Stratigraphy, tectonostratigraphy and the accretion of outboard terranes in the Caledonides of Sunnhordland, W. Norway

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Abstract

The Caledonides between Karmøy and Bergen in western Norway represent one of the best studied sections of the Scandinavian Caledonides, and the area is of particular significance with regard to the geological evolution of the Caledonian outboard terranes. These terranes include ophiolites of Early Ordovician age, immature to mature island-arc and arc-basin lithologies of Early to Middle Ordovician age and Late Ordovician to Early Silurian unconformable transgressive and regressive sequences. The stratigraphy, including several unconformities, as well as the tectonothermal evolution of this composite terrane, demonstrate that the assembly of the terrane was associated with deformation, metamorphism and syntectonic emplacement of arc plutons prior to the Scandian continental collision between Baltica and Laurentia. The evidence for the pre-Scandian deformation of these rocks has previously been used as an argument for the accretion of oceanic rocks to Baltica prior to the Scandian orogeny. We dispute this interpretation and conclude that the early Caledonian deformation of this terrane occurred within the Iapetus Ocean.

1. Introduction

The Caledonides in the coastal region south of Bergen (Fig. 1) have attracted considerable interest since the classical study of Reusch (1888). Reusch discovered and described most of the rare and important fossil localities of the region. A step forward in the understanding of the Scandinavian Caledonides came when major parts of the mafic igneous complexes of western Norway were recognised as ophiolite/island-arc complexes; first on the island of Karmøy (Sturt and Thon, 1978a). The work on the ophiolites and their cover sequences in the late seventies and early eighties resulted in several tectonic interpretations, concluding that ophiolitic terranes were accreted to Baltica in the Early Ordovician (Brekke et al., 1984; Sturt, 1984; Sturt et al., 1985). The initial studies on the ophiolites were succeeded by a comprehensive mapping programme, combined with detailed geochemical and petrological studies, by staff and students from the University of Bergen. An important conclusion of these studies was that the ophiolites of the region were formed in subduction-related palaeoenvironments (Pedersen et al., 1988). U/Pb dating on some of these complexes, carried out by

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Pedersen and co-workers (Dunning and Pedersen, 1988; Pedersen et al., 1988; Pedersen and Dunning, in prep.), together with the geological and paleontological data from the region, have enabled a much better understanding and timing of the processes that occurred within the outboard terranes prior to their accretion to Baltica during the Scandian orogeny (Andersen et al., 1990; Pedersen et al., 1992). Because of the similarity in age and origin of ophiolitic complexes in Scandinavia and Newfoundland, it has recently been suggested that Scandinavian ophiolite complexes of Early to Middle Ordovician age ("Group 1") were accreted to Laurentia during the Ordovician "Taconic orogeny" (Dunning and Pedersen, 1988; Pedersen and Furnes, 1991; Pedersen et al., 1991; Pedersen and Dunning, in prep.) and that they were rifted away from Laurentia by back-arc spreading and emplaced onto Baltica during the Scandian continental collision between Baltica and Laurentia.

The tectonostratigraphic succession between Karmøy and Bjørnafjorden in western Norway (Fig. 2) is the product of polyphase Caledonian shortening events, and the subsequent extensional collapse of the orogen. This paper gives an overview of the tectonostratigraphy of the southwest Norwegian Caledonides, and discusses the tectonostratigraphy in the light of the terrane models into which the nappe stack of the Scandinavian Caledonides normally is fitted (Dallmeyer and Gee, 1986; Roberts, 1988; Stephens and Gee, 1989). It further summarises the internal stratigraphic relationships of the southwest Norwegian outboard terranes and provides the basis for discussing the accretional history of the Caledonian outboard terranes in the coastal region south of Bergen (Fig. 1).

![Fig. 1. Schematic tectonostratigraphic map of southern Norway. The Jotun Nappe and its lateral equivalents along the west coast have speculatively been assigned to the Upper Allochthon as they apparently are structurally underlain by euclidean rocks.](image-url)
1.1. Tectonostratigraphy

The tectonostratigraphy of the Scandinavian Caledonides is normally divided into the following five main units as summarised by Roberts and Gee (1985):

1. The Autochthon–Parautochthon comprises the basement of the Fennoscandian Shield...
and the cover of late Proterozoic and early Palaeozoic age.

