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The Scandinavian Caledonides: event chronology, palaeogeographic settings and likely modern analogues

David Roberts*

Geological Survey of Norway, N-7491 Trondheim, Norway

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Abstract

Following an outline of Scandinavian Caledonide tectonostratigraphy, tracing the Neoproterozoic, Baltoscandian, passive margin of Baltica outboard into the suspect, Iapetus oceanic terranes and farther into the highest allochthons, which carry evidence of Laurentian ancestry, descriptions are presented of the principal tectonothermal events recorded in different parts of the mountain belt. Four major compressive/transpressive events are recognised—*Finnmarkian* (Late Cambrian), *Trondheim* (Early Arenig), *Taconian* (Mid–Late Ordovician) and *Scandian* (Mid Silurian–Early Devonian). The first two events involved subduction scenarios with contraction/accretion between Baltica and/or an adjacent microcontinent and Iapetan arcs. The *Taconian* is also an arc-accretion, tectonothermal event, but this occurred along the margin of the Laurentian plate, remote from Baltica. The later *Scandian* event involved rapid subduction of the Baltican margin beneath Laurentia to depths exceeding 120 km and equally rapid exhumation. This was followed by an episode of orogenic collapse, widespread extension and Devonian basinal sedimentation, with local upright folding (*Solundian* phase). Based on comparisons between geochemical signatures and settings of Caledonide ophiolite fragments and diverse magmatic arcs, and modern examples of such, various analogies have been proposed by several authors with comparable elements in the southwestern and western Pacific region. Taking into account a predictive model for future oblique collision between the Australian and Eurasian plates, this resultant sinistral, oblique-convergent system of semi-linear terrane slices bears many similarities to the Caledonide geology and tectonics of Scandinavia.

Keywords: Scandinavian Caledonides; Baltica; Orogenic events; Iapetus Ocean; Dyke swarms; Southwest Pacific Ocean

1. Introduction

The Scandinavian Caledonides comprise innumerable thrust sheets composed of diverse rock complexes of disparate origins and wide-ranging metamorphic grade that developed via a series of tectonic events in the Early Palaeozoic. Gradual oblique convergence of the plates Baltica and Laurentia ultimately led to a collision involving subduction of the margin of Baltica beneath Laurentia in Silurian to Early Devonian time. This scenario produced a progressive telescoping of the Baltoscandian passive margin miogeocline and shelf successions, as well as exotic, oceanic and arc terranes derived from the Iapetus Ocean, and their eastward translation onto

* Tel.: +47-73-90-42-31; fax: +47-73-92-16-20.
E-mail address: david.roberts@ngu.no (D. Roberts).

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Archaean and Proterozoic crystalline rocks of the Fennoscandian Shield. As a result, a distinctive tectonostratigraphy can be recognised comprising Lower, Middle, Upper and Uppermost Allochthons (Fig. 1), involving nappe translations of up to several hundreds of kilometres (Roberts and Gee, 1985). Subjacent to these major allochthons, there are parautochthonous units and an autochthonous sedimentary cover that can be followed along the entire front of the exposed orogen. In many thrust sheets, slices of Precambrian crystalline basement, with or without sedimentary cover, have been incorporated into the developing orogen and seismic reflection studies in Mid Norway/Sweden have indicated a more considerable involvement of basement in thrusting than hitherto believed (Hurich et al., 1988; Palm et al., 1991).

Detailed investigations in many fields over especially the last 30 years have combined to show that rocks now composing the Lower and Middle Allochthons are shelf and continental rise successions indigenous to the Baltoscandian margin of Baltica, whereas the Upper Allochthon comprises mainly the outboard, oceanic (ophiolitic), diverse magmatic arc (both primitive and evolved) and marginal basin associations from unknown locations within or peripheral to the Iapetus Ocean (Gale and Roberts, 1974; Gee, 1975; Stephens and Gee, 1985, 1989; Pedersen et al., 1988, 1991; Grenne et al., 1999). The Uppermost Allochthon constitutes an even more exotic element in the Scandinavian scene, inferred by many to have likely affinities with Laurentia (e.g., Stephens and Gee, 1985, 1989; Roberts et al., 1985). Recent structural, stable isotopic and radiometric dating evidence has, in fact, now more or less confirmed this notion of a Laurentian ancestry for the rocks and earliest structures in these highest nappe complexes (Roberts et al.,

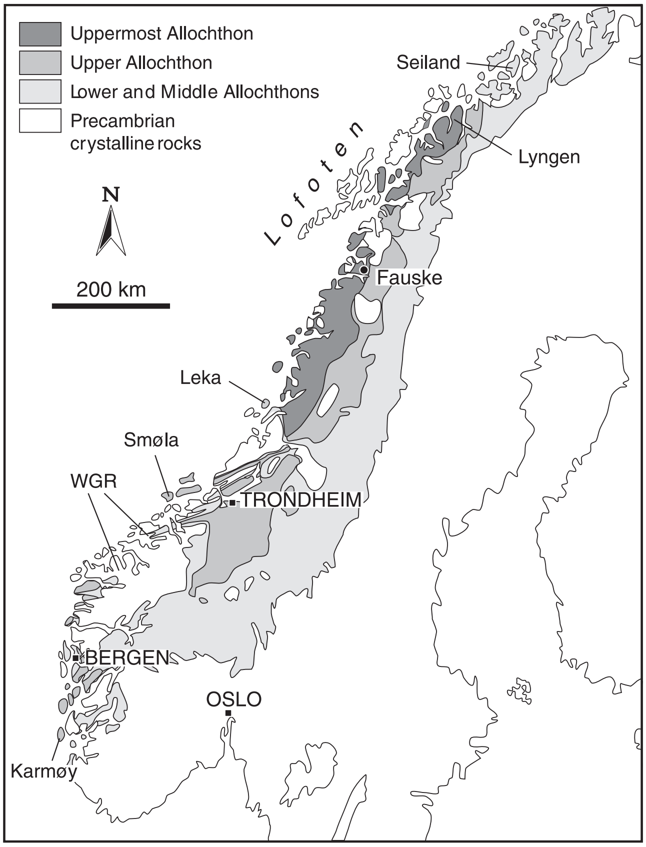


Fig. 1. Simplified tectonostratigraphical subdivisions of the Scandinavian Caledonides, with place names or regions mentioned in the text.

2001, 2002a; Melezhik et al., 2002; Yoshinobu et al., 2002).

