström and others, 1996). Modelling of the impact conditions showed water depths in the range of 700 to 900 m (Ormö and others, 2002).

NUMERICAL MODELS

Earlier calculations on the relationships of the orogenic load and the related foreland basins, which are created by the downflexing of the lithosphere, established constraints on both the character of the load and the strength of the foreland lithosphere (for example, Beaumont, 1981; Watts, 1992; Garfunkel and Greiling, 2002). Calculations and diagrams presented by Garfunkel and Greiling (1996, 2002) relate the width and depth of a foreland basin to the strength of the lithosphere and the taper angle of the orogenic load. Figure 8 shows these parameters, the effects of a change in load taper, and the effects of an advance of the load towards the foreland. With regard to the problems discussed here, both a migration of the forebulge and the basin margin, and a deepening of the basin can be observed (fig. 7). Earlier studies also provided constraints on the strength of the lithosphere (see below). Therefore, the available data can be used to provide new information on the foreland basin geometry and the orogenic load that caused the flexural foreland basin to develop.

Strength of the Lithosphere

The geometry of the Scandian foreland basin and the reconstruction of the orogenic load are relatively well constrained. In particular, the maximum thickness and extent of the orogenic load have been studied by means of fission track analysis, by the colour index of conodonts and by illite crystallinity data (Middleton and others, 1996; Warr and others, 1996; Samuelsson and Middleton, 1998; Larson and others, 1999). It is remarkable that the foreland basin succession is estimated to be relatively thin and, consequently, the basin itself was relatively shallow. Model calculations on the flexure of the lithosphere and the shape of the orogenic load in Silurian times have shown that the foreland lithosphere was mechanically strong and that the orogenic load was relatively thin. Both these factors contributed to the fact that there is no autochthonous foreland basin sedimentary fill exposed today, since the limited space was occupied by the advancing orogenic load (fig. 9C, Garfunkel and Greiling, 1998). Despite subsequent, post-orogenic exhumation and erosion, much of this foreland-

