Alternative to the Finnmarkian–Scandian interpretation on Magerøya, northern Norway

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The mafic and ultramafic rocks of the Seiland Igneous Complex on Sørøya and Honningsvåg Igneous Complex on Magerøya are much alike but have been thought to be of different ages, related to Finnmarkian and Scandian orogenesis, respectively. Hand specimens from two different Honningsvåg gabbros, however, each yielded three-point (cpx, plag, whole rock) internal isochrons, with Sm–Nd dates of 508 ± 18 Ma and 475 ± 22 Ma. (Rb–Sr dates from the same mineral separates were 558 ± 91 Ma and 468 ± 18 Ma, respectively.) These new dates suggest that the Honningsvåg gabbros overlap in age with the youngest mafic rocks of the Seiland complex, and are too old to have intruded the fossiliferous Silurian rocks of the Magerøy sequence. By starting from these pre-Silurian dates and an unpublished geologic map from 1958 by J. J. C. Geul, we believe we can show that the gabbros and the surrounding contact–metamorphic rocks form a tectonic block, the Honningsvåg unit, which is separated by faults from the regional-metamorphic rocks of the Magerøy sequence.

Way-up criteria in the Magerøy sequence of central Magerøya indicate that the sequence there is not overturned and that the fossiliferous rocks and their correlatives lie in synforms at the top of the sequence, passing downward through pelitic rocks into greywacke turbidites, which we equate with the Hellefjord Schist Group on the islands farther west and on Porsangerhalvøya. The basal contact of the supposed 'Magerøy Nappe' over the top of the Kalak Nappe Complex in western Magerøya closely resembles and is probably equivalent to the basal contact of the Hellefjord schist as exposed on Havøya and Porsangerhalvøya within the nappe complex. If so, the Magerøy sequence is an integral part of the Kalak Nappe Complex, and its Silurian fossils would show that the stacking of the Kalak Nappes was Scandian, not Finnmarkian.

The Skarsvåg Nappe of northeastern Magerøya includes not only high-grade regional metamorphic rocks but in our view also the underlying Skarsvåg and Opnan granites, which are equivalent and probably a single continuous granitic sheet. The Skarsvåg Nappe clearly overlies the Magerøy sequence, whereas the turbidites of the Honningsvåg unit may have been faulted upward from near the base of the Magerøy sequence.

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According to the established geologic model for the Scandinavian Caledonides, there are two main phases of Caledonian orogeny: the Late Cambrian to Early Ordovician 'Finnmarkian phase', and the Silurian to Early Devonian 'Scandian phase'. The Scandian phase is recognized as the main Caledonian orogenic phase in most of Scandinavia, but the Finnmarkian phase is thought to have dominated in Finnmark, the northernmost part of Norway, producing the main thrusting, folding, and regional metamorphism there. With the exception of the Magerøy Nappe, only local reheating and reactivation of some thrust faults are recognized as Scandian (Ramsay et al. 1985a; Roberts 1985a). We wish to reconsider this model, because we question some of the evidence that has led to the concept of Finnmarkian orogenesis.

The evidence involves the 4000 km^2 Seiland Igneous Complex (Fig. 1), which consists of peridotites, layered gabbros, diorites, syenites, and carbonatites (Robins & Gardner 1975). These igneous rocks were interpreted as Caledonian and synorogenic, because they intrude strongly deformed psammites on the islands of Seiland and Sørøya (Sturt & Ramsay 1965). When the Seiland

