Structural Succession in a Part of the outer Hardangerfjord Area, West Norway*

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Recent mapping has made possible a reinterpretation of the tectonostratigraphy of this area, situated at the eastern edge of the 'Faltungsgraben'. It is shown that certain rock units occurring over large areas, and formerly thought to be autochthonous, are made up of various allochthonous units. The possible relations of these to the succession of the Hardangervidda–Ryfylke area are discussed. Compared to the east, allochthonous crystalline gneisses seem to wedge out to the west. In this area, the highest thrust sheet, the volcanic-bearing Cambro–Silurian of the western facies appears as a new element, and its allochthonous character is discussed.

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Introduction

The area around the outer Hardangerfjord is a key region for many problems concerning the Caledonides of southwestern Norway. In this area, the relationship between the nappe system of Hardangervidda–Ryfylke (Naterstad et al. 1973) and the Central Trough — 'Faltungsgraben' of Goldschmidt (1912) — may be studied. The latter structure has been suggested by some as a possible root zone for the nappes (Smithson & Ramberg 1970; Smithson et al. 1974). Another point of interest is the transition from 'eastern' to 'western' facies Cambro–Silurian rocks (Strand 1972) which also occurs within the area. Recent field work has changed many of the previous ideas on the geology of this area, and it is intended here to present a summary of the new results.

The geology of the area has earlier been described by Reusch (1888, 1913), Rekstad (1907, 1908), Kolderup (1941), and more recently by Sørbye (1948, 1953, 1964). The geological map of Norway (Holtedahl & Dons 1960) presents the essence of published knowledge of the outer Hardangerfjord area up to now. On this map the following two main units are separated: (1) An autochthonous basement consisting of gneisses partly of certain Precambrian origin, partly of unknown origin but with structures of Caledonian age. The basement is covered by (2) a Cambro–Silurian supracrustal series, mainly pelites, but on the islands Halsnøy, Borgundøy and Fjelbergøy (Fig. 2) also metavolcanics. The contact between basement and cover has been variously interpreted as a tectonized depositional contact or as of a metamorphic gradational type (Kolderup 1941). No major thrust units have been depicted.

