Vendian–Cambrian subsidence of the passive margin of western Baltica – application of new stratigraphic data from the Scandinavian Caledonian margin

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Stratigraphic information from the Neoproterozoic to Cambrian cover sequences at the Caledonian margin in central Scandinavia has been compiled from the literature and our own data. Four flooding events can be recognized in the autochthonous cover rocks and parts of the eastern Caledonian Lower Allochthon: one, at the base of the Vendian at 590 Ma, two Early Cambrian events (540 and 530 Ma), and the fourth at the base of the Mid Cambrian and the alum shales (518 Ma). Stratigraphic successions of the western Baltica margin from northern Sweden to southern Norway are correlated using these flooding events. Based on these correlations, depth and time sections are constructed and subsidence curves calculated. Although Early Cambrian flooding events lead to temporarily higher sedimentation rates, the subsidence appears to have decreased through time. Such a decrease is consistent with models of lithospheric stretching and subsequent thermal subsidence. A review of available age data on tectonic events suggests a transition from continental rifting to ocean-floor formation off western Baltica at ca. 600 Ma ago. Accordingly, the Vendian to Cambrian evolution of the western Baltica continental margin is interpreted as a stage of post-rift subsidence showing the 'steer's head' geometry characteristic of sequences onlapping from an older zone of active rifting and of ocean-floor formation farther west. The gradual decrease in thermal subsidence through Cambrian time also shows that the Baltica lithosphere was essentially thermally re-equilibrated prior to earliest Caledonian tectonic activity in Early Ordovician time.

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Introduction

The late Proterozoic to Ordovician stratigraphic succession of the western margin of Baltica is believed to reflect an evolution from a rifted continent to a passive margin bordering a newly formed ocean towards the west (Iapetus?; Gee 1975; Stephens 1988; Stephens & Gee 1989). The margin was overprinted during the Caledonian orogeny and was destroyed by collision with eastern Laurentia (eastern Greenland). The consensus is that a passive margin formed just before Cambrian time (e.g. Kumpulainen & Nystuen 1985), with Caledonian deformation beginning in northern Scandinavia in Mid to Late Cambrian time (e.g. Ramsay et al. 1985; Mørk et al. 1988; Stephens & Gee 1989; Gromet et al. 1996). Recent changes in the ages assigned to the Vendian and Cambrian periods (Tucker & McKerrow 1995), together with new correlations of regional stages and/or faunal zones (Strauss et al. 1997), bring previously mismatched isotopic and biostratigraphic events into a more plausible chronological framework.

This progress in stratigraphic dating and our new correlations of sedimentary sequences of the marginal (eastern) and low-grade metamorphic thrust units of the Jämtland Supergroup of the Scandinavian Caledonides, provide new insights into the evolution of the passive margin of western Baltica. For reasons discussed below, the stratigraphic sections have not been decompacted and backstripped. Because these sequences were probably laid down outside any actively rifting zone, it is not possible directly to infer stretching factors (β values), though minimum values can be estimated.

Well-constrained flooding events (Vidal & Moczydlowska 1996) have been traced from the autochthonous cover rocks (Figs. 1, 3; Djupdal to Luopakte-Torneträsk) to parts of the eastern Caledonian Lower Allochthon (Gärdsjön Formation) and into areas of the Lower Allochthon of western Scandinavia (Mjøsa, Synnfjell; Figs. 1, 4). The available stratigraphic information has been compiled from the literature and our own unpublished data for the western Baltica margin of northern Sweden (Fig. 3) and southern Norway (Fig. 4). The new data are displayed as both time and depth sections in order to show regional variations in sedimentation rate. From these data subsidence-time graphs (Fig. 5) were constructed, compared with the subsidence-time graph of a typical Tethyan passive margin carbonate platform (Fig. 6) and placed in a regional context (Fig. 7).

Time scale

The biostratigraphic and chronological time-scales adopted here are presented in Fig. 2. The most important changes from time-scales of a decade or so ago are the

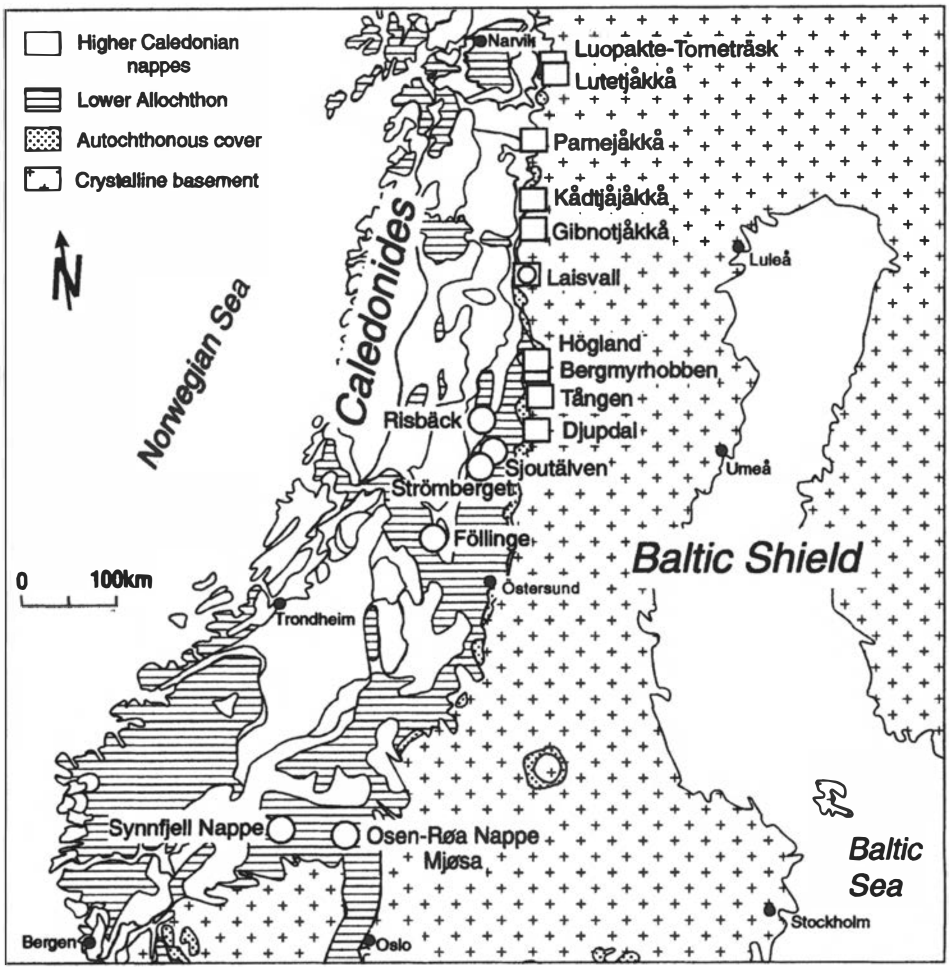

Fig. 1. Sketch map of the central Scandinavian Caledonides with the locations of the sections in the autochthonous cover sequence along the eastern Caledonian margin shown in Fig. 3 (squares) and in the Caledonian Lower Allochthon shown in Fig. 4 (circles). Also marked are the locations of sections from which additional subsidence curves are shown in Figs. 5 and 6 (Risbäck, Föllinge, Mjøsa, Synnfjell).

great reduction in the age assigned to the end of the Varangian ice age and to the base of the Cambrian period (Fig. 2). For example, in 1985 the base of the Varangian tillites was placed at about 650 Ma with a somewhat younger top, but recent data from N. America (see Knoll 1996) suggest that the top of the Varangian tillites is at about 590 Ma. Similarly, the base of the Cambrian, placed at 570 Ma by Harland et al. (1990), is now taken as 545 Ma (Tucker & McKerrow 1995). Other changes are shown on Fig. 2 and discussed below.