This present contribution builds on the tectonic development of the Scandinavian Caledonide fold-and-thrust belt in terms of the sequence of orogenic events recognised in particular regions or in specific allochthons. Following Roberts (2001), the different events are illustrated in postulated, simplified, palaeogeographical profiles and, in keeping with the theme of this IGCP project, suggestions are made regarding likely modern analogues for the palaeotectonic scenarios leading up to these separate orogenic events.

2. Caledonian tectonic events

Until the late 1960s, only one major fold-and-thrust event of orogenic proportions had been recognised in the Scandinavian Caledonides. Culminating in Silurian to earliest Devonian time in extensive, syn- to post-metamorphic, southeastward thrusting of diverse rock complexes onto autochthonous, foreland sedimentary successions, this deformation pattern was generally regarded as a simple mirror image of the situation described from the Caledonides of East Greenland and from parts of NW Britain and Ireland. At that time, too, Cambro–Silurian sedimentation and volcanism was viewed in terms of the old 'geosyncline' concept, though with partitions into mio- and eugeosynclinal belts. However, within the Early Palaeozoic lithostratigraphic record in different areas, some major hiatuses, with or without evidence of folding, had been recognised and referred to as diastrophic 'disturbances' (Holtedahl, 1920; Vogt, 1936). The true significance of these several 'disturbances', or stratigraphic breaks, came later through detailed fieldwork, structural investigations and isotopic studies, and through the careful mapping of first-order unconformities (Sturt and Ramsay, 1999). Today, we recognise some four or five major orogenic or tectonothermal phases/events in Norway within the Caledonian orogen, sensu lato, and, in addition, there is an important late episode of extensional collapse associated, in part, with orogen-parallel sinistral shear.

In identifying these events and their currently accepted timing in type areas, it should not be forgotten that geological processes are diachronous. Thus, juxtaposed thrust sheets may, for example, derive from different parts of one and the same terrane but show subtle differences in their tectonothermal histories and, conversely, the later stages of one particular tectonometamorphic event in one terrane may overlap in time with the early phase of a younger deformation cycle in a contiguous terrane. Moreover, as particular nappe complexes may be traced laterally over several hundred kilometres, specific, high-grade metamorphic phases may ultimately be found to vary in age along strike. Thus, taking Iapetus and its margins as a whole, with its unknown number of island arcs, deformation was inevitably occurring somewhere at any one moment in Caledonian time.

2.1. Finnmarkian event

With the advent and increased application of isotopic dating methods, this led to the realisation that at least one metamorphic event older than the terminal Silurian, main Caledonian, or *Scandian* (Gee, 1975), could be recognised within at least some of the nappes. Indications of a tectonothermal event in northern Norway in Late Cambrian–earliest Ordovician time, then based on K–Ar and Rb–Sr dates, gave birth to the term *Finnmarkian* (Sturt et al., 1978). Although a term dogged by some controversy (e.g., Krill and Zwaan, 1987; Binns, 1989), more precise $^{40}Ar–^{39}Ar$ and Sm–Nd dating from different areas (Dallmeyer, 1988; Dallmeyer et al., 1988, 1991; Mørk et al., 1988) subsequently confirmed this important orogenic phase. Peaking in eclogite facies at around 505 Ma (Mørk et al., 1988; Dallmeyer et al., 1991; Essex et al., 1997), the Finnmarkian event involved the outermost Baltoscandian margin—the continent–ocean transition zone—comprising the basal Upper Allochthon, Seve–Kalak superterrane (Andréasson et al., 1998) and also parts of the Middle Allochthon. This Early Caledonian, Finnmarkian event is believed to have resulted from collision of the Baltoscandian margin with an inferred magmatic arc, above a seaward-facing subduction zone (Dallmeyer and Gee, 1986; Sturt and Roberts, 1991) (Fig. 2). The magmatic arc may have been largely oceanic, positioned in the Ægir Sea (northeastern Iapetus Ocean) between Baltica and Siberia (Torsvik and Rehnström, 2001; Hartz and Torsvik, 2002) (Fig. 3a), or partly developed on a microcontinental block that had earlier rifted away from Baltica (Gayer et al., 1987). The effects of the Finnmarkian event appear to

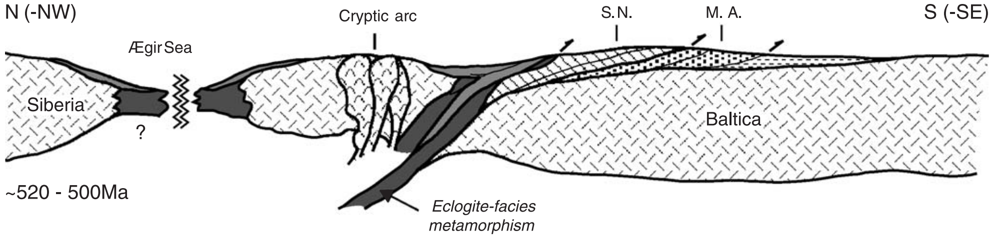


Fig. 2. Schematic, composite profile illustrating the *Finnmarkian* accretionary event, in Late Cambrian time, ca. 520–500 Ma. The profile relates to the northernmost parts of Norway and part of Sweden, roughly northeast of Lyngen in Fig. 1. Oceanward subduction of the continental margin/ocean transition zone down to at least eclogite-facies depths was followed by rapid exhumation and emplacement of Finnmarkian nappes onto the Baltoscandian margin. Baltica is considered to have faced Siberia at this time, across the Ægir Sea (Torsvik and Rehnström, 2001). A microcontinental block (rifted off Baltica) has been inferred to have been involved—the 'Barents microcontinent' of Gayer et al. (1987). See main text for further explanation. S.N.—Seve Nappes; M.A.—Middle Allochthon.

diminish gradually on moving south along the Baltoscandian margin. This may relate to a petering out of subduction, or its termination at a palaeotransform zone, or either tectonic excision or overprinting by pervasive Scandian structures. However, there is also evidence from, e.g., hornblende cooling ages that tectonothermal activity along the Baltoscandian margin during the Ordovician period was polyphasal, including a likely event in Mid Ordovician time (Dallmeyer et al., 1985, 1991). The pre-Scandian, accretionary history along this margin of Baltica may thus be far more complex than hitherto envisaged.