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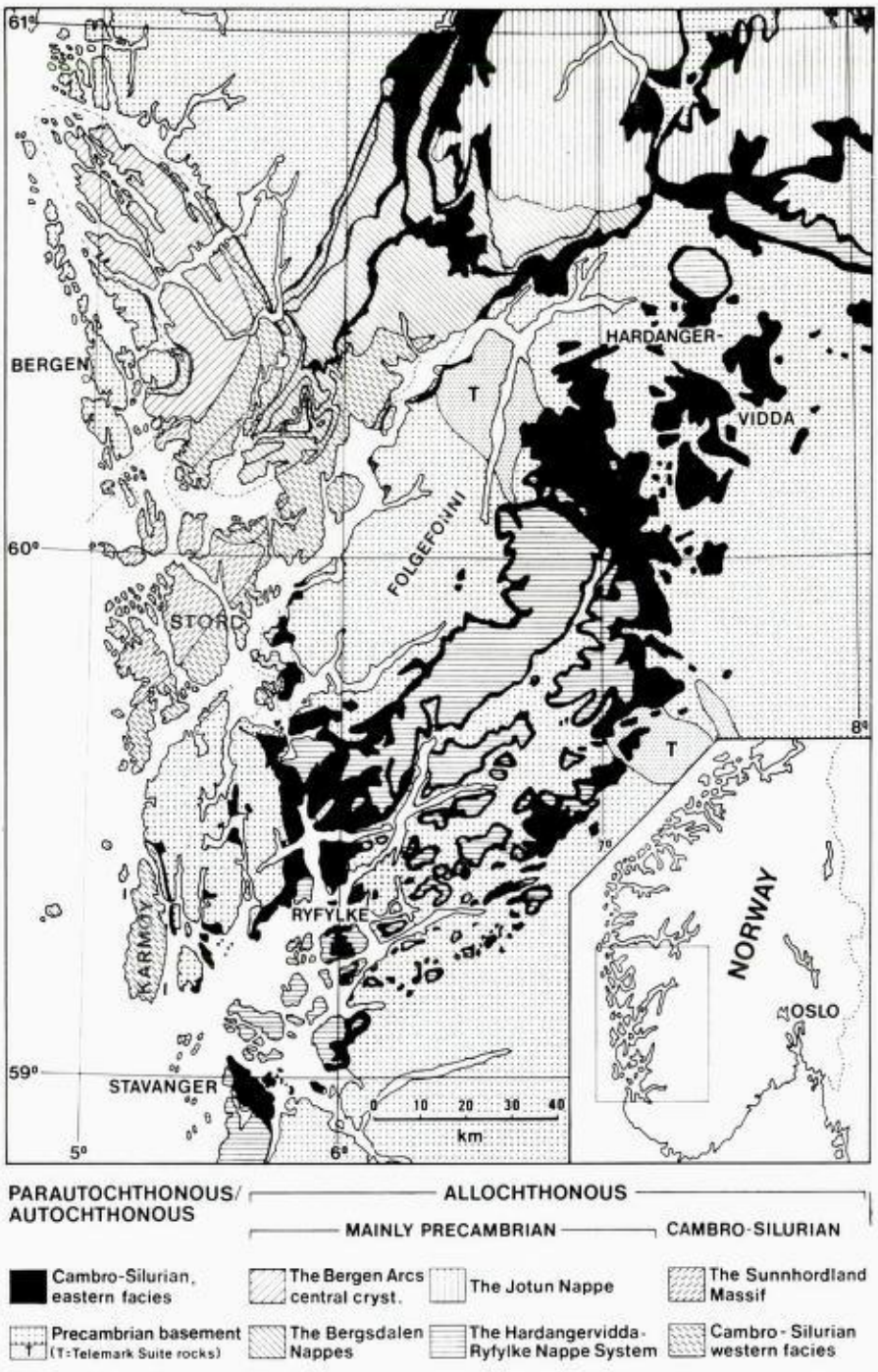

Fig. 1. The distribution of the main tectonostratigraphic units of SW Norway.

As a result of detailed studies in critical areas and reconnaissance mapping and reinterpretation of older data, a revised simplified geological map of the whole region is presented in Fig. 1. We will here deal only with the area covered by Fig. 2, where detailed studies have been undertaken. The purpose of this work is not to give a complete geological description of the area, but rather to present the new ideas on the geological development and also to point out the consequences of these interpretations and results for the region as a whole.

The main reinterpretations of the geology are as follows:

(i) Parts of what was formerly considered autochthonous Precambrian basement are, in fact, allochthonous nappes.
(ii) Large areas of metamorphic supracrustal rocks, previously incorporated within the Cambro–Silurian cover rocks, are shown to be part of the autochthonous Precambrian basement.
(iii) Only a minor part of the previously considered Cambro–Silurian cover rocks can be regarded as autochthonous; the main portion of the pelites is allochthonous and probably of Precambrian age.
(iv) The medium-grade metamorphism and igneous activity of the basement are of Precambrian age.
(v) The basement/cover contact, where not fault-bounded, is depositional. A relict but distinct metamorphic break exists at the boundary.
(vi) The volcanic-bearing Cambro–Ordovician sequence (western facies Cambro–Silurian) on the islands is allochthonous and forms the uppermost part of the nappe pile.
(vii) Late Palaeozoic and Mesozoic faulting is responsible for much of the irregular appearance of the geological boundaries.

The arguments and some of the data leading to these conclusions will now be presented together with a short description of the geology.

Precambrian basement

The basement lithologies have been grouped into three main units (see Fig. 2):

1. Metamorphic supracrustals of both sedimentary and volcanic origin; the Tittelsnes Group.
2. Gabbroic rocks which intrude the Tittelsnes Group. Only the largest of the many bodies is marked in Fig. 2.
3. Mainly granitoid orthogneisses and migmatites with varying age relations to the above-mentioned units.