Vendian and early Cambrian sedimentary sequences and biostratigraphic constraints

The most complete and best-constrained autochthonous sedimentary sequences along the eastern Caledonian margin (Fig. 1) are those of the Torneträsk (Luopakte is the most complete and best-studied example, see Thelander 1982; Jensen & Grant 1998) and Laisvall areas in northern Sweden (e.g. Willdén 1980; Vidal & Moczydlowska 1996). These sequences represent a time interval from the Varangian glacial deposits to the Mid and Late Cambrian alum shales. An idealized section is shown in Fig. 2, where the lower part of the section is from Laisvall and the Mid- and Late Cambrian part is from Djupdal. For a better understanding of the local nomenclature, formation names from along the Caledonian margin in northern and central Sweden are compiled in Table 1.

The base of the Vendian (horizon 1 in Fig. 2) is clearly defined and, in both southern and northern Norway, is followed by a flooding event, documented by the transition from mainly terrestrial Varangian tillites to marine sandstones and shales (e.g. Kumpulainen & Nystuen 1985; Føyn 1985; Gayer & Rice 1989). Higher up in the sequence, two Early Cambrian flooding events have been identified (Vidal & Moczydlowska 1996; horizons 2, 3), followed by a further one at the base of the alum shales in the Mid Cambrian (horizon 4). In addition, at least in the Djupdal section, the base of the Late Cambrian is available as a time constraint (horizon 5; Karis, Zachrisson, unpublished data; see also Warr et al. 1996). At other places, the alum shales are strongly deformed during Caledonian nappe transport (e.g. Gee 1978, 1980) so that no reliable data on the original thicknesses are available.

There are no Vendian–Cambrian radiometric dates from the areas under discussion, and ages have to be based on biostratigraphic correlation with other regions. Large portions of the strata consist of sparsely fossiliferous siliciclastic rocks, but the sections at Torneträsk and

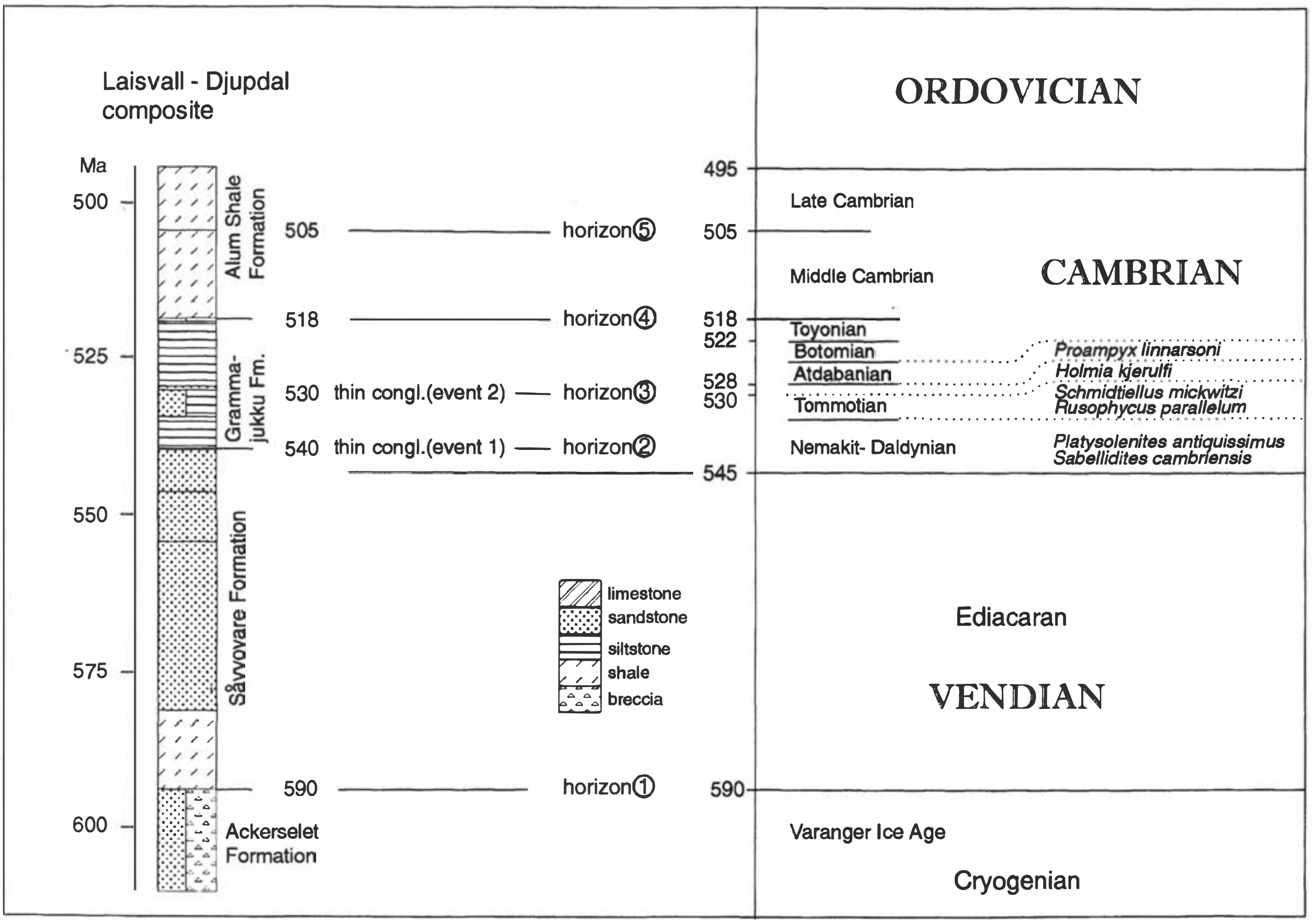

Fig. 2. Time plot showing a stratigraphic section compiled from the Laisvall and Djupdal areas (compare Fig. 3). Four flooding events are used as regional markers (horizons 1–4): the base of the post-tillite sequence, flooding events 1 and 2 of Vidal & Moczydlowska (1996), and an event at the base of the alum shales. The horizons are dated at ca. 590, 540, 530, and 518 Ma, respectively. Horizon 5 at the base of the Late Cambrian is only available at Djupdal. See text for further discussion.