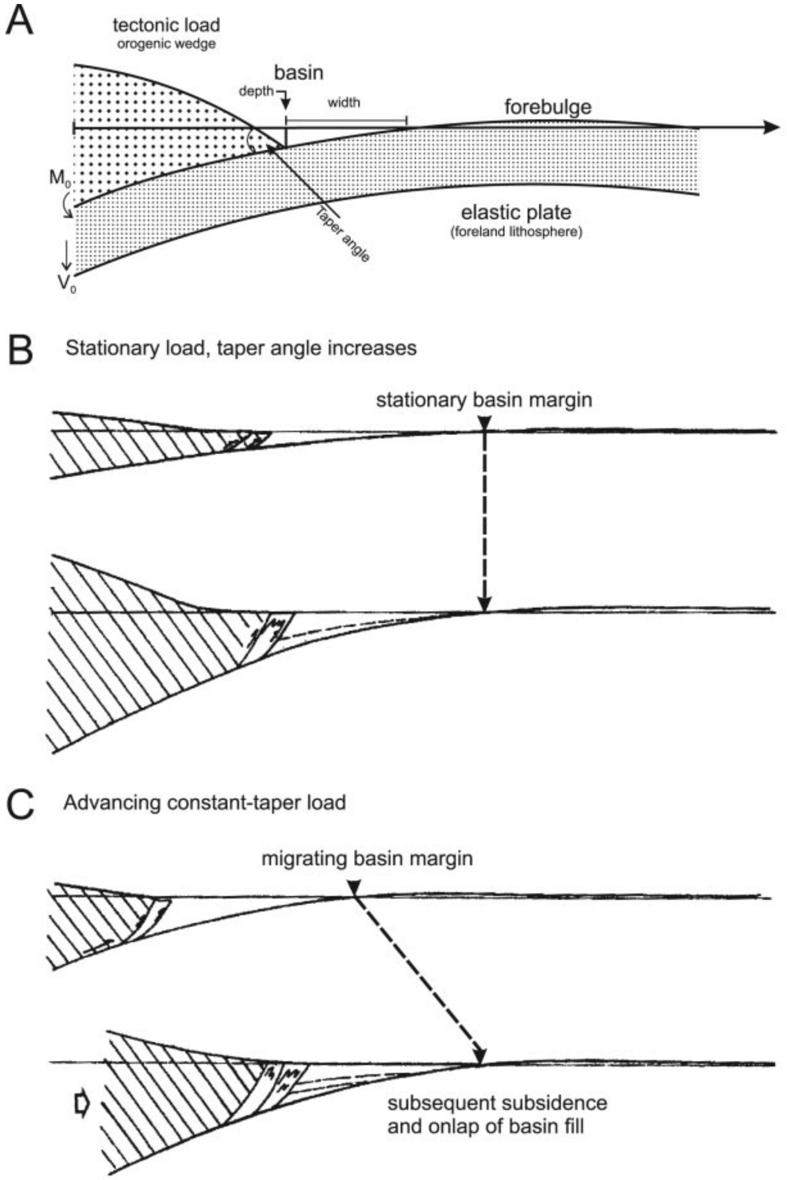


Fig. 8. (A) Diagram showing interrelationships of foreland lithosphere and orogenic load, as a base for modeling lithospheric flexure (modified from Garfunkel and Greiling, 2002). Note forebulge which defines the external margin of the foreland basin. The part of the basin overlying the foreland lithosphere corresponds to the foredeep, the part overlying the orogenic load is a depositional wedge top as defined by Ford (2004). (B) Effects of an increasing, stationary load. (C) Effects of a load advancing towards the foreland.

orogenic load interaction can be reconstructed with some confidence for the late Caledonian foreland basin of the Scandian episode in Silurian times. Important here is that the strength of the lithosphere in Silurian times has been determined by the earlier work. Data on subsidence at the Baltoscandian passive margin (Greiling and others, 1999) show a thermal subsidence decreasing exponentially in Early Cambrian times. Therefore, it is assumed here that the lithosphere acquired its strength in early

