A major early Caledonian igneous complex and a profound unconformity in the Lower Palaeozoic sequence of Karmøy, southwest Norway

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The evidence and conclusions arrived at by Birkeland (1975) for the existence of a metasedimentary sequence on Karmøy of Precambrian age are erroneous. This is also the case in relation to his conclusions regarding the regional tectonic patterns. In this paper, evidence is presented that the rocks of West Karmøy form an igneous complex of diorites and granditoids which, it is proposed, should be subsequently referred to as the West Karmøy Igneous Complex. This complex intrudes an envelope of greenstones, metagabbros, and metasediments, regarded as part of the standard Lower Palaeozoic sequence of West Norway. A profound unconformity occurs between this substrate and the overlying low-grade metasedimentary sequence of Upper Ordovician age in South Karmøy. This unconformity is of regional significance in the elucidation of orogenic stages during the evolution of the western Norwegian Caledonides.

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We have in the past years carried out a number of reconnaissance studies in Karmøy as part of a systematic study of the stratigraphy and tectonics of the Lower Palaeozoic metamorphics in western Norway. We find ourselves in considerable disagreement with Birkeland's (1975) conclusions concerning both the identification of rock types and their relationships on Karmøy. Although our own work, in the Karmøy region, is as yet only at the stage of detailed reconnaissance, we feel it necessary to present a preliminary statement of our own results as a rebuttal of Birkeland's paper.

In his paper, Birkeland, comes to the following principal conclusions:

That the rocks of western Karmøy, with the exception of cross-cutting granodioritic dykes and pegmatites, are meta-arenaceous rudites.

That the rocks of western Karmøy are older than the greenstone/gabbro sequence of eastern Karmøy.

That the rocks of western Karmøy have been subjected to amphibolite facies metamorphism of Abukuma Plateau type.

That the rocks of western Karmøy are Precambrian.

That the Upper Ordovician rocks of southeastern Karmøy and the greenstone/gabbro complex form part of an allochthonous thrust sheet.

We propose to discuss each of these five propositions in turn, presenting the geological field evidence, and then stating our conclusions.

The rocks of western Karmøy, with the exception of granodioritic dykes and pegmatites are meta-arenaceous rudites

Birkeland regards the dioritic/granitoid rocks of western Karmøy as arenaceous rudites or fanglomerates in the west, and as sediments of coarse sand type in the eastern zone. For the latter he also indicates the possibility that epiclastic and pyroclastic materials had been mixed together. However, he gives no sedimentological evidence for this, but merely states for example (*p. 237*): 'The contention that the majority of the rocks of western Karmøy are metasediments is based on thorough studies in the field'. And (*p. 218*): 'Lithologically, western Karmøy falls into two distinct, NNW-SSE oriented contiguous zones, which are both chiefly made up of strongly metamorphosed, coarse, immature, gravelly sediments'.

The rocks of the western zone are certainly characterized by their high content of inclusions, a point appreciated by Reusch (1888). In fact, these inclusions are xenoliths ocurring in a variety of igneous dioritic/granitoid rock types. The xenoliths show variable degrees of assimilation