Laisvall contain fossils of stratigraphic significance, which, together with lithological markers, allow the construction of a time frame. In the Torneträsk area, the occurrence of *Kullingia concentrica* and *Sabellidites* a few metres above the first Cambrian-type trace fossils near the top of the Lower siltstone member indicates a position close to the base of the Cambrian (Jensen & Grant 1998). The Red and green siltstone member and its correlatives in Norway contain fossils typical of the *Platysolenites antiquissimus* Zone. Trilobites of the *Holmia kjerulfi* Zone occur in the top part of the Upper siltstone member (e.g. Ahlberg 1985). In the Laisvall area, Vidal & Moczydlowska (1996) correlated the base of the Gramma-jukku Formation with the Red and green siltstone at Torneträsk. Acritarchs from the top of the same formation were found to be consistent with earlier finds of trilobites of the *Holmia kjerulfi* Zone. Therefore, the Precambrian–Cambrian boundary is likely to be in the upper part of the Såvvovare Formation (compare Fig. 2).

Bowring et al. (1993) provided a U-Pb zircon geochronology for the early Cambrian of northeast Siberia with 543.9 ± 0.2 Ma for the base of the Cambrian and a maximum age for the base of the Tommotian at 534.6 ± 0.4 Ma. However, according to Vidal et al. (1995) the Tommotian date is for the base of the Middle Tommotian. There is no general agreement on correlation from Siberia to Baltica, but recent work suggests that the Baltica sections are older than was previously thought. Strauss et al. (1997) make the *Platysolenites* Zone as being probably older than the Tommotian. This suggests an age for the *Platysolenites* Zone in the range of 534–540 Ma, broadly consistent with an Rb-Sr age of 533 ± 8 Ma for clays from the top of the Lontova Formation in Estonia (Gorokhov et al. 1994), which can be correlated with the upper part of the *Platysolenites* Zone. According to Vidal et al. (1995, p. 508), the age of 530.7 ± 0.9 Ma from the *Rusophycus avalonensis* Zone on Avalonia is within the *Holmia kjerulfi* Zone.

Biostratigraphically, the two Early Cambrian flooding events are dated as taking place during *Platysolenites antiquissimus* Zone time (horizon 2 on Fig. 2) and during *Holmia kjerulfi* Zone time (horizon 3). The later event has been identified by Vidal & Moczydlowska (1996) from the Torneträsk area in the north to Laisvall and Mjøsa in the south. The well-established flooding event at the base of the Mid Cambrian (horizon 4), which initiated the

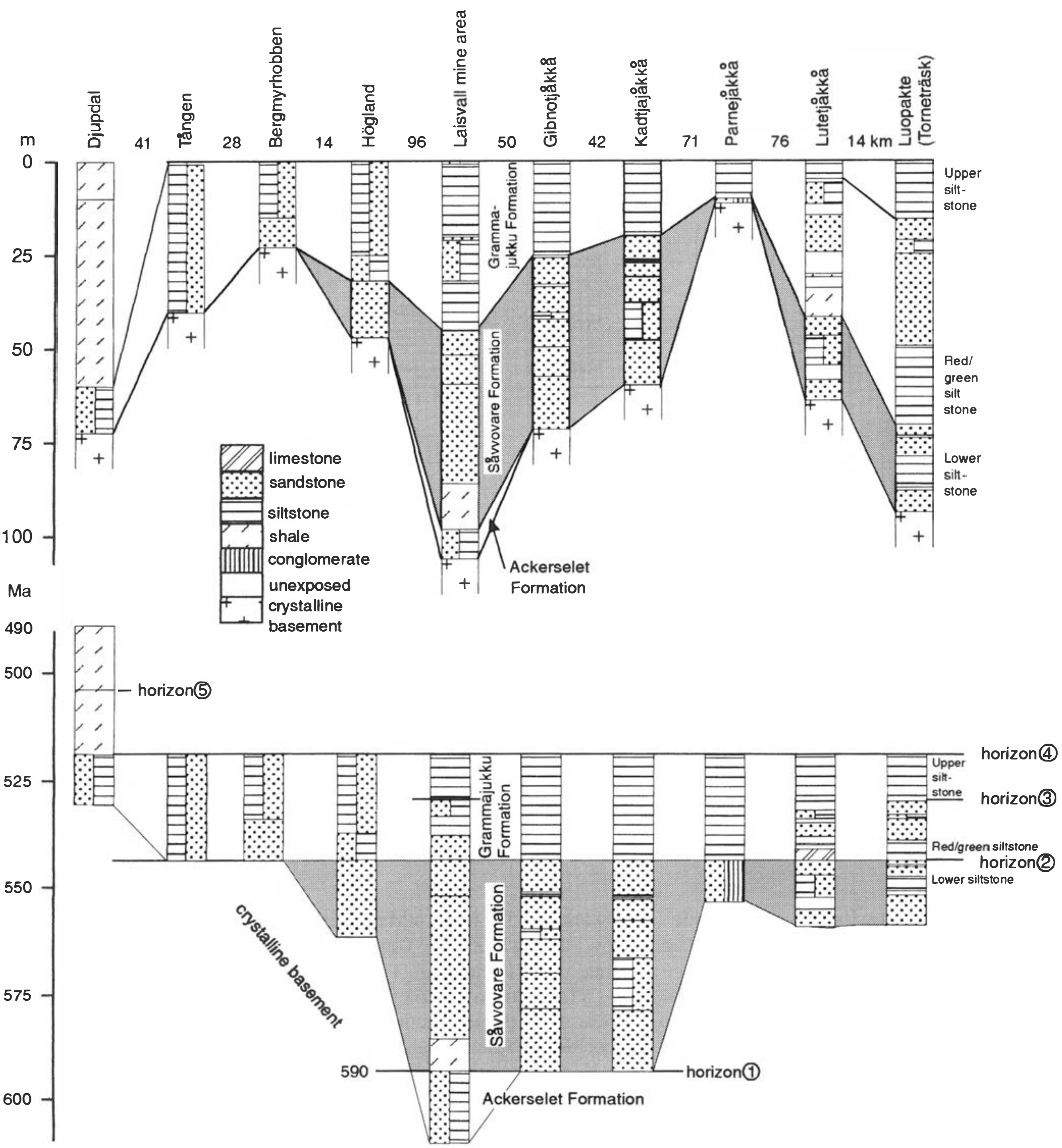

Fig. 3. Stratigraphic columns showing Vendian to Early Cambrian autochthonous sequences in northern Sweden from Lake Torneträsk to Laisvall mine and to Djupdal (see Fig. 1 for location). Sections start at the base of the sedimentary column above crystalline, early Proterozoic basement. They stop at the base of the Mid Cambrian alum shale level, which is taken as a horizontal reference line. An exception is the Djupdal section, which goes up into the Upper Cambrian (all of the autochthonous sequence preserved). From Laisvall northwards, lithological units are taken from Thelander (1982, 1994; see also Willdén 1980). Top: depth section, thickness in metres. Bottom: time section, age in Ma (see text). For easy reference, the interval covered by the Såvvovare Formation is shaded. Kilometre figures between the sections refer to the lateral distance between the column locations.

deposition of the alum shales, can be traced along the entire Caledonian margin, both in the Autochthon and in the Lower Allochthon, and even beyond, because of the conspicuous character of the alum shales (e.g. Gee 1980; Andersson et al. 1985).