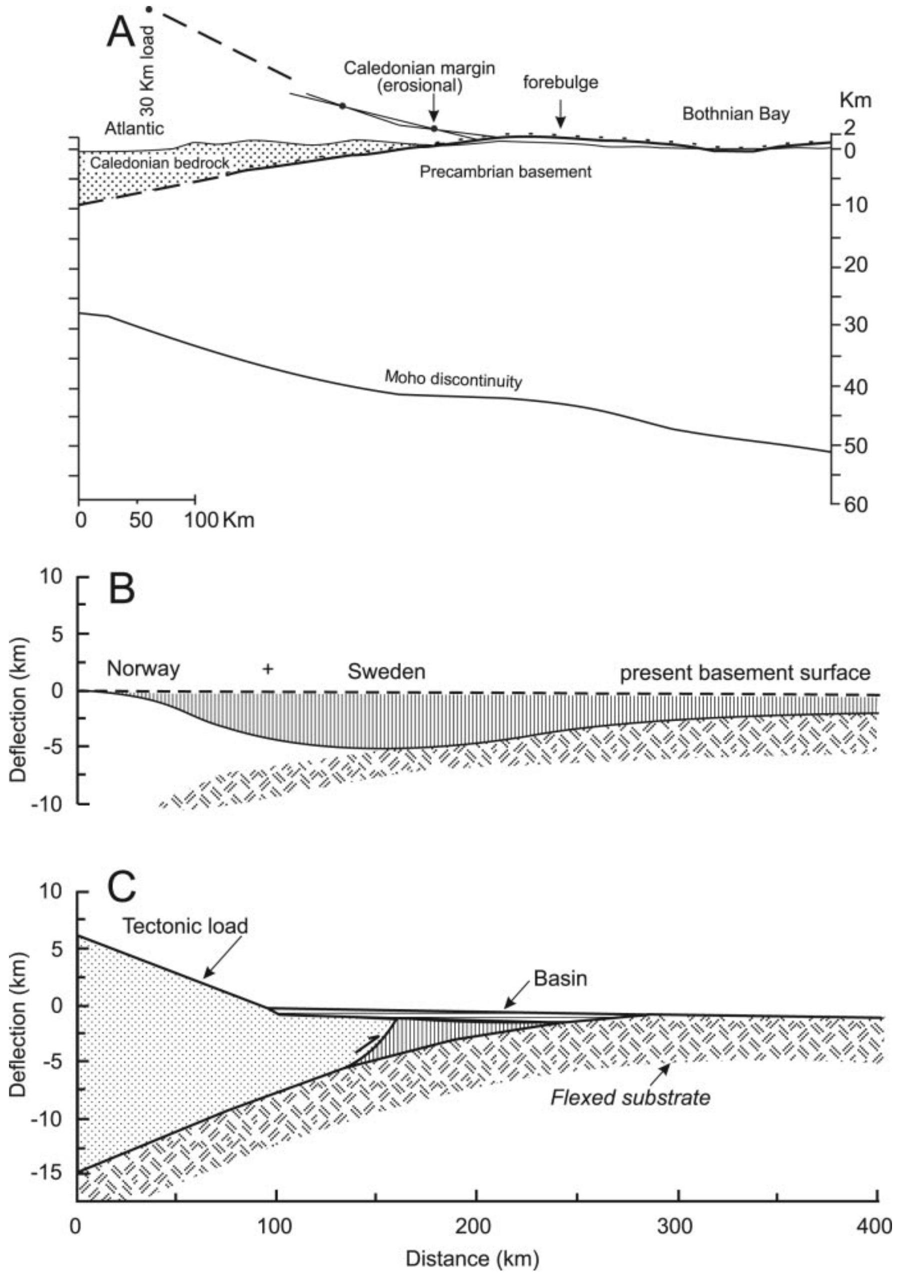


Fig. 9. (A) Lithospheric scale section along the section line C-D on figures 2 and 5, and extending farther towards E, across the Bothnian Bay. Note (half) wavelength of forebulge from the Caledonian margin to the Bothnian Bay. Modified from Garfunkel and Greiling (1998). (B) Section from the Caledonian margin towards NE, across the foreland basin, as restored from fission-track data. Modified from Larson and others (1999); for location see figure 1. (C) Modeling results based on section A. Note thin taper of frontal part of orogenic load, relatively small flexure, and small sediment-filled foreland basin.

Cambrian times, prior to the Finnmarkian tectonic episode. Consequently, a strong lithosphere, with a flexural parameter of $\alpha \approx 100$ km or higher is used here for the model calculations.

Basin and Load Geometry

Figure 7 shows, schematically, the distribution of the Early Ordovician graywackes, which represent the sedimentary fill of the earlier foreland basin on top of the Baltican lithosphere. Whereas the frontal margin of this foreland basin is well constrained, its continuation towards the hinterland cannot be restored with the same precision because the subsequent orogenic evolution led to both tectonic and exogenic erosion and also because it is difficult to infer precisely water depth. As has been argued above, the tip of the orogenic load, which caused the flexure of the lithosphere, and which should represent the deepest part of the basin, must have been situated relatively far towards the western, interior part of the foreland basin. Model calculations by Garfunkel and Greiling (2002) on the relationships between lithospheric strength, basin width and depth, and taper angle of the load makes it possible to quantify these parameters. Assuming a flexural parameter of $\alpha = 100$ km, the basin width should be in the order of 140 km. For $\alpha = 125$ km, basin width increases to 200 km. This value is still too small to explain the basin width in excess of 260 km as discussed above (see figs. 7B and 10A). The observed basin depth implies a relatively thin load with a small taper angle. The diagrams of Garfunkel and Greiling (2002) suggest that a basin depth of 2 km requires a taper angle of less than 5° for $\alpha = 100$ (fig. 10B). Such a value does not compare well with the thickness of 500 m or less of basin fill sediments (Karis, 1998). However, adding a water column of 700 m to 900 m to the load, as discussed above, and considering the fact that water-filled basins are shallower, may support such a result. Both a 2 km basin depth and a 5° taper angle are then somewhat low but still realistic.

DISCUSSION AND CONCLUSIONS

Along the Caledonian margin, Early Ordovician graywackes-turbidites can be followed from Jämtland and northwards and document a wide regional extent of a foreland basin at this time. In contrast to underlying passive margin sediments, which were shed from the Baltican continent towards the (present) west and northwest (for example, Gee, 1975; Greiling and others, 1999), the Early Ordovician basin was filled from the NW. Accordingly, a reversal of slope is indicated, and water depths increased compared with the passive margin situation during deposition of sediments on the Baltican margin. Erosion at the internal part and non-deposition at the external part of the basin in Tremadoc times (488 – 479 Ma) were followed by an onlap of graywacke sediments during Arenig times (479 – 466 Ma). After a quiet period, the Llanvirn time interval (466 – 461 Ma) is characterized by further graywacke sedimentation with little change of the location of the basin margin. Such an evolution is typical for basins situated along the margins of orogens, which develop upon loading of the foreland lithosphere by the evolving orogen, whose margin migrates towards the foreland. Such foreland basins have been shown to be the expression of lithospheric flexure.