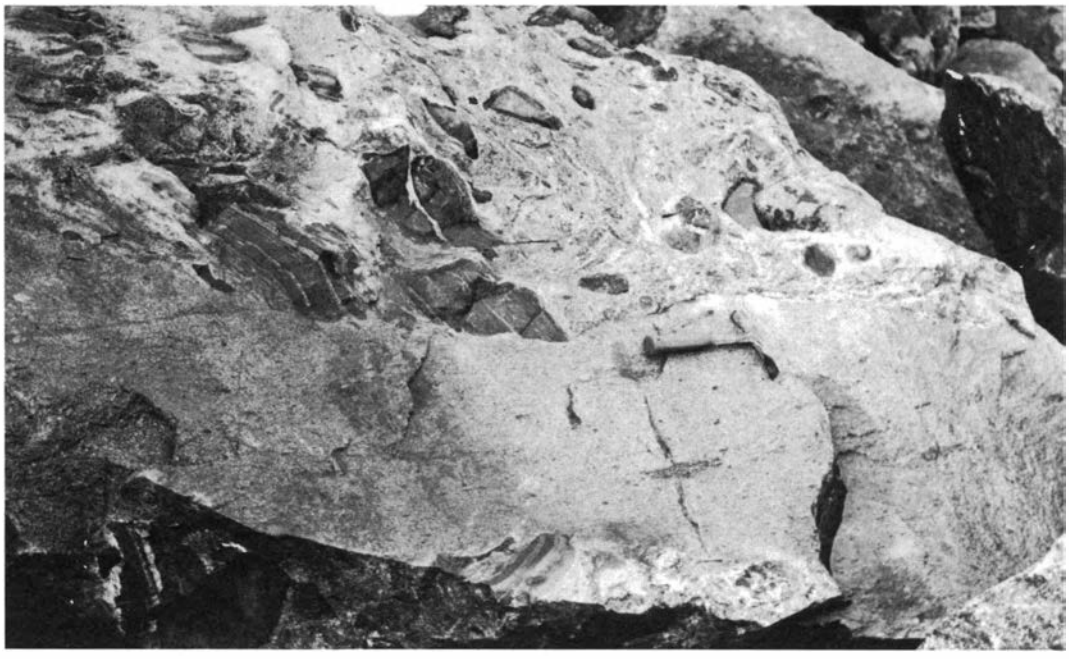

Fig. 1. Intrusive contact between relatively xenolith free diorite and highly xenolithic diorite. Even in the 'xenolith free' diorite, variably assimilated xenoliths can still be distinguished (beneath hammer), northern jetty, Sandvehamn (820 660).

into the host. This latter point had already been appreciated by Reusch (1888:355), and although he did not understand the significance of this observation, it was a feature which puzzled him considerably. Within the western zone many intrusive contacts between various dioritic and granitoid rocks of slightly differing matrix composition occur (Fig. 1). This is contrary to the statement of Birkeland (p. 237): 'Nowhere are there any signs of intrusive plutonic bodies with distinct boundaries towards their surroundings'. These bodies may be sills and dykes a metre or so in width, ranging to bodies several hundred metres across. The rocks of the successive intrusive phases may be either richly xenolithic, or virtually devoid of xenoliths. Within individual intrusive phases, the xenolith 'free' and the xenolith rich types pass transitionally into each other.

Once the fragments in the rocks are recognized for what they are, i.e. xenoliths, many essential features can be appreciated:

The xenolith shapes may vary from angular to rounded. They may be cut by veins of the matrix (Fig. 2).

These veins may become more pegmatitic than the matrix. Sometimes a slightly more pegmatitic facies of the host dioritic rock is concentrated against the margin of a xenolith.

The xenoliths show varying stages of assimilation into the dioritic/granitoid host, dependent on the original composition and texture of the xenolith.

Some of the xenoliths have contamination coronas developed around them in the surrounding igneous matrix.

Complex reactions have occurred between certain xenoliths and matrix, particularly in the case of ultramafic xenoliths.

Large rafts of metasediments, now hornfelses, also occur, and sharply cross-cutting intrusive contacts between hornfels and the intrusive phase are to be observed (e.g. at Li (836 656)). (Numbers refer to national grid, series M711, 1:50 000 (AMS coordinates)).

Flow banding is often well developed within the diorites, and involves xenoliths in varying stages of assimilation (Fig. 3).

Euhedral and subhedral feldspar phenocrysts up to 2 cm occur in the matrix and possess a preferred orientation in flow-banded portions of the rock.