It is important here to note that, in addition to the Finnmarkian, there is now evidence, in northern Norway, of a thermotectonic event, or events, in Neoproterozoic (Late Riphean) time (Aitcheson et al., 1989; Daly et al., 1991; Reginiussen et al., 1995). Although strictly *pre-Caledonian*, this particular event (provisionally termed the 'Porsanger event', Daly et al., 1991, but now changed to 'Sørøyan', Roberts and Robins, in press) is represented by structures which, for a long time, were regarded as Finnmarkian. This Porsanger event involved the development of foliations and folds in the Kalak miogeoclinal prism and, in some of the earlier members of the extensive, ultramafic to alkaline, Seiland Igneous Province (Robins and Gardner, 1975; Bennett et al., 1986; Robins, 2000). Interpretation of the significance of these earlier structures is currently hampered by insufficient and imprecise data, but some local foliations may relate to major extensional shear zones developed in the general transtensional regime that facilitated emplacement of the plutonic and hypabyssal rocks of the Seiland Igneous Province (Reginiussen et al., 1995).

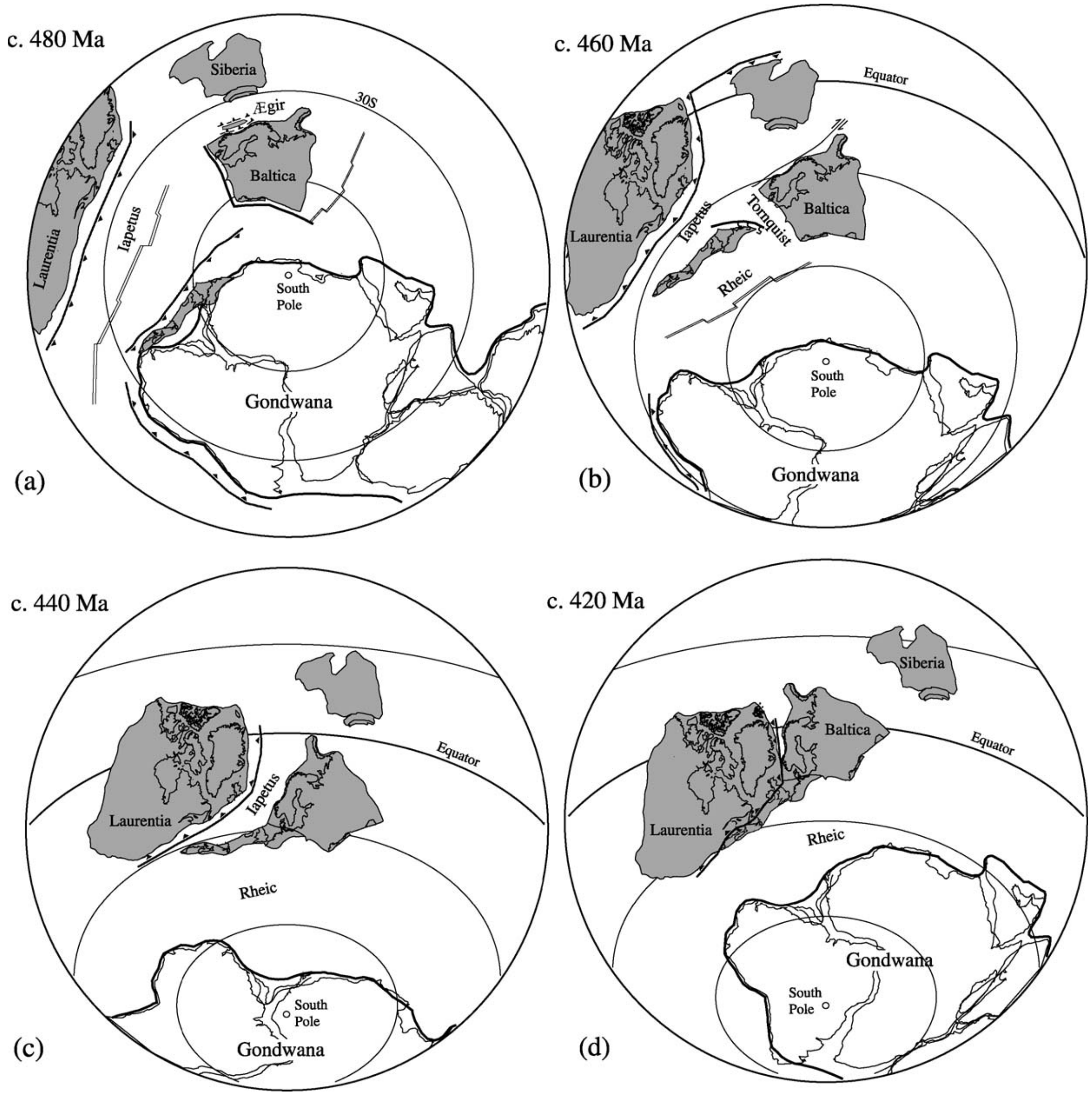
2.2. Trondheim event

In central Norway, another orogenic phase, recognised in parts of the Köli Nappes of the Upper Allochthon, is that of the *Trondheim* event, earlier introduced as the 'Trondheim disturbance' by Holte-

Fig. 3. Simplified palaeomagnetic reconstructions from Early Ordovician to Late Silurian time, with emphasis on the gradually changing positions and interaction between Baltica, Siberia and Laurentia. For simplicity, all peri-Gondwanan terranes, with exception of Avalonia, are omitted. The reconstructions are based on Torsvik (1998), Torsvik et al. (1996) and Cocks and Torsvik (2002) with small modifications by the present author. (a) Approximate situation in latest Tremadoc/Early Arenig time, broadly coeval with the *Trondheim* event (c. 480–475 Ma). This followed the earlier, oceanward subduction of Baltica that led to the *Finnmarkian* event (c. 505 Ma). The Baltoscandian margin of Baltica faced Siberia at this time, but Baltica was rotating anticlockwise. The elongate 'Gula microcontinent' offshore Baltica (eastern Iapetus/Ægir Sea) is indicated in the schematic profile (Fig. 4). (b) Situation at around the Llanvirn–Caradoc boundary (Mid to Late Ordovician boundary), roughly at the time of the peak *Taconian* event along the margin of Laurentia (but not E. Greenland) (cf. Fig. 5). Baltica has continued its anticlockwise rotation and drifted into more southerly latitudes, and Avalonia is approaching the SW margin of Baltica from higher latitudes, across a narrowing Tornquist Sea. (c) Early Silurian (Early Llandovery) situation with Baltica approaching Laurentia across a rapidly closing Iapetus Ocean. Avalonia has docked with SW Baltica by this time. (d) Situation in Late Silurian time during the Baltica/Laurentia *Scandian* continent–continent collision (cf. Fig. 6). Relative motions of the two continental plates produced a major component of sinistral shear that is recorded in most parts of the Caledonian–Appalachian orogen.

dahl (1920). Although this has subsequently been broadly correlated with the Finnmarkian, the palaeogeographical and terrane scenarios for the events, as well as their timing, are different (cf. Gee, 1986). The *Trondheim* event marks a principal phase of deformation and metamorphism, including ophiolite obduction, and blueschist metamorphic parageneses have recently been described from the basal parts of one of the fragmented ophiolites (Eide and Lardeaux, 2002). Plagiogranite dykes and sheets in some of these suprasubduction-zone ophiolites have yielded U–Pb zircon ages in the range c. 493–482 Ma (Dunning, 1987; Dunning, personal communication; in Sturt and Roberts, 1991; Roberts et al., 2002b).