(1) The metamorphic supracrustals of the basement seem to be most complete and best preserved on the Tittelsnes peninsula, and we have proposed the new term Tittelsnes Group as an informal name for these rocks. The Tittelsnes

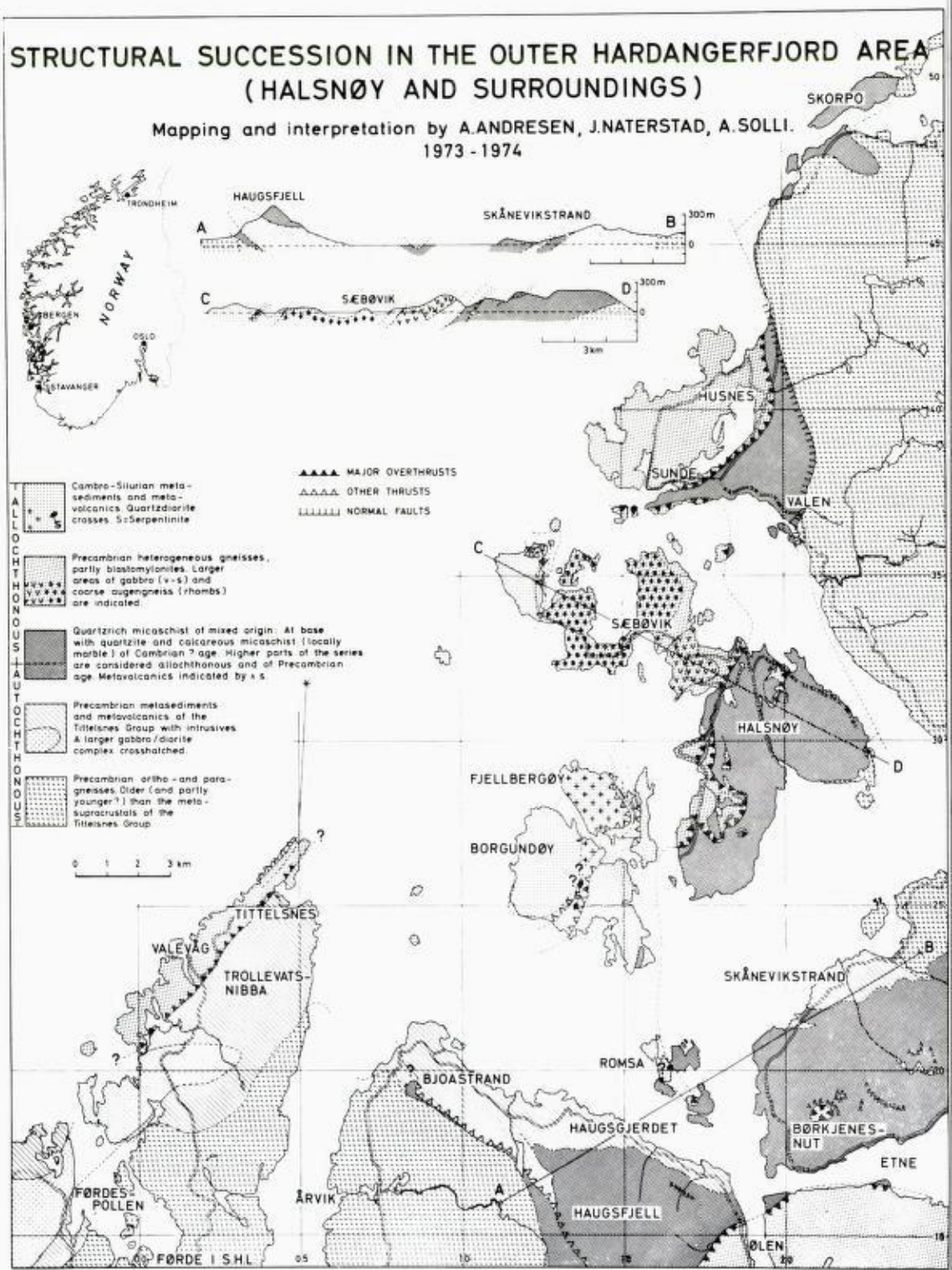

Fig. 2. Simplified geological map of the outer Hardangerfjord area.