In accordance with Tucker & McKerrow (1995), we have assigned numerical ages to the particular horizons (1–5; see Fig. 2): the maximum marine flooding event in the Early Cambrian identified by Vidal & Moczydlowska (1996) at the time of the *Platysolenites antiquissimus* Zone

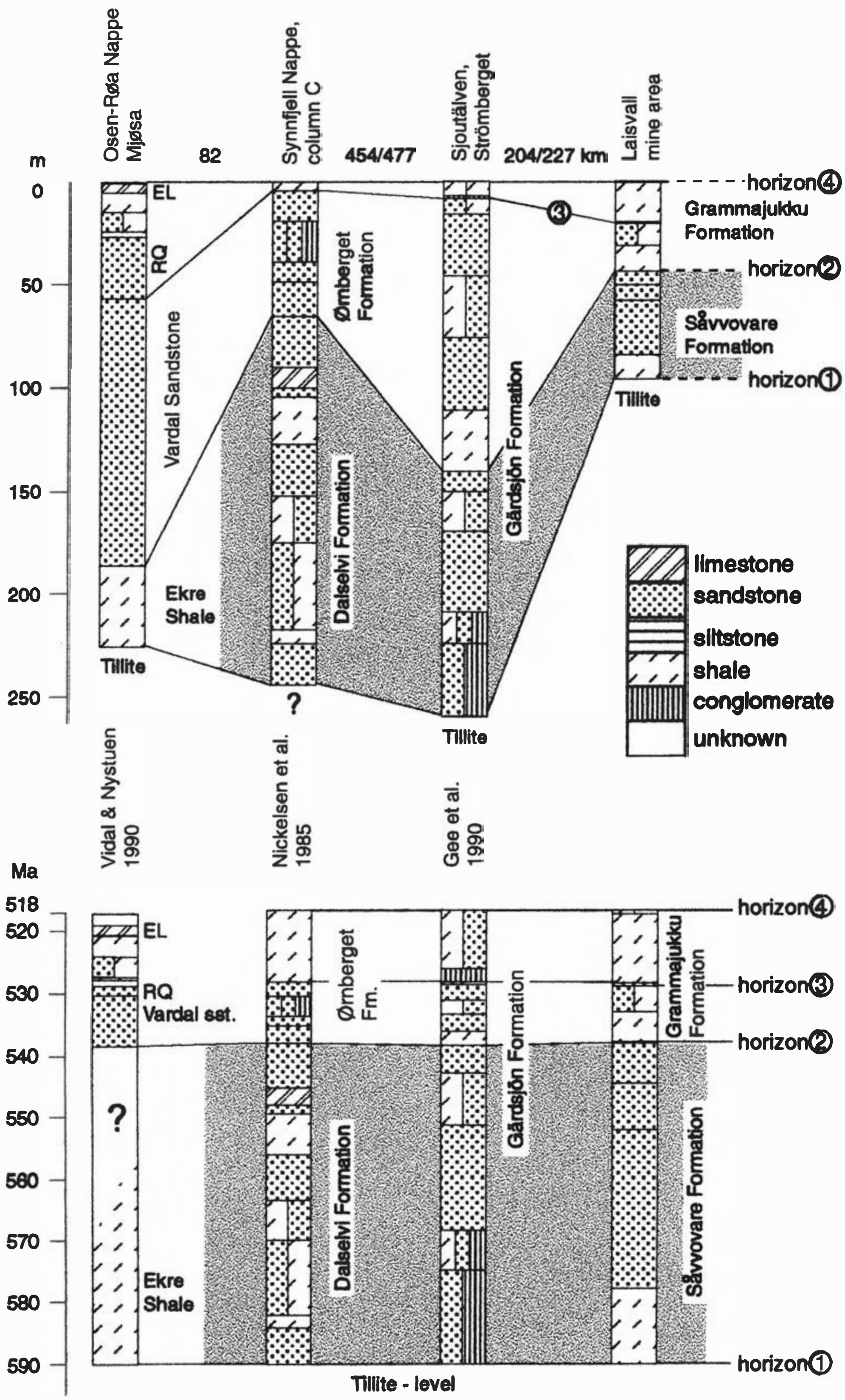

Fig. 4. Stratigraphic columns showing the proposed correlation of sequences in the autochthonous cover (Laisvall) with those in the Lower Allochthon in Sweden (Gärdsjön Formation at Sjoutälven and Strömberget) and southern Norway (Synnfjell Nappe, Mjøsa) between the top of the Varangian tillites and the base of the Mid Cambrian alum shales. Similar to Fig. 3, the interval between horizons 1 and 2 (Såvvovare Formation equivalent) is shaded. Top: depth section, bottom: time section. Key as in Fig. 3. Kilometre figures between the sections refer to the lateral, unrestored distance between the column locations. EL: Evjevik limestone, RQ: Ringsaker Quartzite.