(2) The Lower Allochthon consists mainly of low-grade sedimentary sequences of late Proterozoic to early Palaeozoic age. In the upper parts of the Lower Allochthon, basement lithologies of the Fennoscandian Shield are involved in the thrust sheets.

(3) The Middle Allochthon is dominated by Precambrian gneiss complexes and thick psammitic sequences, which locally are overlain by Vendian to lower Palaeozoic metasediments.

(4) The Upper Allochthon contains the early Palaeozoic outboard terranes, including ophiolites and island-arc complexes. The Lower to Middle Ordovician fossiliferous assemblages in the upper part of this unit contain a Laurentian Toquima–Table Head fauna clearly showing its exotic relationship to Baltica (Bruton and Bockelie, 1980; Pedersen et al., 1992). The lower parts of the Upper Allochthon (the Seve Nappes and their lateral equivalents), however, also contain Precambrian gneisses, schists, amphibolites and eclogitised mafic volcanics, parts of which are believed to have constituted transitional continental–oceanic crust segments of the rifted margin of Baltica (Dallmeyer and Gee 1986; Mørk et al., 1988; Stephens and Gee, 1989; Dallmeyer et al., 1991).

(5) The Uppermost Allochthon is present only in Nordland and Troms. This unit comprises a heterogeneous complex of nappes, dominated by schists, marbles, granitoids and gneisses. It also contains ophiolitic and other ensimatic lithological associations in the Helgeland Nappe Complex. In the Tromsø Nappe, the highly sheared schists and gneisses also include mafic pods with well-preserved Caledonian eclogite facies rocks (Krogh et al., 1990).

1.2. Tectonostratigraphy and terrane analysis

In terrane analysis, the tectonostratigraphic units 1 to 3 as well as the lowermost part of unit 4 are considered to represent Baltic crust, platform, miogeocline and transitional continental–oceanic crust, respectively (Roberts, 1988; Stephens and Gee, 1989). The remaining parts of the Upper Allochthon are considered to form the vestiges of the Iapetus Ocean, while the Uppermost Allochthon represents a composite oceanic–continental terrane, for which a definite evolutionary history and origin is still very uncertain; a Laurentian origin has been suggested for the Uppermost Allochthon (Sturt et al., 1984; Dallmeyer and Gee, 1986; Stephens and Gee, 1989). In the Hardanger–Sunnhordland region, units 1 to 4 are present (Figs. 1 and 2). This tectonostratigraphy represents the main basis for the various terrane models, last summarised by Stephens and Gee (1989), for the Scandinavian Caledonides. In these models, the exotic, composite oceanic terranes have been taken to define one major level in the tectonostratigraphy that consequently may be regarded as a major complex suture zone across which the Iapetus Ocean was closed during the Scandian continental collision between Baltica and Laurentia.

In southern Norway, the interpretation of a single major suture zone must be regarded with some caution. Although poorly preserved, ophiolitic and other oceanic rock complexes occur structurally beneath the Jotun and other continental crystalline nappes that are commonly assigned to the Middle Allochthon as an imbricated part of Baltica (Roberts, 1988; Stephens and Gee, 1989). The occurrences of oceanic lithologies, including large masses of gabbros, amphibolites and serpentinised harzburgites as well as mafic volcanics at low structural levels beneath the crystalline continental crust of the Jotun Nappe along its northwestern margin (Sigmond et al., 1984; Pedersen et al., 1988), and under the Jotun-kindred rocks of the Dalsfjord Suite in Sunnfjord (Furnes et al., 1976; Swenness and Andersen, 1991), indicate that rocks normally interpreted as oceanic are present structurally beneath and above the continental crystalline masses (Fig. 1). Similarly, the dismembered Vågåmo Ophiolite near Otta in central southern Norway (Sturt et al., 1991) apparently occupies an enigmatic tectonostratigraphic position with respect to the Jotun Nappe. On the other hand, the unconformable relationships between the Jotun gneisses and “sparagmites” in the Valdres area (Milnes and Koestler, 1985), and along the north-
western side of the Jotun synform (Lutro, 1988) support a more traditional interpretation that the Precambrian rocks of the Jotun Nappe originally formed part of the Baltic Shield basement.