Group consists mainly of metamorphic pelitic and semi-pelitic rocks, often with well-preserved primary sedimentary structures, chiefly preserved in the contact aureoles to the younger gabbros. There are also volcanic rocks of both acid and basic types, and some conspicuous zones of meta-agglomerates occur (Mortensen 1943; Sørbye 1948).

On existing geological maps much of the areas underlain by this Precambrian series has been designated as Cambro–Silurian metamorphic supracrustals, e.g. Tittelsnes, Bjoastrand (Kolderup 1941; Sørbye 1953; Holtedahl & Dons 1960). The Precambrian age of the series suggested in this paper is indicated by the fact that its rather complex structures are truncated by the sub-Cambrian peneplain and overlain by Cambro–Silurian basal deposits, nicely exposed at Bjoastrand and Skånevikstrand.

The occurrence of staurolite, sillimanite, cordierite and chloritoid in the pelitic parts of this group indicates that in Precambrian times amphibolite facies metamorphic conditions have been reached, a degree of metamorphism never attained in the phyllites of definite Cambro–Silurian age which overlie the Tittelsnes Group. The group is tentatively correlated with parts of the Telemark Suite of South-Central Norway. If this is the case, the sediments here in western Norway seem to be of a more pelitic character than those of the Central Talemark area. (See also Torske 1977).

(2) Only the largest of the gabbro/diorite bodies is shown on the map (Fig. 2), but quite a number of smaller bodies exist, especially in the supracrustals at Skånevikstrand (Mortensen 1943; Rekstad 1908). Textural and mineralogical variations in the bodies are frequent, but have not yet been studied in detail. The gabbros are intrusive into the Tittelsnes Group, and large xenoliths of the supracrustals appear inside the bodies. Extensive contact aureoles with so-called 'knotenskifer' (Rekstad 1908) or spotted slate with andulusite porphyroblasts are developed around the gabbros. Primary structures in the sediments are better preserved in these contact aureoles than in the surrounding areas. The bodies of gabbro and their contact aureoles seem to control the formation and distribution of migmatites of a later event (see below).

(3) Gneissic rocks of different types and with varying age relationships to the two former divisions make up the third main unit of the basement. The gneisses have different appearances in the various regions of Fig. 2. The areas east of Valen–Husnes and east of Skånevikstrand are dominated by a rather uniform granitoid orthogneiss which is intrusive into the Tittelsnes Group. The area east of Førdespollen and much of the area east of Årvik are mainly occupied by granitic migmatitic gneisses. Field relations indicate that the main migmatization phase post-dates the intrusion of the gabbros. Also the youngest granites and pegmatites of division 3 are intrusive into the gabbros.

There may, however, be parts of the gneisses which are older than the Tittelsnes Group. This may prove to be the case west of Bjoastrand where a quartz–dioritic gneiss appears to form the depositional base of the supracrustals.

Quartz-rich mica schist of mixed origin

Under this heading (see legend to the geological map, Fig. 2) is grouped most of the rocks that have been interpreted as Cambro–Silurian schists by earlier workers (e.g. Holtedahl & Dons 1960), but excluding areas of pelitic rocks around Bjoastrand and Tittelsnes which belong to the Tittelsnes Group. Our investigations indicate a subdivision of the two unit into: (a) a lower autochthonous sequence of Lower Palaeozoic age, and (b) an upper allochthonous sequence of possible Precambrian age. The great similarity in the fundamental lithology and a common late metamorphic and tectonic history of the two sequences makes a separation between them very difficult in the field. This has, however, been achieved locally, and the units will therefore be described separately, although we have not yet been able to distinguish between them over the whole region covered by our map (Fig. 2). Similar difficulties with the separation of the two sequences of mica schist have been noted earlier by Sigmond Kildal (1973) and Sigmond (1975) from the Suldal area to the southeast.