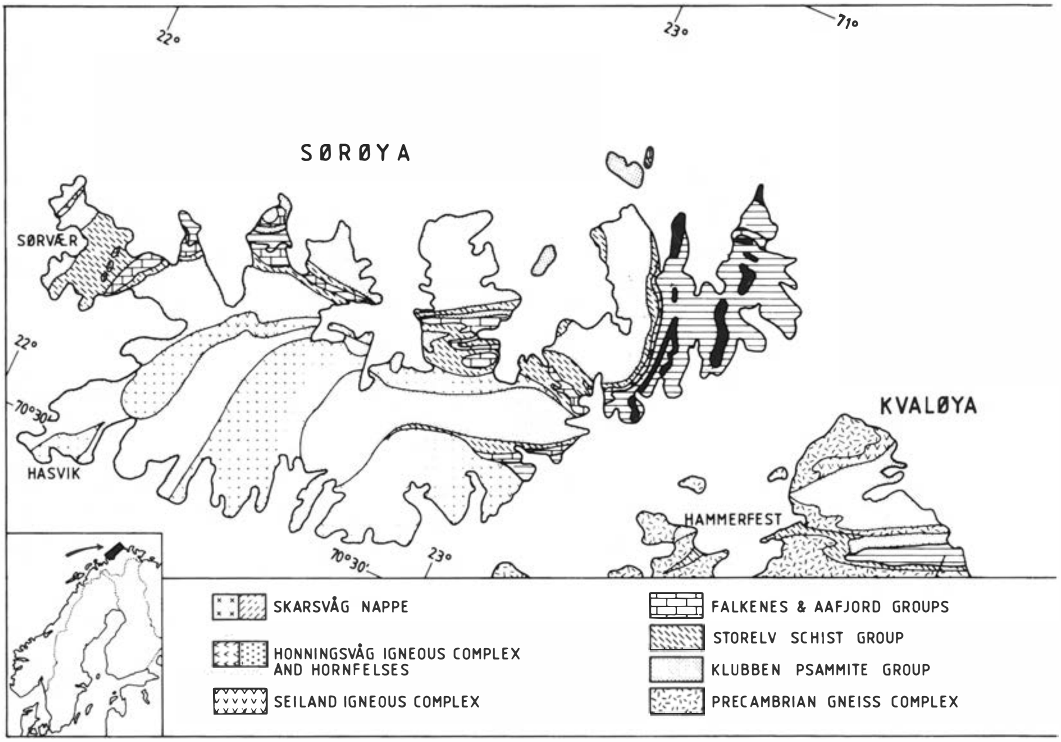
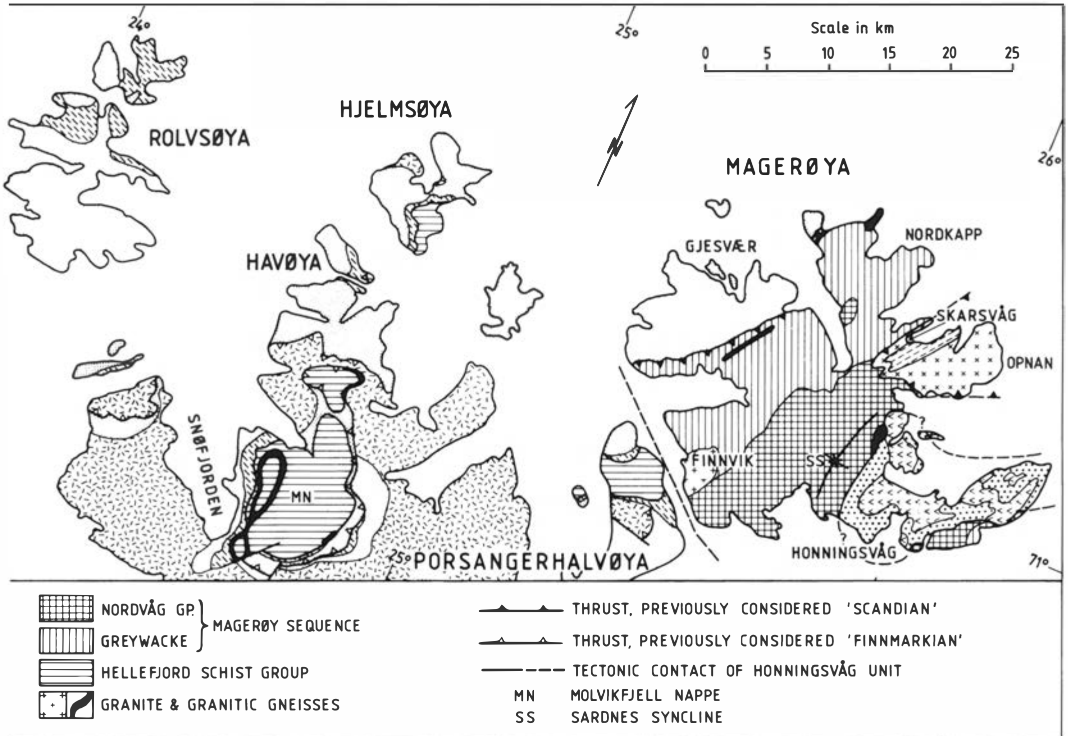