In order to constrain the geometry of the lithospheric flexure and its causative load, restoration of the foreland basin is necessary, since this particular, Early Ordovician foreland basin was subsequently incorporated into the Scandian fold-and-thrust belt. Following published restorations (for example, Morley, 1986), the extent of the Early Ordovician foreland basin was restored (figs. 5 and 7). This restoration shows an irregular shape of the lateral, southern/southeastern margin of the basin (fig. 5B). The restoration also provides, for the first time, some quantitative constraints on the foreland basin. These data are summarized in figure 7 and show a wide foreland basin with a well defined external margin, which moved towards the foreland during Tremadoc and Arenig times (488 – 466 Ma) and, after a shallow interval, deepened in Llanvirn time (466 – 461 Ma). In terms of a foreland basin, the tip of the lithospheric load corresponds to the deepest part. From there towards the S and SE, the basin is shallowing and progressively filled by graywacke-turbidites, which successively overstep

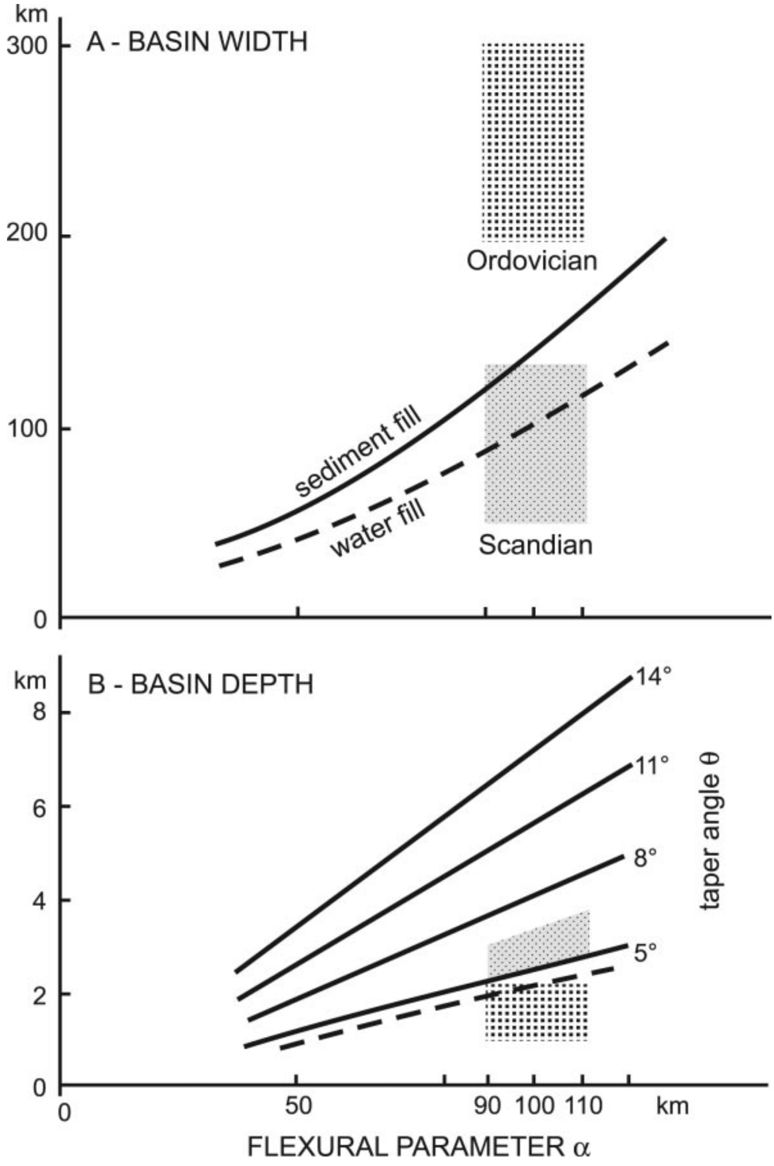


Fig. 10. Relationship between flexural parameter of the lithosphere, taper angle of a load, and basin width and depth, as modeled following Garfunkel and Greiling (2002). (A) Width of a basin caused by a 150 km wide (tectonic) load and a sediment fill (bold line) or a water fill (dashed bold line), respectively. The late Caledonian, Scandian situation with a flexural parameter of 100 km and modelled basin widths of 50-130 km is marked by thin dots. The early Ordovician basin width as restored here (fig. 5) is shown by thick dots. (B) Depth of a basin as related to the flexural parameter and the load taper angle. Scandian and early Ordovician data are shown as in A.

the limestones of the (early) Ordovician carbonate domain of the Fennoscandian Shield. Such a forward movement of the foreland basin can be shown to have been caused by the forward advance of the orogenic load (fig. 8, Garfunkel and Greiling, 2002). Restoration shows the distance between load tip and forebulge to be in excess of 260 km. Accordingly, basin widths (from load tip to forebulge) are in the order of 200 to 260 km or more with basin depths of only a few hundred meters. These data require a high strength of the foreland lithosphere of $\alpha > 100$ km and a small orogenic load with a low taper angle ($< 5°$). Whilst the load taper angle is only slightly lower than expected, the lithospheric strength required by the wide foreland basin is too high.