(a) LOWER AUTOCHTHONOUS SEQUENCE

This part of the sequence corresponds in our opinion to the lower part of what earlier has been named 'Fyllittavdelingen' (e.g. Rekstad 1907, Sørbye 1953) or the Phyllite formation — Cambro–Silurian of eastern facies (Strand 1972, pp. 31–32). Its base is well exposed at Bjoastrand, Skånevikstrand, Halsnøy and north of Husnes. The lowermost member is a medium-grained quartzite, usualy white, but sometimes with a bluish tint and a thickness which varies from zero to about 10 m. In most places only slices of the quartzite are found, due to post-depositional tectonic disturbances, but its basal depositional character is proven by its appearance in numerous non-tectonized localities. A thin marble horizon may be present above the quartzite, and this is followed by a calcareous mica schist, locally of considerable thickness.

This basal quartzite–marble–phyllite association linked to the discordance is found over wide areas in Hordaland and Rogaland. At Ritland in Rogaland (59°14′N, 06°25′E) a Middle Cambrian fauna occurs in an autochthonous dark shale above basal quartzite and breccia, and below an allochthonous mica schist sequence (Henningsmoen 1952, Sigmond 1975). Nearby, in Elfarvik, Nedstrand (59°25′N, 5°47′E) trace fossils have been found in the basal quartzite (Riis 1977). This evidence indicates that the contact represents the sub-Cambrian peneplain.

Intrusives have not been found in this lower mica schist sequence. Garnet and biotite indicate greenschist facies metamorphism (Solli 1976) and hence a lower metamorphic grade than in the sediments of the Precambrian basement. As garnet and biotite are never found in the basal deposits on Hardangervidda or in Ryfylke, an increase in (Caledonian) metamorphic grade towards the northwest is indicated. Indications of the same sort have been found by Riis (1977) in the Nedstrand area. Here a series of thrust sheets is found low in

the nappe pile, all containing the basement/cover and the phyllite/mica schist sequence. The higher the position of a sheet in the nappe pile, the more northwesterly its derivation is thought to have been. These sheets show a distinct increase in metamorphic grade upwards.

(b) UPPER ALLOCHTHONOUS SEQUENCE

The upper and volumetrically more dominant part of the mica schist division is a greenish to greyish quartz-rich mica schist. It is very homogeneous and contains numerous characteristic 5–10 cm long distorted lenses of vein quartz. A few quartzite beds occur, but more conspicuous are 0.5–5 m-thick layers of a massive gneissic rock which are very persistent and can be followed for kilometres. It has a characteristic 'augen' structure, where each 'augen' ($\sim$ 0.5 cm across) is made up of a single plagioclase crystal. The mineralogy of the matrix is quartz, albite, chlorite, hornblende, clinozoisite, and minor amounts of calcite and sericite.

These rocks are almost identical to the meta-andesites described from Skorpeheii, Suldal, 30 km to the east (Sigmond Kildal 1973). These meta-andesites are also interbedded with mica schist, and they occur in a similar tectonostratigraphic posision as here. Based on their appearance in the field and the comparison mentioned, we tentatively interpret the gneissic layers as meta-andesites.

Rb/Sr whole rock dating of the meta-andesites at Skorpeheii has yielded an age of 1145 ± 98 m.y. (λ $1.39 \cdot 10^{-11}$) (Sigmond & Andresen 1976). An attempt at Rb/Sr whole rock dating of the metavolcanics at Ølen has failed to define an isochron, but the data clearly point towards a Precambrian age (A. Råheim, pers. comm. 1977).