Fig. 1. Geological map of the Sørøya–Magerøya area of the northern Scandinavian Caledonides. Based on maps by Gayer et al. (1985), Geul (1958), Ramsay et al. (1979, 1985b), Roberts (1973, 1981, 1985b), Sigmond et al. (1984), Speedyman (1983), and the present study.

rocks were isotopically dated, they yielded relatively old dates of 540–490 Ma, and as the rocks were considered to be synorogenic, these dates were interpreted to define the age of an early Caledonian orogenic event (Sturt et al. 1967, 1975). As new areas of Finnmark were mapped and studied, correlation of the stratigraphic units and metamorphic and structural patterns showed that most of the rocks were affected by the same event. The presence of Silurian fossils on the island of Magerøya (Fig. 1) showed, however, that the orogenesis there at least was later (Sturt et al. 1975), but a thrust fault on western Magerøya and a normal fault south of the island seemed to isolate the fossiliferous rocks structurally, and so the Finnmarkian and Scandian phases were formally established (Ramsay & Sturt 1976; Sturt et al. 1978). Thus Magerøya represents the type area of the Finnmarkian–Scandian dichotomy.

Krill & Zwaan (1978) visited western Sørøya to check the structural evidence that had led to the interpretation of Finnmarkian orogenesis. They thought that the Seiland intrusions may be pre-orogenic, perhaps related to continental rifting and opening of the Iapetus Ocean. They suggested that two types of structure could be reinterpreted. (1) Sheared dikes, presumably related to Seiland plutons, commonly are found subparallel to the axial planes of folds in psammites. These structures had previously been interpreted to indicate that the psammites were already folded and that the dikes intruded along planes of weakness in the folded rocks. In the alternative interpretation, the dikes intruded before the folding, and the folds formed against the dikes. (2) The high-temperature Seiland plutons produced wide contact aureoles where the psammites were melted and plastically deformed. Seiland dikes clearly cut folds within the aureoles, and these folds had been interpreted as orogenic folds. In the alternative interpretation, these are anatectic viscous folds in contact-metamorphic rocks, hence related to intrusion and not to orogenesis.

If the Seiland intrusions are pre-orogenic, and the isotopic dates indicate the intrusive events,