The ophiolitic assemblages in these western parts of central Norway are considered to have been obducted



upon epicontinental rocks of the Gula Complex (representing an inferred microcontinental fragment rifted off Baltica) following oceanward subduction (Figs. 3a and 4). In the unconformably overlying Hovin Group rocks in the Støren Nappe, the oldest fossils are of Mid to Late Arenig age, thus constraining the obduction/metamorphic event to Early Arenig. In this particular nappe, the Early Ordovician faunas are mostly Laurentian in northwestern areas, partly deriving from peri-insular locations within Iapetus (Bruton and Bockelie, 1980; Neuman and Bruton, 1989), but uncommon species of Baltican aspect are recorded in the southeast (Spjeldnæs, 1985). Furthermore, in the basal parts of the Meråker Nappe, just above and east of the Gula Complex, black phyllites of Tremadoc age carry Baltoscandian geochemical signatures (Andersson et al., 1985). The general dominance of Laurentian faunas in the Støren Nappe, however, has tended to favour models in which the ophiolites are inferred to have been generated in a peri-Laurentian situation (e.g., Stephens and Gee, 1985; Grenne and Roberts, 1998; Grenne et al., 1999). More detailed mapping is clearly required, in an effort to separate the different faunal domains, before agreement can be reached on tectonic models for this region.

At the time of the Trondheim event, in the Early Arenig, some 25 million years after the Finnmarkian, Baltica had already started to rotate anticlockwise away from Siberia (Torsvik et al., 1996; Torsvik and Rehnström, 2001), slowly approaching Laurentia in a gradually contracting Iapetus seaway increasingly dominated by Laurentian faunal influx. This would partly help to explain the incursion of Laurentian faunas in the Early Ordovician rocks of the marginal basin and arc that developed shortly after ophiolite obduction (Roberts et al., 1984), in a scenario that is inferred to have involved a subduction polarity reversal, with volcanic arc detritus entering the basin from a northwesterly source and mainly continental material coming in from the southeast.

2.3. Taconian event

A tectonothermal event of increasing significance in terms of Scandinavian Caledonide evolution is that of a Mid to Late Ordovician, *Taconian*-equivalent phase. Evidence for this is largely confined to the Uppermost Allochthon, but also to some of the very highest and most outboard Köli terranes, and was first recognised on the island of Smøla, central Norway (Roberts, 1980). There, Arenig–Llanvirn sedimentary rocks, including shelf limestones with faunas similar to those at Durness, north Scotland (Bruton and Bockelie, 1979), were deformed and weakly metamorphosed prior to intrusion by evolved-arc plutons of the Late Ordovician–earliest Silurian, Smøla–Hitra batholith (Gautneb and Roberts, 1989; Nordgulen et al., 1995). Indications of a probable Mid Ordovician tectonothermal event have also been reported from southern parts of the Uppermost Allochthon (e.g., Nordgulen et al., 1993; Sturt and Ramsay, 1994), where comparable Late Ordovician–Early Silurian plutons cut earlier mylonitic foliations. In this same general area, there is isotopic dating evidence for even earlier magmatism and migmatisation, in late Early to Mid Ordovician time (Nordgulen et al., 1993; Pedersen et al., 1999; Yoshinobu et al., 2002).

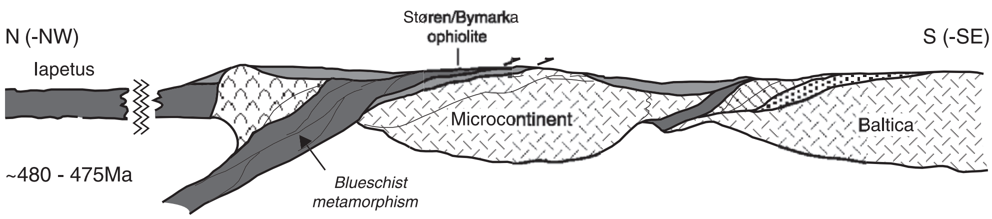


Fig. 4. Schematic, composite profile illustrating the *Trondheim* event, in latest Tremadoc to Early Arenig time, c. 480–475 Ma. The profile relates to the Trondheim region of Mid Norway in Fig. 1. Again, oceanward subduction is inferred, down to at least blueschist-forming depths (Eide and Lardeaux, 2002), prior to or partly coeval with Early to Mid Arenig, ophiolite obduction onto the mainly epicontinental Köli Nappe rocks (Gula complex) covering the 'Gula microcontinent'. The earlier, Finnmarkian-accreted, magmato-sedimentary complexes (Seve/Kalak Nappes, etc.) are shown farther S-SE, draping the margin of Baltica. By this time, Baltica had started to rotate anticlockwise, eventually to face Laurentia, across the Iapetus Ocean. See text for details.

Farther south, detailed work on the fragmented ophiolites and arc-related assemblages in the Karmøy–Bergen district of southwest Norway (Dunning and Pedersen, 1988; Pedersen et al., 1988, 1992; Pedersen and Furnes, 1991) has shown that accretion of these complexes occurred onto a continental margin at around 470–465 Ma. These authors were also convinced that the obduction and associated deformation occurred along the margin of Laurentia and, in one paper (Pedersen et al., 1988), suggested that this happened during the Taconian orogeny. Fossiliferous Late Ordovician to Early Silurian cover sequences draping the deformed ophiolite fragments, and related to subduction flip, have been described by Thon (1985).