2. The Sunnhordland region

2.1. The Autochthon, Lower Allochthon and the status of the Middle Allochthon in central southern Norway

The Hardangervidda section (Figs. 1 and 3) preserves the autochthonous Precambrian basement and a thin autochthonous to parautochthonous fossiliferous cover of Cambrian to Ordovician (Llanvimian) age (Andresen, 1978, 1982; Andresen and Færseth, 1982). The autochthon and parautochthon arc structurally overlain by the allochthonous Holmassjø-Valen mica schists of assumed early Palaeozoic age, and the Precambrian continental crystalline massifs of the Hardanger-Ryfylke and Halsnøy Nappe complexes (Solli et al., 1978). In most of the recent geotectonic reconstructions, these units have been assigned to the Baltic continental margin and constitute the Lower and Middle allochthons in the area (Roberts and Gee, 1985; Stephens and Gee, 1989; and others). As indicated above, the interpretation (Roberts and Gee, 1985; Stephens and Gee, 1989) of the Precambrian nappes on Hardangervidda as part of the original Baltic craton is questionable because they are underlain by spatially restricted but nevertheless important volcanites and volcanioclastics that occur on central Hardangervidda (Fig. 3) (Andresen, 1982).

On central Hardangervidda, the undated pillow basalts and green tuffaceous sediments of calc-alkaline affinity (Andresen, 1982) arc found in contact with the platform sediments (Cambrian to Llanvimian) that constitute the parautoch-
thonous cover (Lower Allochthon) to the Baltic basement (Andersen, 1974, 1978, 1982). The tectonostratigraphic position of these mafic volcanites is clearly beneath the Precambrian Hardanger–Ryfylke and Jotun Nappe complexes (Figs. 2 and 3). In the Sunnfjord area, gabbros and greenschists occur structurally below the Dalsfjord Suite, within the mylonites of the Kvamshesten detachment (Swensson and Andersen, 1991). The Dalsfjord Suite is lithologically and tectonostratigraphically correlated with the Jotun Nappe (Sigmond et al., 1984). It may, therefore, be suggested that suture zones occur both above and beneath the Jotun Nappe and its lateral equivalents of the Middle Allochthon in southern Norway. These fragments of Precambrian continental crust may represent a microcontinent that, at least in parts, was separated from Baltica, presently expressed by the highly deformed and attenuated oceanic rocks that are exposed intermittently along their basal tectonic contacts. Consequently these parts of the Middle Allochthon in southern Norway may be regarded as “suspect” with respect to the Fennoscandian Shield (Andersen et al., 1991a,b; Pedersen et al., 1988, 1992). An alternative explanation may be that the ophiolitic and subduction-related volcanic rocks that occur structurally beneath the Jotun Nappe are related to large-scale out-of-sequence thrusts, or late and very large scale overturned folds of the tectonostratigraphy, which included the already obducted oceanic terranes of the Upper Allochthon. More detailed structural studies, combined with accurate dating of the “oceanic-type” lithologies that are sandwiched between the Jotun Nappe and the allochthonous Baltic basement are required before firm conclusions concerning the status of the Jotun Nappe are reached.

The nappe complexes on Hardangervidda are structurally separated from the overlying undisputed outboard sequences of the Upper Allochthon by a major thrust zone. The thrust zone has been reactivated in a large-scale extensional fold and fault system, that strikes northeast–southwest, parallel with Hardangerfjorden (Figs. 2 and 3). This large-scale composite extensional structure was identified and originally described as the “Faltungsgraben” (Figs. 2 and 3) by Goldschmidt (1912). Throughout Hardangervidda the shortening structures and the generally flat-lying nappe boundaries have been modified variably by “back-folding” and late W-vergent structures (Andersen, 1982). As far east as the Haukeldseter area on south-central Hardangervidda (Fig. 1), a pronounced extensional crenulation cleavage demonstrates that a considerable re-activation can be assigned to the extensional collapse of the orogen. Reconnaissance studies along the southeastern margin of the Jotun Nappe show that the underlying rocks in places are characterised by penetrative, top-to-the-west, extensional fabrics, which may account for the restricted occurrences of oceanic lithologies along this nappe boundary. Fabrics related to the extension are intense and locally mylonitic along the southeastern coast of Hardangerfjorden such as in the Tittelsnes area on northern Haugalandet (Fig. 2). The offshore expression of the “Faltungsgraben” has been imaged in deep-seismic reflection profiles (Hurich and Kristoffersen, 1988) as a strong, NW-dipping reflector to the base of the crust that offsets the present Moho reflectors.