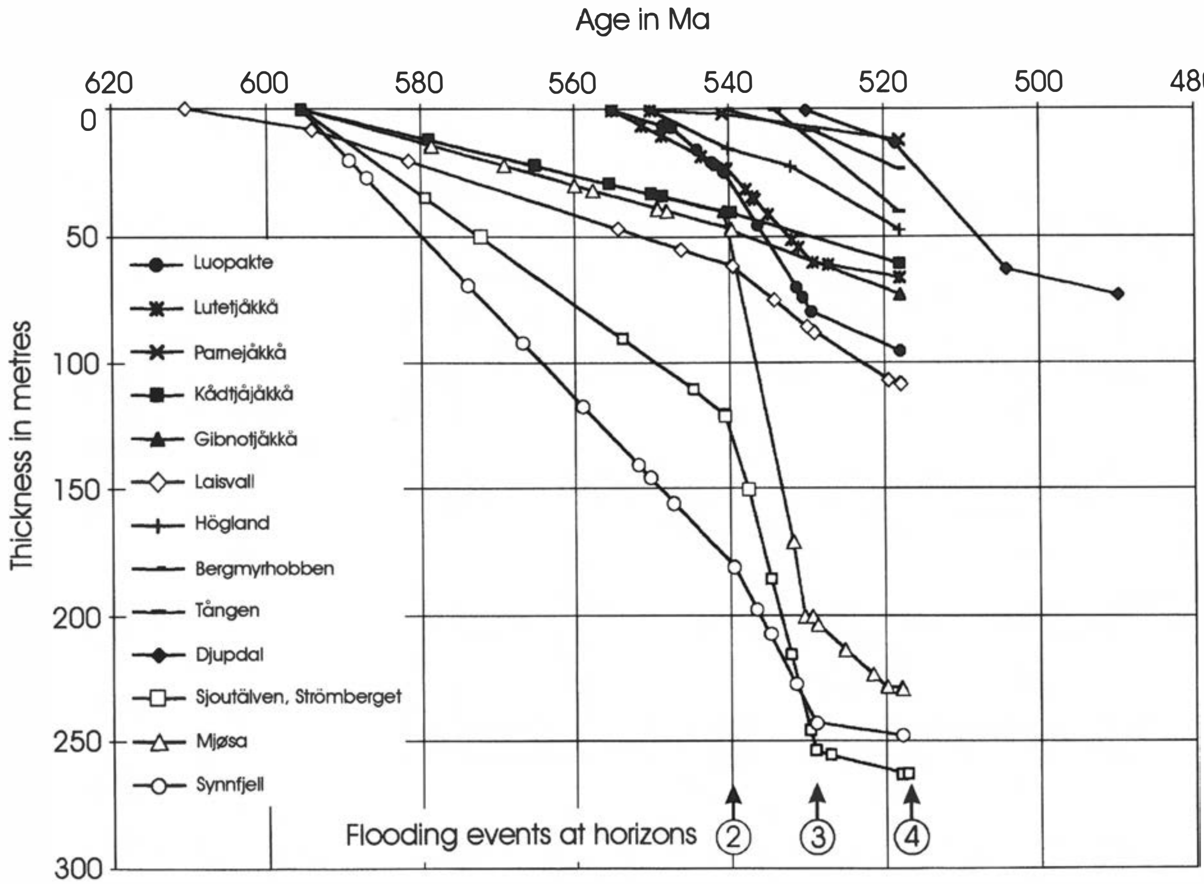

Fig. 5. Subsidence curves derived from the stratigraphic sections of the autochthonous cover successions shown in Fig. 3 and of the Lower Allochthon shown in Fig. 4. The general pattern of decreasing subsidence is 'overprinted' by flooding events at ca. 540, 530 and 518 Ma ago, which are marked by arrows (horizons 2, 3, 4, respectively, as defined in Fig. 2). The legend is arranged according to the location of the sections from NE to SW (compare Fig. 1). Open symbols mark sections from Fig. 4. The somewhat higher thicknesses of the allochthonous sections reflect their palaeogeographic position farther west, closer to the extensional zone.

(horizon 2) is here assigned an age of 540 Ma. In the same way, the event at *Holmia kjerulfi* Zone time (horizon 3) is given an age of 530 Ma (estimated age for base of the *Holmia kjerulfi* Zone in middle Tommotian). A further flooding event, after the Hawke Bay regression and at the base of the Mid and Upper Cambrian alum shales is arbitrarily set here at 518 Ma, the base of the Mid Cambrian (horizon 4). Following Tucker & McKerrow (1995), we place the base of the Upper Cambrian at 505 Ma (horizon 5).

Correlation between Autochthon and Lower Allochthon

The new stratigraphic data from Laisvall (Vidal & Moczydlowska 1996) require a revision of correlations between sections of the autochthonous sequence along the eastern Caledonian margin in northern Sweden. Figure 3 shows a selection of sections along the mountain front, from Luopakte at Lake Torneträsk in the north via Laisvall to Djupdal in the south. In contrast to earlier correlation proposals, the base of the Grammajukku Formation at Laisvall is equivalent to the *Platysolenites antiquissimus* Zone and, therefore, to the base of the Red and green siltstone unit at Luopakte (Vidal & Moczydlowska 1996), as shown in Fig. 3. From Laisvall, the Grammajukku Formation can be followed southwards as far as Bergmyrhobben and Tången (Kulling 1942; our observations). The lithologic correlation is supported by biostratigraphic data from the vicinity of Bergmyrhobben (road between Fristad and Vallträsk; Willdén (1980)). The Bergmyrhobben locality itself is apparently not identical with Willdén's (1980) locality but is situated ca. 1 km farther west (Willdén, pers. comm. – 1997). Northwards, the Grammajukku Formation can be followed at least to Parnejåkkå (Thelander 1994; Fig. 3).

As a consequence, the earlier correlation of the siltstone sequence at Parnejåkkå with the Upper siltstone member at Luopakte (Thelander 1982) is no longer tenable. Instead, the base of the Parnejåkkå siltstone correlates with the base of the Red and green siltstone member. These correlations are shown in Fig. 3 and confirm the importance of the red and green siltstone horizon. This red and green unit is developed extensively farther northeast in northern Norway (Føyn 1967; Vogt 1967) and has also been observed towards the southwest, in central Scandinavia (Gee et al. 1978, 1990). As a consequence, Thelander (1982) proposed a correlation between the Red and green siltstone member at Luopakte (related to horizon 2 or flooding event