In recent years, important evidence bearing on the ancestry of the rocks and earliest structures present in the Uppermost Allochthon have come from sedimentological, isotope-geochemical and structural studies on the thick, barren metalimestones and marbles that occur over strike lengths of several hundred kilometres in the higher nappes of north–central Norway. These shelf and shelf-edge, carbonate rocks and breccias have provided apparent depositional ages ranging from latest Riphean to Mid Cambrian (Melezhik et al., 2000, 2002). In one nappe, at Fauske (Fig. 1), the Cambrian palaeobasin clearly deepened to the southeast away from the carbonate shelf edge, and the earliest internal thrusts and folds are NW-vergent (Roberts et al., 2001), an overall situation which is very reminiscent of the Taconian in the Appalachians of eastern Canada and the USA (St. Julien and Hubert, 1975; Stanley and Ratcliffe, 1985; Roberts et al., 2002a) (Fig. 5). Furthermore, the early thrusts and folds are overprinted by SE-vergent folds, cleavages and minor thrusts, which clearly relate to the later Scandian event. On this basis, the shelf and adjacent slope/rise successions and magmatic arc complexes are now considered to have been incorporated into the Taconian accretionary wedge on the margin of Laurentia (Fig. 3b), following oceanward subduction, and later detached from Laurentia and emplaced high in the Scandinavian Caledonide tectonostratigraphy during Scandian, Baltica–Laurentia collision (Fig. 6). In a wider Caledonian context, the Mid Ordovician Taconian event is broadly time-equivalent to the *Grampian*, arc-accretion, orogenic phase of northern Britain and Ireland (Soper et al., 1999).

Although the geochronological database supportive of Taconian deformation in rocks of the Uppermost Allochthon is so far sparse, there is growing isotopic dating evidence, in conjunction with the chemostratigraphic and structural constraints, of a Mid to early Late Ordovician metamorphism (Dallmeyer and Andresen, 1992; Nordgulen et al., 1993; Selbekk et al., 2000; Yoshinobu et al., 2002) and likely ophiolite obduction (Lyngen ophiolite; Oliver and Krogh, 1995). Metamorphism locally reached eclogite facies and one of the eclogites has now yielded a Caradoc metamorphic age (F. Corfu, 2001, personal communication), a high-pressure event that was followed by rapid exhumation. Evidence favouring a Mid Ordovician, Taconian-related, medium/high-grade tectonothermal event has also been reported from the highest part of the Upper Allochthon in an area in northern Sweden (Stephens et al., 1993). Farther south, in the Trondheim region of central Norway, also in the Upper Allochthon, a stratigraphic hiatus and unconformity in Caradoc time has been termed the ‘Ekne disturbance’ (Vogt, 1936). Gentle folding in post-Llanvirn/pre-Mid Cara-

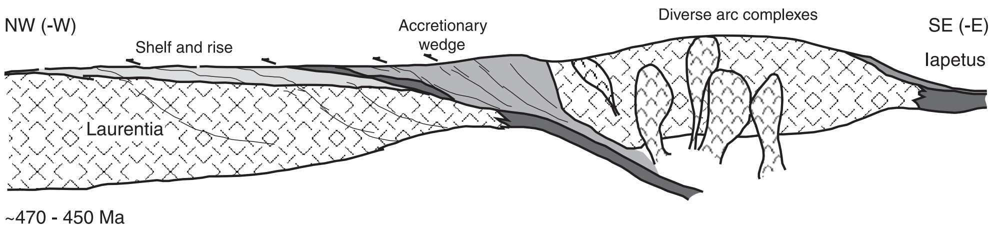


Fig. 5. Schematic, composite profile showing the palaeotectonic situation during the *Taconian* event, in Mid to Late Ordovician (Llanvirn to Caradoc) time, c. 470–450 Ma. In this case, subduction and accretion, including eclogite generation and ophiolite obduction, occurred along the continental margin of Laurentia, quite remote from Baltica. Parts of these Laurentian shelf-and-rise and peri-Laurentian arc-complex terranes were later detached and retransported onto the nappes carpeting the Baltoscandian margin of Baltica during the *Scandian* collisional event (see Fig. 6).

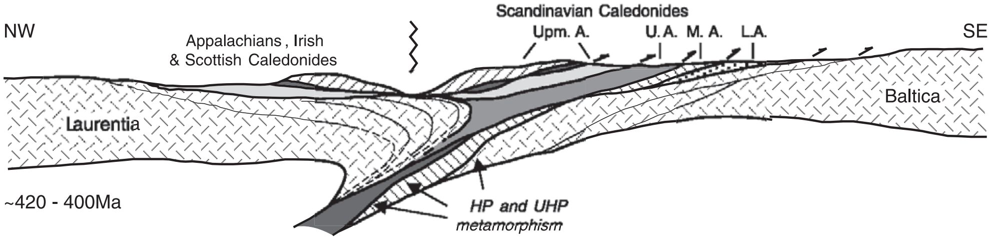


Fig. 6. Schematic, composite profile illustrating the major *Scandian,* Baltica–Laurentia collisional event, in Mid Silurian to Early Devonian time, c. 420–400 Ma. Subduction of the Baltican margin and overlying volcanosedimentary assemblages and earlier nappes beneath the Laurentian plate is generally inferred. During rapid exhumation, numerous thrust sheets were emplaced onto Baltica and partly above earlier nappes. Some Taconian-deformed terranes were uprooted from Laurentia and emplaced into the higher levels of the Scandian orogenic wedge, where they now form parts of the Uppermost Allochthon. L.A., M.A., U.A. and Upm.A.—Lower, Middle, Upper and Uppermost Allochthons, respectively.

doc time has also been recorded in one area (Ryan et al., 1980). This weak diastrophic event was considered by Vogt (1936) as a distant reflection of the Taconian orogenesis in easternmost North America; yet it may also conceivably relate, in some way, to events recorded along the Baltoscandian margin (cf. Dallmeyer et al., 1985).

An upper constraint on this Taconian event in northern parts of the Uppermost Allochthon is provided by faunas of latest Ordovician–Early Silurian age in a successor basin that accumulated material derived partly from erosion of the deformed and inverted Lyngen ophiolite (Bjørlykke and Olaussen, 1981) and also from an unknown arc source (Minsaas and Sturt, 1985), which may have been an arc outboard of Laurentia. These low-grade metasedimentary and metavolcanic rocks were later deformed during the Scandian orogeny. This general development bears many similarities with the situation in the Karmøy district of southwest Norway.