On the northwestern side of the Faltungsgraben, basement and cover are overlain by highly attenuated allochthonous Precambrian rocks (Fig. 3), preserved immediately to the north of the area shown in Fig. 2 (Naterstad and Jorde, 1981; Ragnhildstveit, 1987). Little published structural data are available from these rocks, but J. Naterstad (pers. commun.) considers the lower units (Fig. 3) to represent the westward continuation of the Lower and Middle allochthonous rocks southeast of the “Faltungsgraben”.

2.2. The Upper Allochthon

The geological evolution of the oceanic terranes of the Upper Allochthon in western Norway is relatively well known. This is one of the key areas from which to unravel the geological evolution of the Iapetus Ocean from the Early Ordovician onwards in the Caledonides (Pedersen et al., 1988, 1992).
2.3. Bømlo and Stord

Of particular importance are the islands of Bømlo, Stord and Karmøy (Figs. 1 and 2), where fossils, precise U-Pb zircon ages (Dunning and Pedersen, 1988; Pedersen and Dunning, in prep.) and detailed studies of the field relationships enable refinement and revision of previous models. The geology of Karmøy has been presented in several studies (Sturt and Thon, 1978a,b; Thon, 1980; Pedersen and Hertogen, 1990) and most recently by Pedersen and Dunning (in prep.). The intrusive and stratigraphic relationships of Bømlo and Stord are summarised in Fig. 3 and by Andersen et al. (1991b).

Geochemical studies demonstrate that the formation of the ophiolitic rocks was related to the initiation of ensimatic plate convergence, as all the ophiolites originated in an arc/back-arc environment. The evolution records a long period (~495–470 Ma) when these complexes resided in an oceanic supra-subduction zone setting (Pedersen et al., 1988). With time, this produced a mature magmatic arc, but it is not clear whether it included continental crust. (Andersen and Jansen, 1987; Pedersen et al., 1988; Andersen et al., 1991b). Formation of the arc was associated with local intense deformation during emplacement of various plutons (Andersen, 1989; Andersen et al., 1991b). The regional inversion of the Lykling–Geitung ophiolite/arc complex on Bømlo described by Nordås et al. (1985), occurred prior to the deposition of the Siggjo and Kattnakken volcanites (476–473 Ma) and the intrusion of the calc-alkaline Vardafjellet Gabbro at 472 ± 2 Ma (Pedersen and Dunning, 1991).

This interpretation is at variance with previous interpretations (Brekke et al., 1984; Sturt et al., 1984; Sturt, 1984; Furnes et al., 1985), who argued that the early deformation of the ophiolites occurred during accretion to Baltica in an early Caledonian, Finnmarkian event. The U-Pb ages (Pedersen and Dunning, 1991, in prep.) from the S-type granites of the West Karmøy Igneous Complex (WKIC) (~475 Ma) intruding the Karmøy Ophiolite, and the Siggjo and Kattnakken volcanites with continentally influenced geochemistry, are still enigmatic (Brekke et al., 1984; Nordås et al., 1985). Pedersen et al. (1988) suggested that the ophiolitic rocks were accreted to Laurentia during the Middle Ordovician Taconic event. More recently, however, Pedersen and Dunning (1991) suggested that the continental signature could be a result of partial melting and contamination of subducted, continentally derived sediments and that this probably occurred in an intra-oceanic setting. U/Pb dating of zircons from WKIC demonstrates that the provenance of these rocks was an old, Archaean crust, unlike the exposed southern parts of the Baltic Shield, as there is a massive inheritance of zircons with cores of this age (Pedersen and Dunning, 1991, in prep.).