Thus, the rocks of western Karmøy described by Birkeland as meta-arenaceous rudites and

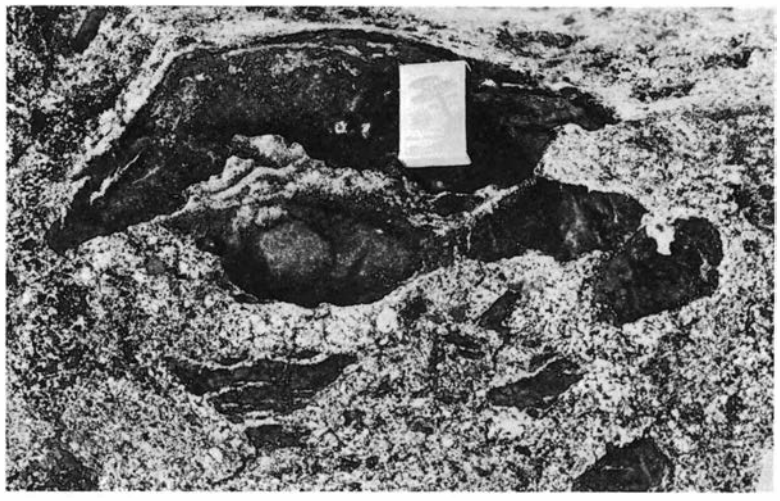

Fig. 2. Breaking up of large amphibolite xenolith by diorite matrix. Detail from highly xenolithic diorite of Fig. 1.

meta-arenites are all part of a major igneous complex of diorites and granitoids. These rocks were intruded in several phases and preserve good internal intrusive contacts. We propose the name West Karmøy Igneous Complex for these rocks.

The rocks of western Karmøy are older than the greenstone/gabbro sequence of eastern Karmøy

This is part of Birkeland's argument in assuming a Precambrian age for the Western Complex (see