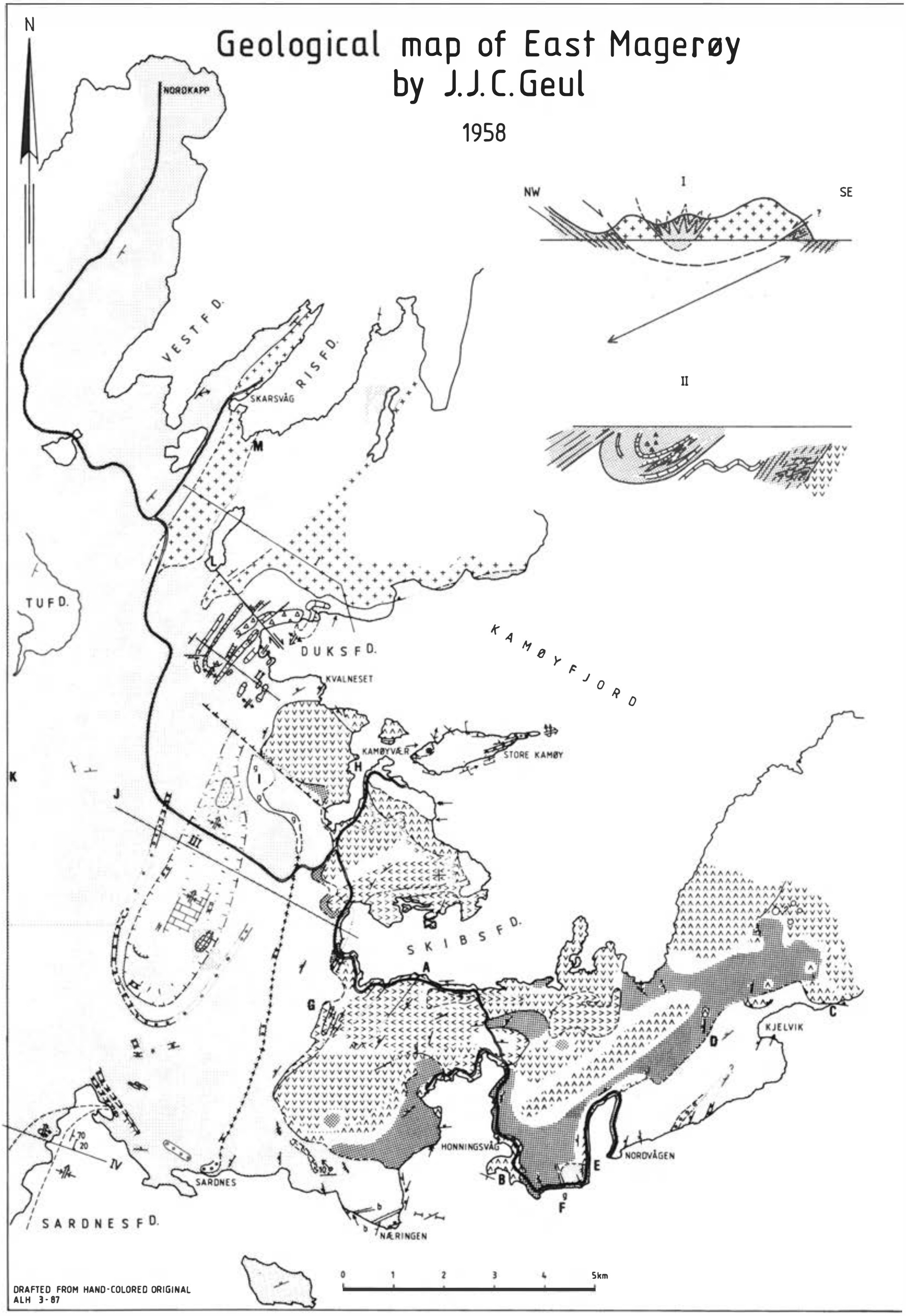


the age of the main orogenic phase in Finnmark must be younger, and there may have been only one Caledonian orogenic event in Finnmark instead of two. With this as our working hypothesis we are attempting to correlate Finnmarkian and Scandian features. We have focused on the island of Magerøya, the only part of Finnmark where Finnmarkian- and Scandian-deformed rocks were thought to be in contact. From the geologic descriptions the stratigraphy, structure, and metamorphism of the Scandian-deformed rocks on Magerøya show many similarities to those of the Finnmarkian-deformed rocks. Indeed, the Scandian phase also appeared to involve intrusion of a suite of synorogenic mafic to ultramafic plutons, known as the Honningsvåg Igneous Complex. Our working hypothesis implied that the Honningsvåg Igneous Complex also pre-dated Caledonian orogeny and could be related to the Seiland Igneous Complex. An obvious problem with this hypothesis was that the Honningsvåg rocks were interpreted to intrude the fossiliferous Silurian strata, and they must therefore be much younger than the Seiland rocks. To test parts of our hypothesis, we isotopically dated two samples of gabbro from the Honningsvåg complex and checked some of the critical field relationships on Magerøya, Havøya, and the nearby mainland.