Of particular importance and significance in the eugeoclinal terranes of southwestern Norway arc the stratigraphic discontinuities, including angular unconformities, non-conformities and disconformities that have been identified (Foslie, 1955; Sturt and Thon, 1976, 1978b; Naterstad, 1976; Thon, 1980, 1985; Thon et al., 1980; Andersen et al., 1984; Brekke et al., 1984; Nordås et al., 1985; Andersen et al., 1991b). The unconformities stratigraphically below the Middle to Upper Ordovician and Lower Silurian rocks were suggested previously to represent a major stratigraphic hiatus following early Caledonian, Finnmarkian obduction of “Group I” ophiolites onto Baltica (Furnes et al., 1985). The unconformity on the ‘Group I’ ophiolites was considered to be traceable along the Scandinavian Caledonides from Lyngen in Troms, northern Norway to Karmøy (Sturt, 1984; Sturt et al., 1985; Thon, 1985).

In southwestern Norway, the pre-Ashgillian Siggjo and Kattnakken (Bømlo and Stord, Figs. 2 and 3) volcanites are unconformable on the Lykling–Geitung ophiolite/arc complex (Nordås et al., 1985). The stratigraphic relationships on Bømlo and Stord, with Middle Ordovician volcanites (476–473 Ma) overlain by Ashgillian sediments, suggested that the early Caledonian orogenetic event affecting the ophiolite and arc lithologies was of Early Ordovician age and broadly coeval with the Finnmarkian phase as originally defined in its type area (Sturt et al., 1978; Sturt 1984). An important problem in as-
signing the pre-Scandian deformation of the ophiolitic rocks to a major phase of obduction onto a continent at this time is the apparent lack of (1) continental, terrane-linking detritus in the unconformable sequences, (2) stitching plutons or (3) observations of terrane-linking, overstepping unconformable contacts in western Norway.

Recently, Sturt et al. (1991), argued that the Vågåmo ophiolite underlying the Arenigian–Llanvirnian serpentinite conglomerates of the Sel Group in the Otta area (Fig. 1) of central southern Norway was obducted onto the margin of Baltica prior to the deposition of the fossiliferous Lower–Middle Ordovician serpentinite conglomerates. They suggested that the stratigraphic relationships between the Late Precambrian (?) Heidal series, the Vågåmo ophiolite and the unconformable Arenigian–Llanvirnian Sel Group show that the ophiolite was obducted onto the Heidal series prior to the deposition of the Sel Group. The Heidal series rocks are traditionally correlated with the Vendian “sparagmites” of Baltica (Strand, 1951, 1964). The evidence that is presented in support of their tectonic model is discussed below, and alternative interpretations for major obduction-related deformation invoked by Sturt et al. (1991) may be suggested to explain the ultramafic-dominated Arenigian–Llanvirnian conglomerates described from the Sel Group.

2.4. Varaldsøy

Until recently, the stratigraphic relationships on the island of Varaldsøy in the central parts of Hardangerfjorden (Figs. 2 and 3) have not been studied since Foslie’s impressive mapping in the forties, published post-mortem; Foslie (1955, edited by Dietrichson). Although not specifically stated in this paper, Foslie’s map and petrographic descriptions clearly indicate the presence of two major stratigraphic discontinuities on the island, and this has been supported by recent mapping by the present authors and two students (Mæland, pers. commun.; Adolfsen, pers. commun.). The Varaldsøy–Ølve Complex (Figs. 2 and 3) comprises undated ophiolitic and island-arc lithologies including talc schists, a high-level gabbro/sheeted dyke complex, intrusive quartz-di-
cherts and greywackes, makes a correlation with the Late Ordovician–Early Silurian shallow-marine, transgressive sequences (see below) in western Norway unlikely. It is tentatively proposed that the Mundheim–Langevåg groups may represent a Middle Ordovician arc-basin sequence more akin to the Torvastad Group on Karmøy (see below, Figs. 2 and 3).