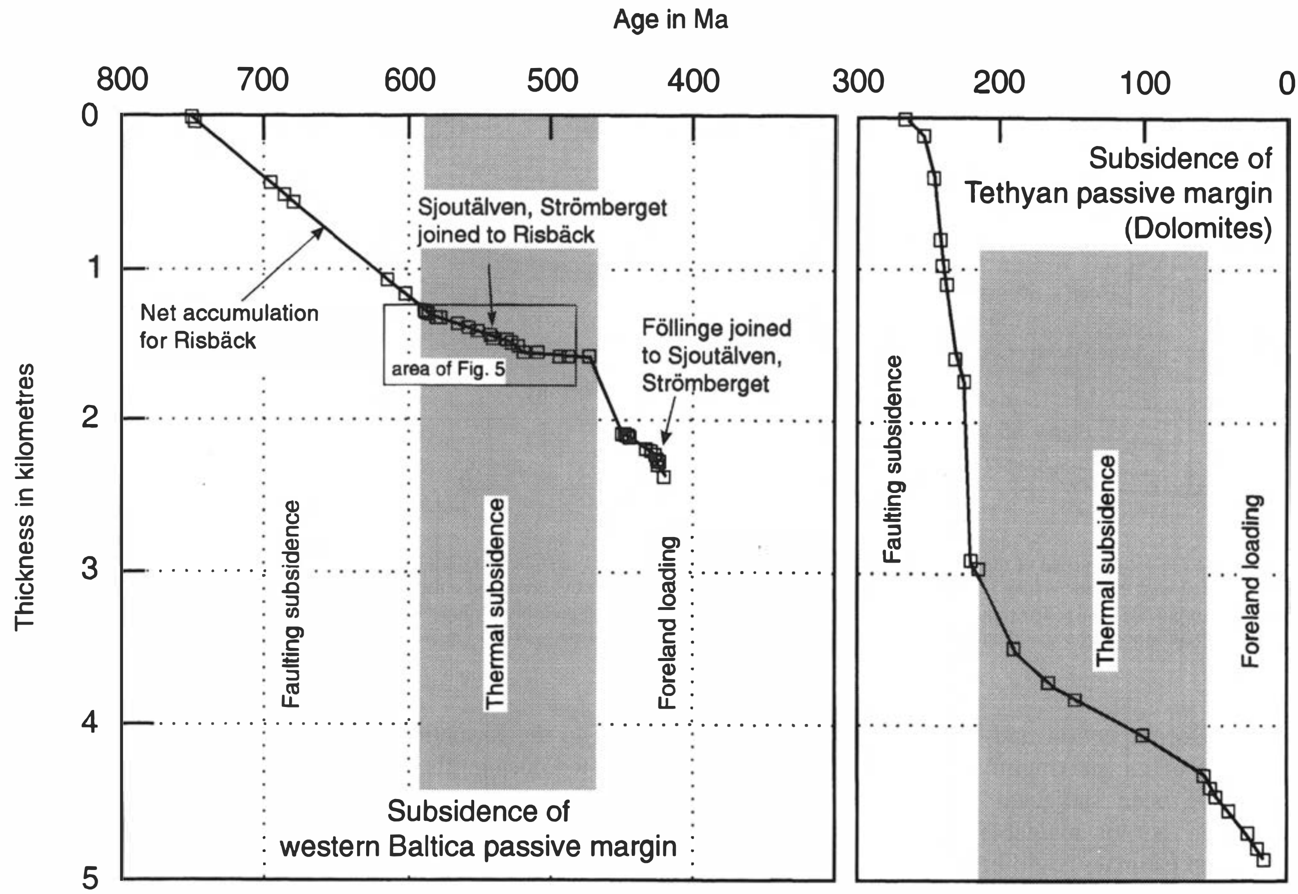

Fig. 6. Subsidence curve from a composite section of the Jämtland Supergroup (e.g. Gee et al. 1978; 1990), comprising both syn-rift (Risbäck), post-rift (as discussed in detail here) and foreland-basin sequences (Föllinge; compare Stephens & Gee 1989), is shown on the left of the Figure. This curve shows the subsidence history as documented on Fig. 5 in a wider tectonic frame. The western Baltica subsidence history can be compared with a Tethyan passive continental margin subsidence curve, which is shown on the right.

1 of Vidal & Moczydlowska (1996)) with the red and green shales of the Gärdsjön Formation in the Lower Allochthon of north–central Sweden. As yet, no supporting biostratigraphic information is available from the level of horizon 2 of the Lower Allochthon. However, the second flooding event (horizon 3) is dated at a number of localities in the Lower Allochthon of north–central Sweden (Ahlberg & Bergström 1983; Ahlberg 1984) and the lithologic sequence from horizon 2 to 3 at Luopakte, at Laisvall (Fig. 3) and in the Lower Allochthon are closely comparable (Fig. 4). Therefore, it appears probable that the red and green siltstones at both Luopakte and in the Gärdsjön Formation and the basal part of the Grammajukku Formation at Laisvall are time equivalents. A comparison of the post-Varangian sequence at Laisvall and in the Gärdsjön Formation reveals further similarities. The five lithological units of the Gärdsjön Formation including and overlying the red and green shales are composed of alternating sandstone- and shale-dominated sequences (units VI to X of Thelander 1982; Gee et al. 1990) and are similar to those of the Grammajukku Formation at Laisvall (see Fig. 4).

Farther southwest, the Lower Allochthon in southern Norway, particularly the Synfjell Nappe, shows a comparable sequence between the Varangian tillites at the base and Mid Cambrian shales on top (Nickelsen et al. 1985). For example, there is also a characteristic red shale in the Dalselvi Formation of the Synnfjell Nappe at the same place in the lithological sequence. Consequently, Fig. 4 shows the red and green units of the Synnfjell, Gärdsjön and Laisvall sections as time equivalents. Correlation between the Synnfjell and Osen–Røa Nappes (e.g. Bockelie & Nystuen 1985; Kumpulainen & Nystuen 1985) is well established biostratigraphically at the horizon 3 level (event 2 of Vidal & Moczydlowska 1996) and more vaguely at the horizon 2 level. However, in the absence of further data, the base of the beds overlying the Ekre Shale (e.g. Vidal & Nystuen 1990) is assigned here a 540 Ma age (Fig. 4).

Subsidence during Vendian and Cambrian time

Most of the sediments in the sections of Figs. 3 and 4 were deposited in a shallow-water environment (e.g. Willdén 1980; Thelander 1982; Nickelsen et al. 1985; Nystuen 1987; Vidal & Moczydlowska 1996). Total thicknesses of almost 300 m exist in the SW of the area with net accumulation rates of about 2 m Ma^{-1}. Such thicknesses and rates reflect slow net subsidence of western Baltica

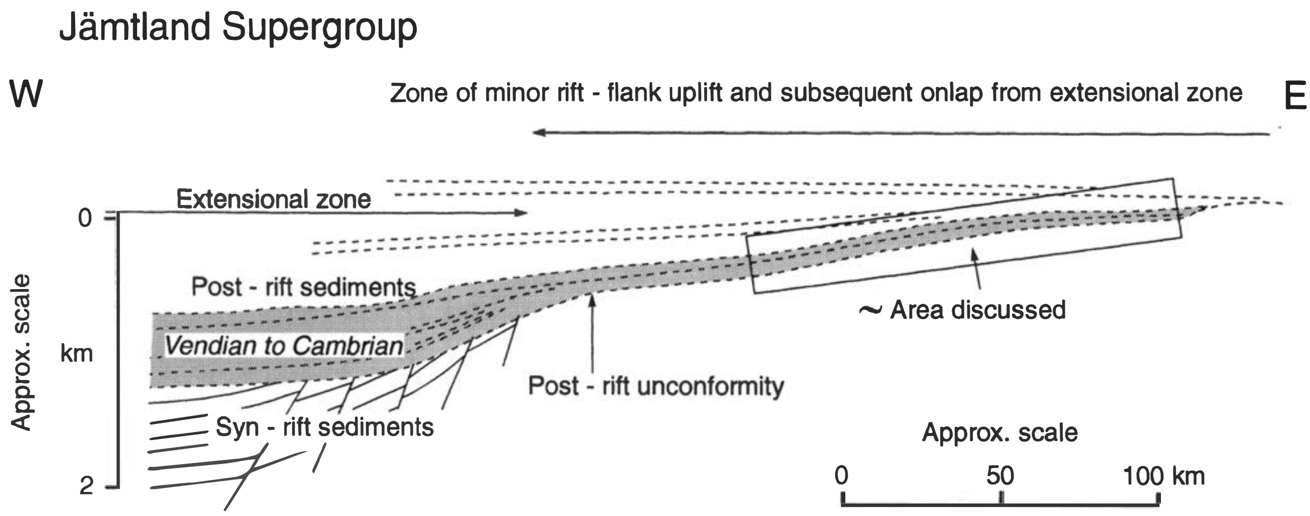

Fig. 7. Pre-tectonic reconstruction of the Jämtland Supergroup, modified from Gee (1972) and Stephens & Gee (1985, Fig. 2). The principal modifications are the explicit subdivision of the stratigraphy into syn-rift and post-rift sediments, labelling of extensional and onlap zones, and the placement of some extensional faults further E than originally shown. The post-rift unconformity reflects early (limited) erosion probably attributable to rift-flank uplift. During the post-rift passive margin phase, the sediments of the area discussed above are interpreted to reflect slow and steadily decreasing thermal subsidence modulated by four highstands of sea

(Fig. 5). Decompaction and backstripping require some knowledge of the maximum sedimentary load that sediments have been subjected to prior to exposure. This information is not available for the present sections, although an estimate could be made from the densities of any shales present. However, model calculations on the Palaeozoic cover thickness in the Caledonian foreland suggest only a few kilometres of thickness (Middleton et al. 1996). Nevertheless, even if it is assumed that the sections have been buried to several kilometres' depth, the decompacted thicknesses are small.