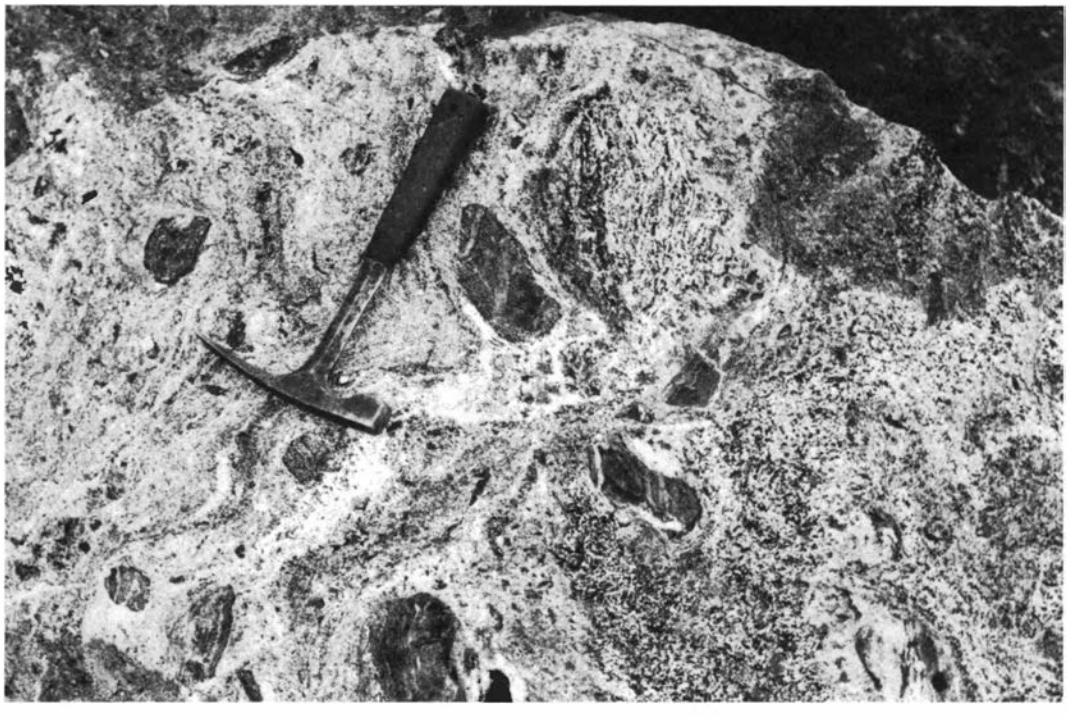

Fig. 3. Flowbanding in highly xenolithic diorite. The xenoliths show various degrees of assimilation. Note how the form of the most strongly assimilated xenoliths conforms with the flowbanding of the diorite. Same locality as Fig. 1.

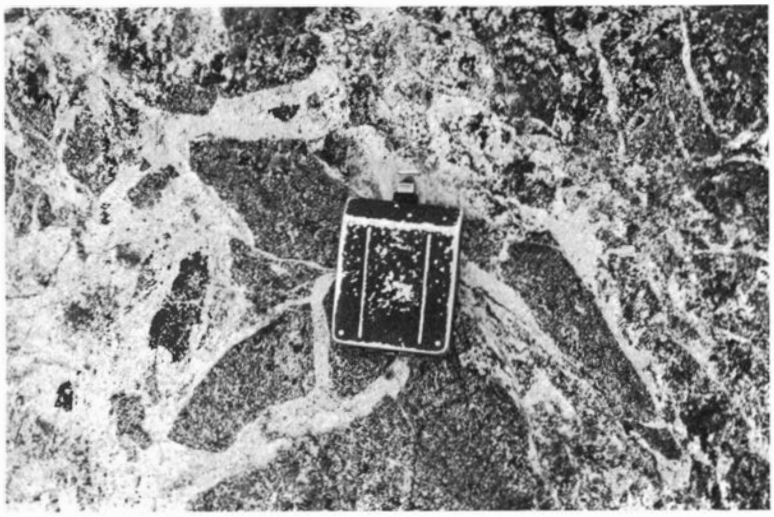

Fig. 4. Net-veining of saussurite gabbro by massive quartz diorite. Bay west of Vikestøl (840 833).

p. 234). On *p. 238* he states, 'Reusch (1888) claims to have observed dikes of "quartz augen gneiss" in the saussurite gabbro belonging to the adjoining Karmsund syncline of low-grade rocks. Dikes of a granitoid intrusive rock have also been located in the saussurite gabbro by the present author. These dikes, however, display the same textural and structural features as those of the Bergen area, and occur independently of the "quartz augen gneiss" of western Karmøy. Besides, marginal dikes or apophyses penetrating from the "quartz augen gneiss" into the adjacent low-grade metabasites of the Karmøy syncline have never been observed by the author'.

The field-relations, however, show the contrary. On the coast east of Vikene (835 829) in NW-Karmøy, the intrusive relationships of the quartz diorites/quartz augen gneisses of the West Karmøy Igneous Complex with the greenstone/gabbro complex are clearly displayed. At the bay west of Vikestøl (840 833), the rocks of the West Karmøy Igneous Complex vary from massive quartz dioritic/granodioritic rocks to foliated varieties, the latter being typical quartz augen gneisses. These rocks contain abundant xenoliths of deformed greenstone and gabbro, which increase in amount towards the contact. At the contact there is a transition from quartz diorite/quartz augen gneiss with abundant rafts and xenoliths of greenstone and gabbro, towards the greenstone/gabbro contact where many intrusive dykes, sills, and sheets of quartz diorite/quartz augen gneiss form net-vein patterns within the greenstone/gabbro complex (Fig. 4). It is clear that the major deformation and metamorphism of the greenstone/gabbro complex predate the emplacement of the quartz diorites. The typical quartz augen gneiss, on the other hand, results from post-intrusion deformation.