The unconformable Grønåt Formation on Varaldsøy (Figs. 2 and 3) was first mapped by Foslie (1955), and is preserved in a tight syncline on the central part of the island. The metasediments in this formation are dominated by mature, quartzite conglomerates, quartzites and muscovite-rich phyllites (Adolfsen, pers. commun.). The Grønåt Formation clearly has a provenance more akin to a continental margin-type source area than the dominantly mafic rocks of the underlying Ølve–Varaldsøy Complex and the Mundheim Group. Fragments of gabbro and greenstone from the substrate are found only locally. As the Grønåt Formation shares the main Caledonian compressional foliation and gneiss schist facies metamorphic assemblages with the underlying rocks, it was deposited most likely either shortly before or during the main collisional event at the time when the oceanic terranes were sufficiently close to the continent to receive coarse-grained detritus from it. The only sequence lying unconformably on ophiolitic rocks in western Norway that resembles the Grønåt Formation is the post-middle Llandoveryian shallow-marine sediments of the Vaktdal Formation in the O’s Group of the Major Bergen Arc (Ingdahl, 1989). Hence, we tentatively suggest an Early to Middle Silurian age for the Grønåt Formation.

3. Discussion

As already outlined above, a major controversy in the Caledonian geology of Scandinavia has been whether the continental margin of Baltica was affected by collisional tectonics prior to the Scandinavian orogeny. In several recent plate reconstructions outlining the development of the Iapetus Ocean, Baltica has been shown as a continent that was surrounded by passive continental margins until it collided with Laurentia in the Late Silurian (McKerrow et al., 1991; Scotese and McKerrow, 1991). On the other hand, an early Caledonian, Finnmarkian orogeny affecting the continental margin of Baltica along most of the Norwegian Caledonides have been argued by Sturt, Ramsay and co-workers (including the first author of this paper) in a number of papers since the seventies (Sturt et al., 1978, 1985, 1991; Sturt, 1984; and others). The geology in the outer Hardanger–Sunnhordland and Karmøy region has been used as an argument for an early Caledonian, Finnmarkian orogeny. In the type area in northernmost Norway, the existence of an early Caledonian, Finnmarkian phase as defined by Sturt et al. (1978) has been questioned; and much of the deformation associated with the emplacement of the Seiland Igneous Province is of Proterozoic age (Pedersen et al., 1989b; Aitcheson, 1990; Daly et al., 1991).

In the central Scandinavian Caledonides, a Late Cambrian–Early Ordovician (510–490 Ma) metamorphic event (Dallmeyer and Gee, 1986; Mørk et al., 1988) has affected rocks of the Seve Nappe in the lower part of the Upper Allochthon which are suspected to have formed parts of the outer margin of Baltica (Stephens and Gee, 1989). This orogenic event is thought to have originated by collision of an arc terrane with the rocks inferred to belong to the outer margin of Baltica (Dallmeyer and Gee, 1986). The metamorphic terrane including the eclogites in the Seve Nappe was, however, emplaced onto the Baltoscandian platform during Scandinavian thrusting (Stephens and Gee, 1989). Torsvik et al. (1991), on the basis of paleomagnetic data, suggested that pre-Scandian deformation along the margin of Baltica may have been associated with large-scale anti-clockwise rotation of Baltica in the Early to Middle Ordovician.