Viewed in isolation, the sequences resemble the Palaeozoic sequences of other continental platforms, such as are found at later periods on eastern Baltica or on the N American continent, i.e. a relatively thin and varied shelf accumulation showing one or more high stands of sea level. At least some of the low stands could be due to the formation of ice caps that are known to have existed during this period, such as that associated with the Mid Cambrian Tamale group tillites of NW Africa (Villeneuve & Cornee 1994).

However, the sequences are also linked to the structurally higher Middle and Upper Allochthons, which were situated palaeogeographically to the west of the present area and whose Vendian–Cambrian evolution suggests that they were continental rift and passive margin sequences at the time (e.g. Stephens & Gee 1985; 1989; Nystuen 1987; Andréasson 1994; see following chapter).

Table 1. Selected stratigraphic names for the sedimentary succession along the Caledonian margin in northern and central Sweden. Following Vidal & Moczydlowska (1996), the nomenclature of Willdén (1980) is used here.

Lower Allochthon		Autochthon				
	Fjällbränna Fm.	Alum Shale Formation				
Sjoutälven Group	Gärdsjön Formation	Siltstone Fm.	Grammajukku Fm.	Laisvall Group	Torneträsk Formation (*Thelander 1982*)	Torneträsk Group (*Kulling 1982*) Dividalen Group (*Føyn 1967*)
Sjoutälven Group	Gärdsjön Formation	Laisvall Formation	Såvvovare Fm.	Laisvall Group	Torneträsk Formation (*Thelander 1982*)	Torneträsk Group (*Kulling 1982*) Dividalen Group (*Føyn 1967*)
Sjoutälven Group	Långmarkberg Formation	Laisvall Formation	Ackerselet Fm.	Laisvall Group	Torneträsk Formation (*Thelander 1982*)	Torneträsk Group (*Kulling 1982*) Dividalen Group (*Føyn 1967*)
central Sweden *Gee et al. 1978* *Kumpulainen 1982*		Laisvall *Liljequist 1973*	*Willdén 1980*	northern Sweden		N-Norway

Tectonic events and their age constraints

Neoproterozoic rifting at the western Baltica margin is well documented (e.g. Kumpulainen & Nystuen 1985; Nystuen 1987). Continental rifts with synsedimentary faulting, thick conglomerates, subordinate igneous activity, and occasional marine ingressions prior to the Varangian glaciation are succeeded by more widespread and mostly shallow marine post-glacial deposits (Hossack et al. 1985; Nystuen 1987).

Rift to drift transition

The evolution of the Baltica passive margin has been reviewed recently by Andréasson (1994), Torsvik et al. (1996), Andréasson et al. (1998) and Bingen et al. (1998). Accordingly, occasional dyke magmatism may have started as early as ca. 850 Ma ago (Andréasson 1994). Intensive dyke intrusion between ca. 670 and 600 Ma ago probably ended the protracted history of rifting. There are only imprecise younger Sm–Nd ages (e.g. 573 $\pm$ 74 Ma) from dykes in northern Sweden with a positive ε Nd (Andréasson et al. 1998). The latter may point to the fact that these dykes intruded into an oceanic environment and, therefore, after the onset of the drift stage. These young dyke intrusions may also be generally related to the Seiland Igneous Province in Arctic Norway, where localized magmatic activity continued until ca. 520 Ma ago and was probably related to local, synorogenic extension (e.g. Leaver et al. 1989) or a hot spot, and not necessarily to the break-up of the Baltica continent. From the available evidence it may, therefore, be concluded that the rifting stage ended after intense dyke intrusions at ca. 600 Ma ago and was succeeded by the formation of oceanic lithosphere off western Baltica.

Passive margin to subduction

Radiometric dating of early subduction-related HP metamorphism as at ca. 505–480 Ma ago (Mørk et al. 1988; Gromet et al. 1996) provides an upper age limit on the onset of subduction. The dated HP metamorphic assemblages originated at depths of 50 km or more. As a consequence, the onset of subduction must have been considerably earlier. If a simple subduction zone geometry with a 30° subduction angle is assumed, a convergence rate of 1 cm a^{-1} requires 10 Ma of subduction in order to bring the tip of the subducting plate down to 50 km depth. If these 10 Ma are added to the oldest date of HP metamorphism, the onset of subduction can be assumed to be as early as ca. 515 Ma. Such an age is close to that of the base of the alum shales in the Mid Cambrian.

Discussion

The new stratigraphic data (Figs. 2, 3) provide a basis for regional correlations from the autochthonous sequences at the eastern Caledonian margin westwards, into the Lower Allochthon (Fig. 4). These results can now be evaluated in order to gain new insights into the evolution from continental rifts to passive continental margins, in particular on their subsidence history (Fig. 5). Whereas in most other N-Atlantic areas Varangian tillites were deposited on top of marine successions, frequently carbonate platforms (see reviews by Hambrey & Harland 1981; Winchester 1988), the present area appears to be exceptional in that Varangian and younger sediments record the onlap onto an older continental domain. Such a palaeogeographic situation close to sea level is most sensitive in order to show changes in the elevation of the lithosphere relative to sea level.

Although the Vendian to Cambrian sections presented above are clearly contemporaneous with passive margin formation farther west since ca. 600 Ma ago (e.g. Stephens & Gee 1989; Andréasson 1994; Torsvik et al. 1996; Andréasson et al. 1998) they show net accumulation rates and total accumulations that are distinctly smaller than more recent, for example Tethyan extensional margins (Fig. 6). In the Tethyan example from the Dolomites three phases of evolution are clear: a stretching phase lasting about 70 Ma during which subsidence was rapid (>40 m Ma^{-1}); about 160 Ma of gradually decreasing thermal subsidence; followed by an abrupt increase in subsidence attributed to foreland loading (Wooler et al. 1992). In the present example, the time of onset of the stretching phase varies across the area and is poorly defined. It may be as old as 850 Ma (Andréasson 1994) but may be as young as the age of the oldest dykes related to rifting, i.e. 670 Ma (see above). In the latter case, the pre-drift stretching phase lasted ca. 60 Ma with a subsidence of ≤ 25 m Ma^{-1} for the thickest pre-drift sequences discussed here (c. 1500 m; Risbäck, e.g. Kumpulainen 1982). However, if a time span of 290 Ma is assumed, subsidence will be as low as 5 m Ma^{-1} or even lower for sequences less than 1500 m thick. Since ca. 600 Ma ago and until the onset of 'Finnmarkian' turbidite deposition in Ordovician times (ca. 470 Ma ago), there is gradually decreasing thermal subsidence. A minor bend in the subsidence curve between ca. 520 and 510 Ma may be significant with regard to subduction loading (see below). The small thicknesses and absence of substantial synsedimentary extensional faulting in the sequences discussed here, both suggest that the sequences lay some tens of or even hundreds of kilometres continentward of the active rift zone that would have been associated with the formation of a passive continental margin, and further still from the ocean–continent boundary. This conclusion is supported by the more than 200 km of shortening between the autochthonous foreland and the eastern edge of the thick, Late Proterozoic sediments in the present Lower and Middle Allochthons (Gee 1978, 1980; Hossack et al. 1985; Morley 1986; Gayer et al. 1987; Gayer & Greiling 1989) that mark the rift zone itself (e.g. Nystuen 1987). Restoration of the Lower Allochthon in northern Sweden implies that areas with thin cover sequences extend as far west as 270 km west of the present eastern Caledonian margin (Greiling et al. 1998). Consequently, the essentially unstretched Baltica lithosphere extends westwards for a similar distance. Thus, the sedimentary sequences discussed here most probably reflect the onlap commonly found on the edges of extensional basins, giving rise to a characteristic 'steer's head' geometry (Fig. 7). Such onlap may be attributed to a eustatic rise in sea level. That there are four highstands represented in the Scandinavian sections (horizons 1 to 4, see Fig. 2) suggests that there were indeed eustatic sea-level changes, but they were episodic changes superposed on a pattern of overall subsidence (Figs. 5, 6). This subsidence is clearly related with rifting and separation of the Baltica continental terrane from another continental terrane towards the west (see previous chapter). However, there may be several ways to explain the tectonic significance of the observed pattern of subsidence.