At the northwestern side of the bay (836 836), the relationships between the two complexes are excellently exposed in large bare outcrops along the wave washed shore. Here, the greenstone/gabbro complex is dominated by greenstones, which have characteristics of highly deformed and metamorphosed pillow lavas. The greenstones are fine-grained and contain an intricate pattern of epidote rich veins. These veins are both strongly folded and extended. In a number of cases, refolding is also apparent. This polyphasal deformation of the greenstone-gabbro complex predates the intrusion of the quartz diorite/quartz augen gneiss group to the west. The greenstones are truncated by dykes and sills of massive unfoliated quartz diorite (Fig. 5), and highly deformed greenstone xenoliths are found included in such massive igneous rocks. The igneous complexes show several phases of injection of the quartz dioritic/granodioritic assemblage, and are cut by later dykes of granodiorite and pegmatite. Localized zones of post-intrusion deformation occur within these rocks, producing the characteristic quartz augen gneiss fabric.

The authors thus conclude that rocks of the West Karmøy Igneous Complex not only postdate the greenstone/gabbro complex of eastern Karmøy, but also postdate a polyphasal

structural development within these rocks. This is also in accord with the quoted personal communication of Naterstad in Birkeland (1975: 239).

The rocks of western Karmøy have been affected by amphibolite facies metamorphism of Abukuma Plateau type

This conclusion of Birkeland is based on the observation that the paragenesis cordierite + andasulite, occupping together with potash feldspar and brownish hornblende, is common in certain rock types (*p. 236*): 'The assertion that the rocks of western Karmøy were formed under PT conditions which correspond to the upper portion of the amphibolite facies is deduced from two facts, namely, (a) that rock types of a particular bulk chemistry ocurring in the southwest of the island, contain cordierite, with or without andalusite, in apparently stable equilibrium with potash feldspar (microline), and (b) that a brownish hornblende is a common constituent of certain subtypes of the "quartz augen gneiss", a rock which makes up the major part of the eastern zone of western Karmøy'.

However, cordierite is a well known feature of many late orogenic granite/diorite sequences, particularly where much assimilation of xenolithic materials has occurred contaminating the magma, e.g. Dartmoor Granite of Devon, England (Brammall & Harwood 1932), the late Caledonian granites/tonalites of Loch Awe, Scotland (Nockolds 1934), the Terip Terip Granite Complex of Victoria, Australia (Baker 1940), and the quartz monzonites of Kinsman, New Hampshire, U.S.A. (Heald 1950). The cordierite in western Karmøy often occurs as an integral part of the groundmass mosaic, in the rocks of the igneous complex, and has almost certainly originated via contamination of the original melt phase.

Andalusite has also been recorded, though more rarely, as having been formed by the contamination of granites (Rose 1957, Webb 1943) and tonalites (Nockolds 1934). Rohr-Torp (1974) reported the co-existence of cordierite and andalusite as a result of contact-metamorphism of Lower to Middle Ordivician metasediments, by the Innset massif in the Trondheim area. The andasulite we have so far observed in Karmøy occurs in xenoliths and rafts of metasedimentary hornfels and is thus a result of contact metamorphism, though it is likely that andalusite