Brekke et al. (1984) used the stratigraphy and geochemistry of the sedimentary and volcanic rocks on Bømlo to suggest a plate-tectonic model for the southwest Norwegian Caledonides. In this model, the Lykling ophiolite and the Geitungen island arc were thought to have been accreted to Baltica in the Tremadocian–Arenigian. The Sig-
gjo, Vikafjord and Langevåg Groups which overlie the Lykling ophiolite and the Geitungen island arc were thought to record a convergent plate-margin environment related to an E-dipping subduction zone under the western margin of Baltica from the Middle Ordovician until Middle Silurian times. The model was inspired by the ideas of early Caledonian, Finnmartian Group I ophiolite accretion (Furnes et al., 1983, 1985; Sturt, 1984). The stratigraphic succession as described by Brekke et al. (1984) on Bømlo was partly based on very uncertain lithostratigraphic correlation of non-fossiliferous marbles and the limestones of Ashgillian age in the Vikafjord and Dyvikvågen groups (Fig. 3). Within the Siggjo volcanites (473 Ma) on Bømlo, an intraformational sequence of conglomerates, sandstones, phyllites and limestone/marble was regarded to be of Ashgillian age (Brekke et al., 1984). These sediments are overlain by a thick sequence of volcanics (the Eriksvatn Formation) with geochemical characteristics similar to the Siggjo volcanics. Consequently they were believed to be of Silurian age and assigned to the upper part of the Vikafjord Group (Brekke et al., 1984). Similarly, the limestones and marbles on southeastern Bømlo and Huglo (Fæserth, 1982) were thought to be of Ashgillian age. The deep-marine cherts, phyllites and metagreywackes overlying the limestone/marble sequence are in strike with the Langevåg Group on southern Bømlo. This correlation suggested a Silurian age for the Langevåg Group (Brekke et al., 1984), which is in faulted contact with the fossiliferous Ashgillian rocks of the Vikafjord Group in its type area on Bømlo (Brekke, 1983). Comparison of the lithostratigraphy and geochemistry of the Langevåg Group on Bømlo and the Torvastad Group on Karmøy (Fig. 2) shows many similarities; Pedersen and Dunning (in prep.) argue that these two units probably have a common origin in an Ordovician (~ 470 Ma) arc basin environment, but it is uncertain if older continental crust formed part of the substrate of the arc. Feldspar Pb-isotope data from the I-type granitoids in the Sunnhordland Batholith (unpublished report by Curti, 1988) show a primitive mantle isotopic-ratio composition. This suggests that an older crustal component was insignificant in the source area for the granitoid magmas that formed the Sunnhordland Batholith (Andersen and Jansen, 1987), and that contamination by old crust during ascent was minimal.

To our knowledge, no record of clastic material other than that akin to the underlying ophiolites and ensimatic arc complexes occur in the basal parts of the transgressive sequences in southwestern Norway. Only the youngest parts of these successions, including the Utslettefjell Formation (Fig. 3) deposited with an angular unconformity/ non-conformity on the fossiliferous Llandoveryian rocks and the inverted Vardafjellet Gabbro on Stord (Thon et al., 1980; Andersen et al., 1991b) and in the undated unconformable Grånut Formation (see above) on Varaldsøy, contain clastic material that are exotic (quartzites and granites) with respect to the ensimatic substrate. Similar clastic materials are also found within the Os Group of the Major Bergen Arc, where the Skarfell Formation dominated by quartz-rich sandstones and quartzite conglomerates, disconformably overlies fossiliferous Llandoveryian phyllites (Inghdahl, 1989).

In southern Norway, evidence for a pre-Silurian orogenic event affecting Jotun-type continental basement (the Dalsfjord Suite) and cover of continental margin deposits (the Høyvik Group) is documented from Atløy in Sunnfjord (Andersen and Dæhlin, 1986; Brekke and Solberg, 1987; Andersen et al., 1990). This tectono-thermal event is not dated and only a minimum age provided by the unconformable Silurian Herland Group, is available. As pointed out above, the status of the allochthonous continental crust of the Dalsfjord Suite that has been correlated with the Jotun Nappe, should be considered “suspect” with respect to Baltica as it is underlain and separated from the Western Gneiss Region by highly deformed rocks of the Kvamshesten detachment (Swenson and Andersen, 1991). Consequently, a pre-Scandian orogeny affecting undisputable Baltoscandian miogeoclone or platform has not yet been documented with certainty in this area, and the orogeny affecting the Høyvik/Dalsfjord cover/basement pair may have occurred on a “Jotun microcontinent” separated
from Baltica by the highly deformed rocks of the Askvoll group and the ophiolite/arc lithologies that occur structurally beneath the Jotun Nappe.

In the outboard terranes, the fossil-dated Ashgillian to Llandoveryian sedimentary sequences on Bømlo, Stord and Karmøy were deposited on a deformed substrate dominated by ophiolitic and island-arc supracrustals and intrusions. On Karmøy, Ashgillian sediments (Skudesneset Group; Thon, 1980) postdate S-type granites of the West Karmøy Igneous Complex, which are derived by partial melting of rocks with a continental provenance (Sturt and Thon, 1978b; Pedersen and Dunning, 1992). It is questionable whether these rocks also could be derived by partial melting of continental detritus carried down an ensimatic subduction zone as suggested by Pedersen and Dunning (1991). Apart from these uncertainties, there is no evidence from southwestern Norway that, with certainty, demonstrates that the composite ophiolite/arc terranes were accreted to a continent (Baltica or Laurentia) prior to their obduction onto Baltica in the Late Silurian, Scandinavian orogeny. Thus, the numerous stratigraphic and structural discontinuities recorded in the composite oceanic terranes between Bergen and Karmøy (see above) must be related to orogenic events that took place within the Iapetus during construction of the composite ophiolite/arc terrane. This interpretation is in agreement with traditional interpretations of Early to Middle Ordovician faunal provinciality in the outboard terranes of the Scandinavian Caledonides (Bruton and Harper, 1988).