2.4. Scandian event

The principal, evorogenic, tectonometamorphic event that gave rise to the characteristic distribution of Caledonide allochthons in Norway and Sweden has been designated the *Scandian* (Gee, 1975). This orogenesis is generally seen as a product of oblique collision between the plates Baltica and Laurentia in Late Silurian to Early Devonian time, involving a subduction of the Baltoscandian margin of Baltica beneath Laurentia (Figs. 3 and 6). Biostratigraphic and geochronological evidence from different areas and, in particular, from different thrust sheets has shown clearly that the timing of the Scandian event varies widely, both transversely and laterally. As our geochronological database has expanded, so has our realisation that any long-range correlation of orogenic events should be avoided, in view of a natural diachroneity arising from the obliquity of collision between arcs, plate promontories or microcontinental blocks. Also, evidence from monazite geochronology from UHP rocks in the Western Gneiss Region has shown that both subduction (to depths of c.125 km), at 407 Ma, and exhumation were very fast processes (Terry et al., 2000), thus showing that Scandian tectonometamorphism, in any one place, was an event of comparatively short duration, perhaps less than 10 million years. Similar, rapid subduction, to eclogite–facies depths, and fast exhumation has been described from the western and central Alps (Gebauer, 1999; Rubatto and Hermann, 2001) and central Rhodope, northern Greece (Liati and Gebauer, 1999).

All the principal allochthons (Fig. 1) were involved in the Scandian orogenesis to greater or lesser extents, including those affected by the earlier Finnmarkian, Trondheim or Taconian tectonothermal events. In Fig. 6, the Uppermost Allochthon is shown to be detached from its Laurentian roots and retransported to lie upon the suspect, Iapetan terranes of the Upper Allochthon, above the Baltoscandian margin; effectively forming Laurentia-derived Taconian outliers now perched upon a foreign plate.

Recent finds of high-pressure and ultrahigh-pressure eclogites in Northeast Greenland have led to speculations that crustal thrust-imbrication and thickening may have been involved in Scandian collision, rather than the generally accepted mechanism of continental subduction (Elvevold and Gilotti, 2000; Ryan, 2001; Gilotti and Ravna, 2002). Precise dates for the eclogite–facies metamorphism in NE Greenland are required in order to determine the validity of these ideas. If the Greenland and Norwegian eclogites are of different ages, then separate subductions may be inferred. In Norway, as the thin-skinned Caledonide tectonics also involve Laurentia-derived thrust-sheets at higher levels, then this basic structural asymmetry between the Greenland and Scandinavian Caledonides would tend to favour the long-accepted scenario of a Baltican plate subducting westward beneath Laurentia.

2.5. Late- to post-Scandian events

An important element in the Scandian story is that of late-stage extensional deformation, partly arising from gravitational collapse of the orogen (Roberts, 1983; Andersen, 1998). This involved major, low-angle, ductile detachments relating to top-W to -SW shear and Early to Mid Devonian basinal sedimentation (Hossack, 1984; Norton, 1987; Séranne, 1992; Fossen and Dunlap, 1998; Osmundsen et al., 1998, 2003; Braathen et al., 2000) (Fig. 7), and linked, ductile, sinistral shear along vertical faults (Grønlie and Roberts, 1989; Grønlie et al., 1991; Robinson, 1995; Watts, 2001), especially in western and central

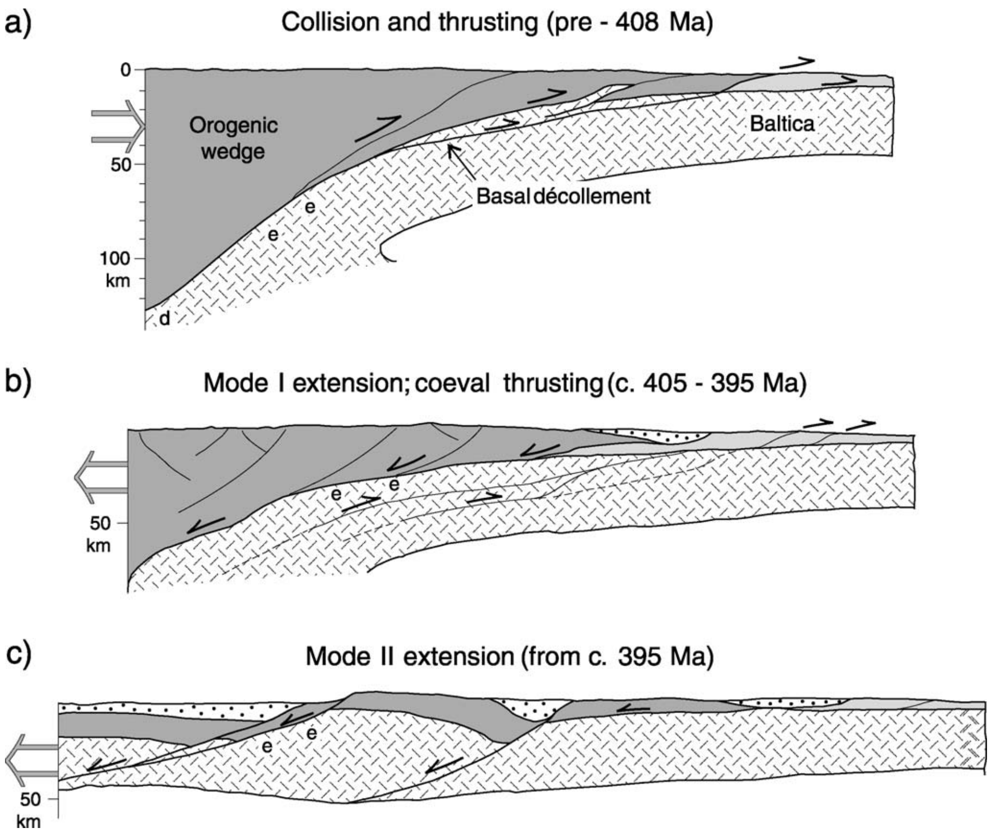


Fig. 7. Simplified, c. WNW-ESE profiles depicting contractional and extensional development of the southern Scandinavian Caledonides; based on Fossen (2000) and Fossen and Dunlap (1998), with modifications. (a) Scandian continent–continent collisional stage. e—eclogite formation; d—microdiamond formation. (b) Stage of initial orogenic collapse and backsliding (Mode I extension of Fossen), with coeval Devonian molasse sedimentation (dotted ornament) and contractional deformation at depth and farther east in the platformal domain (see also Terry et al., 2000). (c) Main crustal collapse stage with prominent, steeper down-W shear zones cutting earlier, extensional detachments and with continuing Devonian deposition (Mode II extension of Fossen). Some minor contraction persisted in the extreme eastern parts of the foreland domain. This phase of extension continued into Late Devonian and even possibly Early Carboniferous time.