The arguments for dividing the mica schist into autochthonous and allochthonous parts are as follows. At the base of the sequence there is an angular unconformity with a break in metamorphic grade, and in a nearby area Cambrian fossils are found above what appears to be the same unconformity. Higher up in the sequence are found several horizons of interbedded, possibly metavolcanic rocks of indicated Precambrian age. It seems therefore reasonable that the upper part is allochthonous. The main argument against this theory is that we have not been able to ascertain the presence of a single main thrust between the two sequences of mica schists. Locally, however, many thrust faults occur, and we therefore interpret the boundary between the sequences as represented by an imbricate zone where mica schists of Cambro–Ordovician and Precambrian age are tectonically mixed and overprinted by a common, early Caledonian, regional metamorphic event.

Although no obvious break in metamorphic grade has been found between the upper and lower mica schist sequences, some textural differences seem to exist. The upper part contains more vein quartz and also has a more coarse-grained texture. This conclusion is supported by recent detailed studies in the same mica schist complex at Nedstrand, Rogaland (Riis 1977).

The existence, and Precambrian age, of the metavolcanics should, however,

be accepted with some caution. On Halsnøy (Solli 1976) and Nedstrand (Riis 1977) it can be demonstrated that gneisses form thin tectonic wedges or sheets in the mica schist and that the cataclastic products of these in the field show a striking similarity to metavolcanics. The larger part of these thin and persistent gneissic layers have, however, a field appearance as well as mineralogical and textural relations strongly suggesting a volcanic origin as tuffs or lavas. For this reason we favour a Precambrian age for the upper sequence.

Allochthonous Precambrian heterogeneous gneisses

Most of the rocks of this unit are banded orthogneisses which are easily distinguished from the orthogneisses of the basement by the presence of a more marked foliation in the former. A Precambrian age is suggested from correlation with other nappe areas (e.g. Heier et al. 1972, Andresen et al. 1974, Andresen & Heier 1975).

The gneisses represent very heterogeneous rock-types, but the following main lithologies have been recognized. Large parts of the unit are occupied by various types of foliated granitic gneisses, the most spectacular of which is a coarse-grained augen gneiss with porphyroblasts of microperthitic microcline. Intrusive into the augen gneiss are gabbroic/dioritic rocks. In intimate accociation with the gabbros are quartz–dioritic rocks which probably represent a late stage in the magmatic evolution of the gabbros.

Studies of the allochthonous gneisses show that they have undergone several stages of deformation. Fieldwork demonstrates that the gabbros were intruded into a foliated augen gneiss and that the gneisses have suffered at least one episode of foliation and tectonism after this intrusion. Generally, the gneisses now show a greenschist facies mineralogy with chlorite, albite, biotite, microcline and garnet. Locally, gneisses with relics of higher grade metamorphism (mesoperthite) are found. Some gabbroic bodies with primary magmatic minerals (clinopyroxene, labradorite) also occur (Solli 1976).

The lower boundary of the gneisses (major thrust on the map, Fig. 2) is not one single thrust surface, but a series of imbrications between gneisses and mica schists. This is indicated on the map in the profile section of Halsnøy, Fig. 2 C–D, and described in more detail by Solli (1976). The same phenomenon has also been reported by Sigmond Kildal (1973) from the Suldal area.

Most of what have been intepreted as allochthonous gneisses is shown on earlier maps as autochthonous basement, e.g. Tittelsnes, Halsnøy and Husnes.

Allochthonous metasediments and metavolcanics of supposed Cambro–Ordovician age

This is the uppermost tectonostratigraphic unit in the mapped area. Further west, a more complete section of these rocks can be seen. They have earlier been designated Cambro–Silurian rocks of western facies (Strand 1972). The reason for this is that there are some scattered fossil localities, e.g. on Karmøy (59°15′N, 5°15′E) (Broch et al. 1940), Stord (59°52′N, 5°23′E) (Færseth &

Ryan 1975, Ryan & Skevington 1976), and in the Os area (60°9′N, 5°30′E) (Kolderup & Kolderup 1940), indicating Upper Ordovician and Silurian ages (Ashgill & Llandovery). It would seem, however, that the rocks in the mapped area might belong to a lower part of the sequence and hence would have a pre-Ashgillian age (Solli 1976), but palaeontological evidence for this notion has yet to be found.