Sturt et al. (1991) have reported recently on stratigraphic relationships in the Otta area of central southern Norway. The units discussed are the Vågåmo ophiolite, the underlying Heidal metasedimentary series and the Sel Group, which contains the fossiliferous Otta serpentinite conglomerate at its base. The fossils arc of Arenigian–Llanvirnian age, and constitute a mixed North American–Baltic fauna (Bruton and Harper, 1981). There is little doubt that the serpentinite conglomerates are unconformable on the underlying, highly dismembered, Vågåmo ophiolite (Sturt et al., 1991). Without discussing alternatives, Sturt et al. (1991) conclude that the Vågåmo ophiolite was accreted to Baltica prior to the deposition of the Arenigian–Llanvirnian fossiliferous conglomerates. Both in forearc settings and along transform/fracture zones (Bonatti et al., 1983; Saleeby, 1984) detrital serpentinites and ultramafic protrusions are common, and serpentinite protrusions may reach shallow-marine conditions or even form islands. As also pointed out by Pedersen et al. (1992), erosion and deposition of ultramafites may occur without obduction and should be considered in the interpretation of detrital serpentinites. During the buoyant rise of the ultramafic rocks these are penetratively deformed together with parts of the oceanic crust. The latter interpretation was suggested for detrital serpentinites that occur within the Silurian obduction mélangé of the Solund–Stavfjord ophiolite complex of western Norway (Andersen et al., 1990; Skjerlie and Furnes, 1990). If, however, Sturt et al. (1991) are correct in their identification of a terrane-linking unconformity in spite of the lack of continental debris in the fossiliferous conglomerate, the relationships between the Jotun Nappe, the Heidal series, the Vågåmo ophiolite and the Sel Group become critical and a third tectonic interpretation may be suggested. If the Jotun Nappe and other parts of the Precambrian allochthonous gneisses in southern Norway are exotic with respect to Baltica, the ophiolitic rocks of the Otta area may have been accreted to a "Jotun microcontinent" prior to the final Scandian emplacement of the composite terranes onto Baltica. Thus, an early Caledonian event may have affected the Jotun Nappe, its cover and the Dalsfjord/Høyvik basement/cover pair. These units may, however, have been separated from Baltica at the time of their deformation and only been emplaced onto Baltica during the Scandian orogeny.

We conclude that, from the available geological and geochronological data from the Sunnhordland–Hardanger region there is no evidence to suggest that the southwestern Norwegian ophiolitic terrane was accreted to Baltica before its final emplacement during the Scandian orogeny in the Middle to Late Silurian. It is suggested that intra-oceanic plate convergence progressively amalgamated ophiolitic and immature to mature
arc complexes from the time ensimatic subduction was initiated in the Early Ordovician. The amalgamation of this terrane was associated with deformation and metamorphism which accounts for the many stratigraphic discontinuities that occur at several stratigraphic levels. With time, a mature magmatic arc was formed within the Iapetus. It remains a possibility that continental crust such as the Jotun Nappe and its sedimentary cover may have constituted a part of this arc, and that it formed part of very large system of composite terranes within the Iapetus Ocean (similar to the Oliverian-Midland Valley arc terrane of McKerrow et al., 1991). The Iapetus finally closed in the Silurian and the composite outbound terranes were emplaced onto Baltica during the Scandian orogeny. Undisputable Baltic crust and cover have apparently not been affected by Caledonian crustal shortening until the Silurian Scandan orogeny.

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4. References


Andersen, T.B. and Dæhlin, P.C., 1986. Basement–cover con-


Bruton, D.L. and Bockelie, J.F., 1980. Geology and paleontol-