One factor that can increase basin width is high sea-level. The observed shallowing at c. 466 Ma corresponds to a short period of low sea level (Gradstein and others, 2004) so that it may not be tectonically significant. However, during the time interval 460 to 456 Ma, which includes the deep water period at Lockne impact time a low sea level was prevalent. Therefore, this period of relatively high water depth may be significant. Another, perhaps more important factor is that the total basin width represents a history. As the load advances, the basin migrates, while the sediments in its internal (hinterland) side may be preserved. Thus the total width determined by the basin-fill may be larger than the depression at any single moment in time. However, there is no indication of early Ordovician deformation in the Lower Allochthon of the area. Only in northern Norway an Early Ordovician cleavage-forming event has been documented at an equivalent tectonic level (Sundvoll and Roberts, 2003). Therefore, an additional load has to be considered.

The obduction of the Vågåmo and Raudfjellet ophiolites in the Trondheim Nappe Complex may also relate to this event. The ophiolite obduction and lithospheric loading was followed by erosion and sedimentation (Sturt and Ramsay, 1999; Nilsson and others, 2005). If the character of the post-ophiolite succession as a terrane-linking sequence is accepted (Sturt and Ramsay, 1999), then the ophiolite represents the tip of a lithospheric load on top of the Baltican lithosphere, which stretches farther towards NW and N. If loading by ophiolites of the Köli nappe down-flexed Baltica, then when they were emplaced all these terranes must have been amalgamated with Baltica, for otherwise there would not be any mechanical/flexural coupling between the substratum of the ophiolites and the Baltica foreland. However, as it is now, the Köli nappe ophiolites are separated from the Baltica foreland units by the Seve Nappes, which were metamorphosed at c. 440 to 460 Ma ago, broadly at the end of graywacke sedimentation. Therefore, the Köli ophiolites do not qualify as a tectonic load responsible for the Early Ordovician basin on Baltica. In western parts of the Trondheim Nappe Complex, the Trondheim event (Roberts, 2003) of Early Arenig age (c. 475 Ma ago), involved ophiolite obduction upon a Gula microcontinent (Roberts and others, 2002) and related blueschist metamorphism (Eide and Lardeau, 2002). Since the graywackes record a basin on what was originally a part of Baltica, then the loading should have been directly on Baltica, and not on some terrane separated from Baltica by an oceanic region. Thus, also the Trondheim event may not be relevant for the foreland basin discussed here.

In contrast, throughout many parts of the Seve Nappe Complex of the Upper Allochthon, Finnmarkian tectonic and metamorphic activity, and magmatism have been documented extensively (for example, Gee and Sturt, 1985; Stephens and others, 1993; Brueckner and van Roermund, 2004). As summarized by Essex and others (1997), Roberts (2003), Brueckner and van Roermund (2004), or Hacker and Gans (2005), the Finnmarkian metamorphic event occurred from c. 515 to 475 Ma ago (table 2). This event has been documented to the north of the present area.

The Finnmarkian HP metamorphic ages generally pre-date the deposition of the Early Ordovician graywackes. However, if the orogenic wedge continues to move over the foreland after stacking and metamorphism of the internal units – as apparently was the case in the Alps – then the foreland basin can be younger. This appears to have been the case also in the Devonian of the Appalachians (for example, Garfunkel and Greiling, 2002). Such a model may be supported by post HP-cooling ages from the Norrbotten Seve units (Dallmeyer and Gee, 1986; Dallmeyer and Stephens, 1991; see table 2), which range from c. 490 to 460 Ma. Subsequently, subsidence increased but sediment-supply decreased (fig. 7C) and graywacke sedimentation terminated at c. 460

Ma. Increased subsidence implies increased load. However, decreasing sediment supply suggests a lowering of topographic relief. A possible explanation may be a load at depth, which may develop during the subduction of crustal material to HP depth and eclogitization, as suggested, for example by Dewey and others (1993) for the Scandian eclogites in western Norway. Such a model may explain the synchroneity of Jämtland phase, eclogites, subsidence, and decrease and termination of graywacke sediment supply.

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