Pelitic schist, metagreywacke and greenschist are the major components of the series. A rapid alternation combined with a strong tectonic deformation often makes distinction between metasediments and metavolcanics impossible. In some of the schists are found polymictic conglomerates. One larger body of quartz–diorite (Fjelbergøy) and some smaller bodies of gabbro occur. On Borgundøy there are a few lenses of serpentinite. All rocks seem to have suffered a greenschist facies metamorphism.

The boundary of the unit to the allochthonous gneisses below is strongly tectonized, but even so it has a rather uniform appearance, not only in this area, but also along the entire northwestern side of the Hardangerfjord. This must mean that: (1) a thrust contact has been established against the gneisses below, without the stratigraphy of the sequence being too much disturbed; or (2) that the contact to the gneiss unit was originally a depositional one, subsequently disturbed. The authors favour the first alternative.

Mesozoic igneous and tectonic activity

A swarm of alkaline dykes has recently been described from the Sunnhordland area (Færseth et al. 1976). Of the approximately 80 dykes which have been recorded, 8–10 are located within the map area (Fig. 2). The dykes have a width ranging from 10 cm to 2 m. Both the major element chemistry and the high abundances of incompatible elements of these dykes are typical of alkali olivine basalts.

K–Ar dating on amphibole and whole-rock samples demonstrates a spread in age from 280 m.y. to 160 m.y. with a major activity about 220 m.y. B.P. (Triassic) (Færseth et al. 1970).

The dykes have a N–S to NNW–SSE strike and seem to be associated with a system of fractures and faults in the same direction. It can be demonstrated that some of the fractures have suffered more than one episode of brecciation. East of Husnes–Valen one of the largest faults is found with a westerly downthrow of about 500 m. Partly as an effect of this, the Cambrian peneplain on Halsnøy and Skånevikstrand reaches much further to the east than would be expected from its attitude at Tittelsnes and north of Husnes.

Concluding remarks

The main results of the tectonic reinterpretation of the different lithological units are summarized in the introduction (p. 41). We will here only discuss some further implications of the new results.

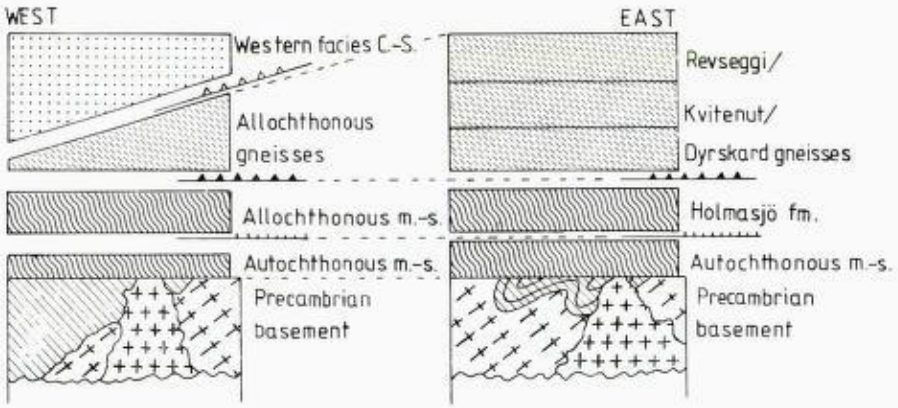

Fig. 3. A comparison between the tectonostratigraphy of the Hardangervidda–Ryfylke area (east) and the outer Hardangerfjord area (west).