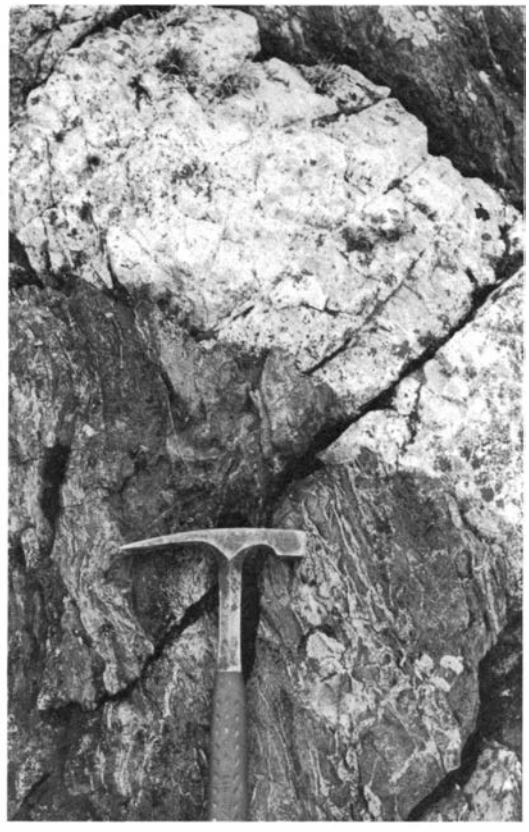

Fig. 5. Dyke of massive quartz diorite cutting highly deformed greenstone. Bay west of Vikestøl (836 836).

may also be present as a contamination product in the igneous rocks. The brown hornblende appears to be a primary igneous phase, and indeed it is a typical mineral in many granitoid/dioritic igneous complexes. Perhaps the most telling point against Birkeland's proposal is the fact that the rocks of the West Karmøy Igneous Complex at Vikestøl (see p. 232) intrude the previously deformed and metamorphosed greenstone/gabbro complex of eastern Karmøy. This latter group of rocks has never been in higher than greenschist facies conditions of regional metamorphism.

Thus, there is no evidence for the contention of Birkeland that the rocks of western Karmøy have been subjected to amphibolite facies of Abukuma Palteau type. Instead, the cordierite and andalusite are the results of magma contamination and contact metamorphism, and the brownish hornblende is a primary igneous mineral. The West Karmøy Igneous Complex is also

intrusive into a greenschist facies complex of greenstones and gabbros, effectively precluding an amphibolite facies metamorphism for the igneous complex.

That the rocks of western Karmøy are Precambrian

Birkeland concludes that the rocks of western Karmøy are Precambrian because (*p. 216*): '(1) The high-grade metamorphic character of the rocks of western Karmøy. (2) The composition and structures of the rocks concerned are totally different from those known Cambro-Silurian rocks ocurring in southwestern Norway. On the other hand, the same rocks may have a certain resemblance to the Precambrian granitoid rocks of southern Rogaland. (3) The structures are well preserved, which indicates that the rocks have escaped Caledonian deformation to a considerable extent'.

On *p. 218* he also uses the argument that the granodioritic dykes do not penetrate the Upper Ordovician rocks of southern Karmøy as evidence for a Precambrian age for the dykes.

However, on (p. 233) it has been shown that the claim for high-grade metamorphism (amphibolite facies Abukuma Palteau type) is invalid. On p. 232 it has been shown that the rocks of West Karmøy Igneous Complex are intruded into a deformed sequence of greenstones and gabbros (in greenschist facies condition of metamorphism). This sequence also includes phyllites, micaschists, quartzites, and conglomerates (Reusch 1888), and forms part of the major sequence of Cambro-Ordovician rocks in the coastal regions of western Norway. Birkeland's observation that the granodioritic dykes do not penetrate the Upper Ordovician sandstone-conglomerate sequence is correct, but this is explained by the presence of a major stratigraphic hiatus in the sequence; where the Upper Ordovician sediments rest unconformably on a substrate of the West Karmøy Igneous Complex and the greenstone/gabbro sequence with associated metasediments (see p. 235).

The greenstone/gabbro complex of eastern Karmøy, with its associated metasediments, is traditionally regarded as being of Lower Palaeozoic age (Strand & Kulling 1972), and forms part of an extensive sequence in west Norway. As the rocks of the West Karmøy Igneous Complex intrude this sequence it is highly unlikely that they are of Precambrian age. They are also demonstrably older than the Upper Ordovician sandstone-conglomerate sequence in southeastern Karmøy.