Norway. This early phase of extension was partly coeval with ongoing convergent deformation at lower crustal levels and at the surface in the foreland (Fig. 7) (Fossen and Dallmeyer, 1998; Fossen and Dunlap, 1998). It was succeeded by late- or post-Scandian components of lower grade, brittle reactivation and NE-SW to E-W trending open folding of possible Late Devonian to Carboniferous age. This folding event, termed the *Solundian* phase by Sturt (1983), is perceived by Krabbendam and Dewey (1998) to relate to sinistral transtensional deformation.

Summing up, the sequence of major tectonothermal phases recognised in the Scandinavian Caledonides today involved, firstly, three discrete, arc–continent collisional or accretionary events spanning some 50 million years of Late Cambrian to Mid/Late Ordovician time. These events were followed by the Scandian, Baltica–Laurentia, continent–continent, oblique collision with rapid subduction and exhumation, major nappe emplacement, crustal overthickening and the gradual imposition of an extensional and sinistral shear regime. Sinistral strike-slip movement is also a hallmark of the Late Caledonian deformation history of the British and Irish Caledonides (Soper and Hutton, 1984; Soper et al., 1992; Stewart et al., 1997, 2001) and Canadian and New England Appalachians (Blewitt and Pickering, 1985; Currie and Piasecki, 1989; Goldstein, 1989), and is also recorded widely in East Greenland (Holdsworth and Strachan, 1991; Larsen and Bengaard, 1991; Strachan et al., 1992), pointing to significant relative plate motion in a left-lateral sense immediately following the suturing of Baltica and Laurentia.

3. Likely modern analogues

Tracing the sequence of events that culminated in the present distribution of allochthonous terranes and their diverse magmatosedimentary assemblages in the Caledonide orogen of Scandinavia is fraught with countless difficulties. Apart from the accepted imperfection of the stratigraphic and faunal record over an interval of more than 300 million years of time, the periodic destruction of that record in the accretionary or transpressive events outlined above has left us with just scattered shreads of evidence for the detective work of trying to piece together the evolving orogen. By comparison, unravelling the stages of development of a younger orogen such as, for example, the Alpine, holds far greater chances of success. Nevertheless, over the last 30 years, detailed fieldwork and geochemical and geochronological studies in Norway and Sweden have, in fact, led to many advances and to reinterpretations in terms of plate tectonic modelling and tentative comparisons with modern analogues.

The early stages of development of the Caledonide orogen in Scandinavia involved extension, rifting and plate separation during Neoproterozoic break-up of the postulated megacontinent Rodinia, followed by formation of a major ocean, Iapetus, which began to contract in Late Cambrian time. Evidence for the initial stage of crustal extension comes from the thick, Riphean to Vendian, mostly psammitic successions of the Seve–Kalak superterrane and subjacent Middle Allochthon in northern and central areas (Andréasson et al., 1998), and the Hedmark Basin in the south (Kumpulainen and Nystuen, 1985). These successions constitute the miogeocline or continental rise prism of the developing Baltoscandian passive margin of Baltica (Roberts and Gale, 1978), including the continent–ocean transition zone (Andréasson, 1994), and have generally been compared to the Atlantic-type passive margins of today. In the north, Riphean extension or transtension allowed periodic emplacement of plutons of the Seiland Igneous Province, perhaps plume or hot-spot related (cf. Andréasson et al., 1998), or even situated at or close to a triple junction (Siedlecka, 1975; Roberts and Gale, 1978) by Vendian–Cambrian time when alkaline rocks and carbonatites were emplaced. Rifting, as reflected by mafic dyke intrusion, began in the Late Riphean and culminated in the emplacement of dyke swarms in Vendian time (Solyom et al., 1979, 1992; Roberts, 1990; Andréasson, 1994; Stølen, 1994; Svenningsen, 1994, 2001) prior to actual Iapetus (or Ægir Sea) opening in the Late Vendian. The geochemistry of dykes in two separate thrust sheets, marking the initiation of Iapetus (Ægir) sea-floor spreading, has also allowed analogies to be made with Early Tertiary dykes and lavas of the Vøring Plateau (Roberts, 1990) and of a dyke swarm of similar age in East Greenland (Svenningsen, 1996), that coincide with the early stages of opening of the present North Atlantic.

By comparison with this well preserved, passive margin assemblage, remains of the ocean floor of

Iapetus (or the Ægir Sea) are restricted to fragmented and dismembered ophiolites caught up in the many thrust sheets of the oceanic terranes of the Upper Allochthon. Recognition that many of the scattered mafic igneous complexes in central Norway traditionally called 'greenstones' actually represent ophiolitic ocean floor or island arc products came through the geochemical and field studies of Gale and Roberts (1972, 1974). In identifying low-K tholeiitic arc material, ocean floor basalts and, in one area, ocean island volcanites, these authors appealed to the convergent, west and southwest Pacific Ocean scenario as a modern analogue for their arc–trench and subduction model, with an Ordovician volcanosedimentary succession developing in a Japan Sea-type back-arc basin. As more geochemical and field data on the Norwegian 'greenstones' came to light, it became even clearer that the complexities were reminiscent of the fascinating interplay of arc, fore-arc, back-arc and rifted arc developments, with intervening and rotating microcontinental plates, that we see in the SW Pacific region today. It was also evident that geochemical data from certain mafic or bimodal, Cambro–Ordovician volcanite formations were surprisingly similar to those of Tertiary or Recent lavas from, e.g., the Parece Vela Basin or the Sunda Arc (Roberts, 1982; Pedersen and Furnes, 1991). At the same time, however, the presence of more evolved, calc-alkaline, high-K rhyolites and also shoshonitic porphyrites of Mid Ordovician age pointed to a continental margin origin following a reversal in subduction polarity (Roberts, 1988; Grenne and Roberts, 1998) after the Trondheim orogenic event. The presence of boninites in the Karmøy ophiolite of SW Norway suggested to Pedersen and Hertogen (1990) analogies with the Marianas fore-arc system of the SW Pacific Ocean. Younger, Late Ordovician, marginal-basin type ophiolites in Norway have been compared to an Andaman Sea situation (Furnes et al., 1990), and also with the system of basins in the area of the Bransfield Strait, between Antarctica and South America (Pedersen et al., 1991).