Flexural rigidity at rift margins and flank uplift

The observed onlap may be due to increasing flexural rigidity of the continental lithosphere after rifting (see discussion and references in White & McKenzie (1988)).

However, subsequent modelling suggests no significant changes in lithospheric strength after stretching (e.g. Watts 1992; Sahagian & Holland 1993). The Baltica lithosphere acquired a high thickness already in Palaeoproterozoic times (e.g. Blundell et al. 1992; Gorbatschev & Bogdanova, 1993; see also Garfunkel & Greiling 1998) and can be assumed to be relatively strong prior to Neoproterozoic rifting. Where the initial lithosphere strength is relatively high, flank uplift is expected to take place during rifting (Weissel & Karner 1989; Watts 1992; Roberts & Yielding 1994). However, in the present case, the distance to the active rift is relatively large, as is the distance to any possibly uplifted rift flank. Therefore, only a minor amount of rift flank uplift can be expected, if any at all. Such a subordinate uplift may have produced minor erosion and thus may account for the limited and irregular distribution of the Varangian glacial sediments at the present Caledonian margin and in the Lower Allochthon.

Thermal subsidence

An alternative model for onlap is that the extensional zone in the mantle is slightly wider than that of the overlying continental crust but that both zones have identical integrated values of β (White & McKenzie 1988). In this modified lithospheric stretching model the subsidence of the onlapped region is, of course, much less than that of the rift zone, but, as within the rift zone, the rate of subsidence decreases with time. With the old time-scales, the rate of subsidence may actually increase as one moves from the Vendian to the Cambrian, but the new time-scale shows it to decrease as required by the model (Figs. 2, 5). However, an 'overprint' by the flooding events leads to temporarily higher (apparent) subsidence.

In this modified model, the age of the oldest onlapping sediment is close to or slightly younger than the cessation of extensional faulting, corresponding to the beginning of thermal subsidence. In the case of some stretched basins, such as the North Sea (e.g. White & McKenzie 1988; Blundell & Gibbs 1990), extension did not lead to the creation of an ocean floor, but in the case of western Baltica it did (e.g. Stephens & Gee 1985; 1989; Andréasson 1994; Torsvik et al. 1996; Bingen et al. 1998). The oldest ocean floor formed adjacent to the margin will also have an age close to that of the age of the oldest onlapping sediment. Just how close is unclear because the model predicts uplift of the rift shoulders. These will have to be eroded before any sedimentation takes place if they rise above sea level. This model implies that the younger part of the Varangian glacial sediments at the base of the post-rift sediments until about 590 Ma ago is contemporaneous with or just post-dates the beginning of spreading of the (Iapetus?) ocean off western Baltica, rather than spreading having started at a time closer to the base of the Cambrian, at, say 550 Ma. The thick (>1 km) pre-Vendian Neoproterozoic sections of the western Jämtland Supergroup (Kumpulainen 1982; Kumpulainen & Nystuen 1985) or in the Lower Allochthon of southern Norway (Kumpulainen & Nystuen 1985; Nickelsen et al. 1985), which underlie the SW part of the area, have been interpreted as syn-rift sediments (Gee 1975; Stephens & Gee 1985; Nystuen 1987). They would be analogous to the syn-rift phase of Tethyan passive margin sequences (Figs. 5, 6).

Subduction loading

Another view is that the Vendian to Early Ordovician sections reflect processes on a distant *active* margin and that the passive phase of the continental margin of Baltica is older than has been commonly assumed. Some support for the second view may come from the evolution of island-arc volcanics in the Virisen terrane, which is thought to be closely spatially related to Baltica (Stephens 1988; Stephens & Gee 1989). However, the earliest time information on this terrane is from the Early Ordovician (e.g. Stephens et al. 1993) and no earlier traces of island-arc activity are found at or close to the continental margin of Baltica. Therefore, a genuine active continental margin tectonic scenario at the western Baltica margin with eastward subduction is unlikely for Vendian to Cambrian times. Better constrained is the transition from the passive margin stage to early (westward) subduction of oceanic lithosphere attached to the passive Baltica margin in Mid to Late Cambrian times. Following Gee (1987), subduction loading and consequent subsidence of Baltica can be inferred in order to explain the transition from relatively shallow marine successions to deeper water, anoxic environments at about the beginning of the Mid Cambrian (horizon 4 in this paper). Such an onset of subduction loading may explain the 'bend' in the subsidence curve at Mid Cambrian times (Fig. 5). However, apart from this minor bend, there is no general change in the pattern of decreasing subsidence until the onset of 'Finnmarkian' loading in Mid Ordovician times (Fig. 6).

Conclusions

In conclusion, we interpret the presented Vendian to Cambrian evolution of the western Baltica continental margin as a stage of post-rift subsidence starting at ca. 600 Ma ago and following earlier continental rifting. This post-600 Ma subsidence occurs simultaneously with ocean floor formation farther west and leads to an onlap sequence onto the continental domain towards the east (Fig. 7). The observed post-rift subsidence decreases through time (Figs. 5, 6) and this decrease is consistent with models of lithospheric stretching, in particular that of White & McKenzie (1988), and subsequent thermal re-equilibration. Early Cambrian flooding events lead to temporarily higher sedimentation rates 'overprinting' the general pattern of decreasing subsidence (Fig. 5). A further minor overprint may be related to the onset of subduction loading in the oceanic realm off Baltica in Mid Cambrian times. The gradual decrease of thermal subsidence through Cambrian times also shows that the Baltica lithosphere was essentially thermally re-equilibrated after (Iapetus?) ocean opening and prior to the onset of Caledonian compressional tectonic activity (Finnmarkian phase) in Early Ordovician times.

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