It is the author's impression that the tectonostratigraphic succession in the area bears a great resemblance to that established in the Hardangervidda area to the east (Naterstad et al. 1973). This is illustrated in Fig. 3. In both areas the Precambrian basement is overlain by an autochthonous Cambro–Ordovician or Cambro–Silurian sequence, fossiliferous in the Hardangervidda area (Andresen 1974). In the latter area this sequence is succeeded by an allochthonous/parautochthonous sequence of mica schists; the Holmasjö Formation (Naterstad et al. 1973). It has not been possible to identify a similar tectonic unit in the outer Hardangerfjord area. However, the mica schist found just above the basal quartzite and marble is lithologically indistinguishable from the Holmasjö Formation.

The next unit of regional extent in the Røldal–Haukelisæter area is the Dyrskard Group. This unit is dominated by quartzites, rhyodacites and metabasalts (Andresen & Gabrielsen, in prep.) with some horizons of mica schists. The amount of mica schist seems to increase westwards and also contains layers of meta-andesites (Andresen & Gabrielsen, in press), the unit showing great similarities to parts of the upper allochthonous mica schist unit in the outer Hardangerfjord area. Following this, a correlation between the Dyrskard Group and the volcanic-bearing parts of the upper mica schist unit in the outer Hardangerfjord area may be suggested.

We also consider the Kvitenut Complex in the Røldal–Haukelisæter area (Naterstad et al. 1973) to represent the same tectonostratigraphic unit as the allochthonous Precambrian heterogeneous gneisses in the outer Hardangerfjord area.

The main difference between the areas seems to be that the gneissic Precambrian part of the eastern allochthon wedges out towards the Hardangerfjord, and in this area the next nappe unit, the Cambro–Ordovician metasupracrustals of western facies, appears as a new and major element on top. It has to be stressed that the suggested Cambro–Ordovician age of this series

has never been proven. It is separated from the fossiliferous series on Stord (Færseth & Ryan 1975, Ryan & Skevington 1976), and from the Rb/Sr dated volcanics (455 ± 5 m.y.) on the same island by faulting (Priem & Torske 1973, Lippard 1976), and its grouping with the Cambro–Ordovician is still only based on 'long range' correlation made on specific lithological characters. This correlation is accepted with caution for the present by the authors. There is a great similarity between retrograde parts of the volcanic-bearing Tittelsnes Group and the volcanic-bearing series of supposed Cambro–Ordovician age, a fact that makes misinterpretations possible. It might be expected that the supracrustals of the Tittelsnes Group continue to the northwest beneath the rock sequence in the Faltungsgraben, and that during Caledonian nappe movements they are likely to have been moved southeastwards together with slices of their own substrate, these slices now being represented by the heterogeneous allochthonous gneisses.

The contact between the supposed Cambro–Ordovician series of western facies and the autochthonous/parautochthonous sequence capping the basement is always a thrust, almost everywhere with a sole og gneisses in between, e.g. on Halsnøy and Tittelsnes. This sole may have been: (1) short-transported slices of the local basement caught by the advancing allochthon; (2) the tecthonized base of the sequence derived from somewhere to the north-west; or (3) more likely a part of the continental edge on to which the Cambro–Ordovician sequence was obducted during the early stages of its movements (Gale & Roberts 1974).

The point that the volcanic-bearing Cambro–Ordovician sequence is allochthonous in this region has not yet been recognized explicitly in the literature. Up to now, only brief remarks have been made, e.g. by Strand (1972, pp. 69–70) and Naterstad et al. (1973, Fig. 1 and p. 17).

The allochthonous nature of the Cambro–Ordovician succesion is also indicated by the common occurrence of widely diverse intrusive rocks of Caledonian age, from ultrabasic to granitic, that have never been found in the local basement. Some of the intrusive rocks, e.g. the stratabound serpentinites and the greenstones, are generally accepted as originating in tectonic situations very different from their present setting within a seemingly unbroken continent. If the suggested Cambro–Ordovician, pre-Ashgillian age is correct, this strongly volcanic sequence would be a partial time-equivalent to the nearby autochthonous Hardangervidda series (Andresen 1974a) which is almost devoid of volcanic elements, a situation which can best be explained by considering the western volcanic-bearing series as allochthonous.

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