Since the time of discovery of ophiolites, arcs and intervening basins in Norway, and also partly in Sweden, a plethora of tectonic models have attempted to portray suggested subduction, arc development and ultimate obduction. Although the Scandinavian Caledonides are quite well exposed, the intense polyphase deformation and high-grade metamorphism, and later extensional dissection of the nappe pile, present a level of complexity that is a hindrance to complete analysis. Another negative side is the comparative dearth of precise isotopic dates in critical areas or successions and the virtual lack of mineral provenance studies. Thus, suggested subduction polarities will inevitably be less well constrained than in the case of younger mountain belts.

In the British sector of the Caledonide orogen, attempts have also been made to present modern analogues to help support the interpretations of certain regions or terranes and, not surprisingly perhaps, the west and southwest Pacific region has proved to be a favourite (Mitchell and McKerrow, 1975; Leggett, 1987; Van Staal et al., 1998). In the British and Irish Caledonides, as well as in the Appalachians of Maritime Canada and New England, a feature of terranes is their near-linearity over long distances, a result of many processes but not least the strains imposed by the climactic terminal collision and sinistral strike-slip shear motions (Van Staal et al., 1998). This is also the case in Scandinavia, but there the degree of multiphase deformation is even more advanced, such that one can hardly expect to unravel the full range of complexities that have accumulated through time from the Vendian to the Devonian. The present-day architecture of the SW Pacific, especially the Indonesian region, with its many single and aggregated arcs, subduction complexes, accretionary prisms and continental fragments, as well as variable azimuths and velocities of plate and microplate motion, is extraordinarily intricate. It is not unlikely that large parts of the Iapetus Ocean and Ægir Sea were characterised by similar levels of geometric complexity—a complexity ultimately ironed out in the Scandinavian domain by progressive arc–arc or arc–continent accretions and final continent–continent collision.

As pointed out first by Hamilton (1979), should the Australian plate continue to approach Asia at its present velocity of ca. 10 cm/year and assuming a stability of other plate motions, then projecting this convergence forward in time over some 30–50 million years would eventually see the Indonesian and Philippine land masses—island arcs and continental fragments—crushed between the obliquely converging Eurasian and Australian plates. This scenario has been taken further and elaborated upon quite elegantly by Van

Staal et al. (1998). In their model, covering the future 45 million years, the result is a broad zone of lensoid, semi-linear terranes that are exotic in relation to the adjacent cratonic plates and, to each other, located within a sinistral, oblique-convergent system. The details of this exercise, and of the ultimate map pattern, are fascinating but outside the topic of this contribution. However, the end product of this oblique convergence bears many similarities to the principal features of the Caledonide geology and tectonics of Scandinavia.

4. Summary

The Caledonian orogen in Scandinavia has been divided into a series of major allochthons, with parautochthonous and autochthonous units in the foreland to the east, along the Baltoscandian margin of the palaeocontinent Baltica. Platform and shelf successions characterise the thin foreland units and Lower Allochthon, while the Middle and basal Upper Allochthon levels comprise the thick, late Neoproterozoic, mafic dyke-intruded, continental rise accumulations of this ancient passive margin. Outboard of these are the diverse, suspect oceanic terranes of the bulk of the Upper Allochthon, and above that the more exotic carbonate shelf, slope/rise and evolved magmatic arc assemblages of Laurentian or peri-Laurentian ancestry.

The above tectonostratigraphic and palaeogeographical backcloth serves as a basis for comprehending the sequence of major, Caledonian, tectonothermal events or phases that have contributed to the present-day geometrical distribution of terranes and thrust sheets. Following a major period of Riphean–Vendian extension or transtension with incipient rifting along this Baltoscandian margin, Iapetus sea-floor spreading commenced in Mid to Late Vendian time and oceanic expansion reached a peak during the Cambrian. The first signs of contraction of the Iapetus Ocean, or Ægir Sea, are recorded by the *Finnmarkian*, continent–cryptic arc, accretionary event in Late Cambrian time, with oceanward subduction and metamorphism locally in eclogite facies. The next recognisible event, the *Trondheim* phase, involved subduction, also inferred oceanward, to blueschist-forming depths, quickly followed by ophiolite obduction in Early Arenig time. The third principal event, the *Taconian*, is recorded in the Laurentian terranes of the Uppermost Allochthon and some of the highest segments of the Upper Allochthon, notably in southwest Norway. This was an arc accretion event in amphibolite to locally eclogite facies, also involving some ophiolite obduction, that occurred along the Laurentian margin in Mid to earliest Late Ordovician (Llanvirn–Caradoc) time. Thereafter, followed the oblique convergence and ultimate collision between Baltica and Laurentia yielding the *Scandian* orogeny, involving inferred subduction of the Baltican margin to UHP depths exceeding 100 km. Both subduction and exhumation occurred very rapidly, in Late Silurian–Early Devonian time. Following and in part coeval with this major thrusting event was an important phase, or phases, of extensional deformation and sinistral, transpressive shear, with upright folding in some areas.

Aided by geochemical and detailed field studies, recognition of the likely genetic affinities of many of the mafic igneous complexes and bimodal volcanic formations occurring in the nappes has allowed comparisons to be made with similar ocean floor, marginal basin and magmatic arc complexes reported from modern convergent margins in different parts of the world. It was soon apparent that many features of the Scandinavian Caledonide, suspect oceanic terranes could be recognised in different parts of the southwest and west Pacific Ocean region, and many authors have suggested analogies with specific arc–trench–basinal systems within this extensive region. Moreover, models predicting the likely, future scenario arising from oblique collision between the Australian and Eurasian plates depict a resultant sinistral, oblique-convergent system of semi-linear terrane slices, which bears many similarities to the Caledonide geology and tectonics of Scandinavia.

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Appendix A. Addendum

After completion of the manuscript, news filtered through of reported Sm–Nd ages from eclogite, garnet pyroxenite and garnet peridotite from the Seve Nappe in Jämtland, central Sweden, that cluster around 455 Ma (Brueckner and van Roermund, 2001, abstract, 6th Int. Eclogite Conference; H.L.M. van Roermund, 2002, personal communication). This appears to provide further evidence of another HP orogenic event along the Baltoscandian margin and one that is interpreted by the above authors as possibly involving collision with a microcontinental fragment just outboard of Baltica. Although this Early Caradoc age is comparable to that reported from an eclogite in the Uppermost Allochthon (F. Corfu, 2001, personal communication), the latter relates to Taconian deformation along the margin of Laurentia, whereas the Jämtland eclogite–facies event occurred along the edge of the Baltican plate.

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