That the Upper-Ordovician rocks of southeastern Karmøy and the greenstone/gabbro complex are part of an allochthonous thrust sheet

As indicated by Andresen et al. (1974), the entire sequence in Karmøy is probably allochthonous. Birkeland postulates the presence of a nappe unit containing the greenstone/gabbro complex and the Upper Ordovician sediments (termed the Karmsund syncline by Birkeland), and separated from the rocks of western Karmøy which he considered to be of Precambrian age. We have already demonstrated (p. 232) that the rocks of western Karmøy represent an igneous complex intruding the greenstone/gabbro sequence with its associated metasediments. We will here confine our comments to the relationships between the Upper Ordovician sediments of southern Karmøy with its underlying substrate.

Birkeland concludes that there is no evidence for an unconformity between the quartz augen gneiss of the western Karmøy and the Upper Ordovician sandstone-conglomerate series, and tht the latter form part of an allochthonous thrust sheet. This conclusion is based on the following lines of argument (*p. 239*): 'The absence of an intervening basal layer or breccia above the quartz diorite/quartz augen gneiss (*p. 238, 239*) "That the fragments within the conglomerate were not derived from the rock sequence of western Karmøy, but mainly from a greenstone/gabbro complex." As a minor point he also uses the argument of the absence of dykes of granodiorite and pegmatite in the Upper Ordovician rocks.

At a series of outcrops, however, on the western shore of Vikevågen (870 630) east of Skudeneshavn, the primary stratigraphic unconformity between quartz augen gneiss and the sandstone-conglomerate sequence is exposed. Here typical quartz augen gneiss crops out in the small hills to the west. In the quartz augen gneiss, xenoliths of well foliated greenstone and gabbro are abundant in certain zones. The quartz augen gneiss is unconformably overlain by a chloritic grit, containing abundant quartz grains which are identical to the quartz augens of the gneiss. Indeed, the presence of clastic quartz grains derived from the quartz augen gneiss is

typical of this sequence. Interbedded with these rocks are thin beds of sandstone, slate, and phyllite, the whole zone varying from 10–20 m in thickness. Above these sediments, is a zone of about 10 m of conglomerate containing mainly boulders of meta-basalt. This is succeeded by a development of phyllites above which the thick conglomerate sequence of southern Karmøy occurs.

It is of interest to note here that Reusch (1913:15) described the relationship between the quartz augen gneiss and the conglomerate north of Falnes (885 633) in a manner that would fit well with the features at the unconformity at Vikevågen.

Following the contact between the sediments and the quartz augen gneiss further north from Vikevågen, there is a facies change above the unconformity, and a thick development of coarse conglomerate overlies a varying thickness of grits which rest directly on the quartz augen gneisses. This conglomerate is very well exposed along road cuts of an old farm-road leading to Røyningsvatn (860 665). Here boulders are up to 1 m across and include a variety of rock types from the West Karmøy Igneous Complex together with characteristic members derived from the greenstone/gabbro complex. The most prominent blocks are of quartz augen geneiss, contrary to the statement by Birkeland (p. 239). There are also many boulders of diorites and granitoid rocks, which bear a striking similarity to the diorites and granitoids further west. Other boulders include saussurite gabbro, foliated greenstones with epidote veins, fine grained greenstone and pillow-lava, quartzites and vein quartz. Occasionally, pebbles of pegmatite and of granodiorite are present, resembling closely dykes within the West Karmøy Igneous Complex. As mentioned previously, Birkeland used the argument that the late granodiorites and pegmatites of the West Karmøy Igneous Complex do not intrude the sandstone-conglomerate sequence as a support for his nappe hypothesis. The dykes, however, form part of the older and unconformably underlying substrate to the conglomerate. To give further support to his nappe hypothesis, Birkeland states that strong shearing has occured in the rocks along the contact. At Vikevågen, however, although the rocks are foliated, bedding is still clearly seen and the primary unconformity is visible. To the north, the degree of deformation apparently increases and at Vikestøl the later deformation is responsible for folding of the granodioritic-pegmatitic dykes. In the area around Mannes, within the West Karmøy Igneous Complex, the authors found several zones of strong shearing. These can be specially seen at an old quay in Mannes (832 788). Here mylonites and phyllonites are developed from quartz augen gneisses. A strong fibre lineation (115°/10) is developed within the mylonitic rocks. These rocks were mapped by Birkeland as micaceous schistose gneisses (*fig. 2, p. 217*), which he believed to represent a 'metamorphosed clayey sand', (*p. 231*).

The Upper Ordovician rocks of southeastern Karmøy do not form part of a separate allochthonous nappe. Therefore, in the regional context, all the rock units on Karmøy are probably allochthonous as indicated by Andresen et. al. (1974). The contact between the West Karmøy Igneous Complex and the Upper Ordovician sandstone-conglomerate series represents a major stratigraphic uncomformity of regional importance, as indicated also by Naterstad (1976).

Summary

The basic premise of Birkeland (1975), that the rocks of western Karmøy constitute a Precambrian sequence of coarse sediments, which had been metamorphosed under low-pressure (Abukuma Plateau type) amphibolite facies conditions, is invalid. The rocks concerned, in fact, represent an early Caledonian igneous complex of diorites and granitoids. We here propose that the term West Karmøy Igneous Complex be adopted for these rocks. The complex intrudes a polyphasally deformed and metamorphosed (greenschist facies) sequence of Lower Palaeozoic greenstones, gabbros, and metasediments, which form the major part of eastern Karmøy. Thus Birkeland's postulate that a major thrust separates the sequences of western and eastern Karmøy is also incorrect. Furthermore, the Upper Ordovician metasediments of southern Karmøy rest with profound stratigraphic unconformity upon a substrate of both the West Karmøy. Thus Birkeland's postulate that a major sequence. This unconformity represents a stratigraphic hiatus of major regional importance, and clearly demonstrates the existence of an early stage of Caledonian orogenic development on Karmøy, involving both polyphasal deformation

and metamorphism. In this context the West Karmøy Igneous Complex would appear to represent a phase of late orogenic magmatism relating to this early stage of Caledonian evolution. The events-sequence established on Karmøy fits well with that which has been demonstrated in the Major Bergen Arc, where an unconformity of similar significance occurs beneath the Middle/Upper Ordovician Moberg Conglomerate (Kvale 1960, Sturt & Thon 1976, Naterstad 1976).

The authors intend to follow up this preliminary survey with a detailed investigation of the tectonics, stratigraphy, petrology, and geochronology of the region as an integral part of the IGCP project 'Caledonian Orogene' (Project 27).

Postscript. – Since this commentary on Birkeland's paper was submitted in May 1976, a comment and reply have been published in this journal by Geis (1976) and Birkeland (1976). Concerning the origin of the saussurite gabbros we agree in general terms with the view stated by Birkeland in his reply to Geis.

Birkeland, T. 1976: A reply. Western Karmøy, an integral part of the Precambrian basement of South Norway. *Nor. Geol. Tidsskr. 56,* 327–329.

Geis, H.-P. 1976: A comment. Western Karmøy, an integral part of the Precambrian basement of South Norway. *Nor. Geol. Tidsskr. 56,* 325–326.

Additional postscript. – Since this manuscript was submitted, the greenstone/gabbro complex of Karmøy has been shown to form part of a stratified ophiolite complex and the rocks of the West Karmøy Igneous Complex have been dated to give a Lower Palaeozoic age (Sturt & Thon, 1978).

Sturt, B. A. & Thon, A. 1978. An ophiolite complex of probable early Caledonian age discovered on Karmøy. *Nature 275,* 538–539.

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Editor's note:
This contribution was submitted in May 1976 as a commentary on the paper by Birkeland (1975) with title 'Western Karmøy, an integral part of the Precambrian basement of South Norway.' The editor regrets the delay, which in no way can be attributed to the authors, in publication of this contribution.

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