Isotopic dates from the Honningsvåg Igneous Complex

Descriptions of the dated samples

During the summer of 1958, J. J. C. Geul studied the Honningsvåg Igneous Complex and surrounding rocks. His complete geological map has now been drafted and is shown in Fig. 2. His collection of small rock samples and thin-sections is stored at Norges Geologiske Undersøkelse in Trondheim. We chose two of his gabbro samples consisting largely of plagioclase and clinopyroxene for this isotopic study. Sample W2–22B was collected by Geul on the mountain


Geological map of East Magerøy
by J.J.C.Geul
1958
N
NORDKAPP
VESTFD.
RISFD.
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M
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KVALNESET
KAMØYFJORD
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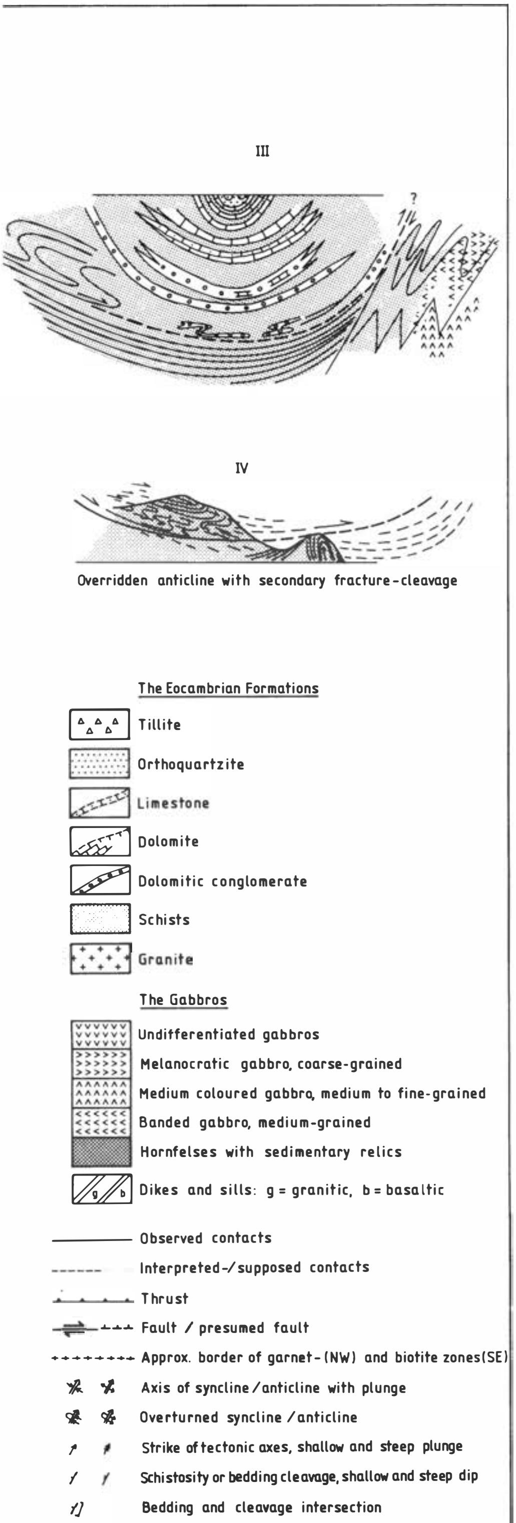

Skipsfjordtind from the unit mapped as 'banded gabbro, medium-grained' (near Location A, Fig. 2). Banding is not seen in the uniform gabbro sample. It shows subophitic texture dominated by unzoned plagioclase (labradorite) and clinopyroxene (augite). Both the plagioclase and clinopyroxene are fresh and unaltered. There is minor olivine, which is slightly altered to iddingsite, as well as hypersthene and magnetite.

Sample W2–18E was collected by Geul near the old Honningsvåg post office, in rock mapped as 'medium coloured gabbro, medium to fine-grained' (near Location B, Fig. 2). In thin-section it is similar to the Skipsfjordtind sample, but the plagioclase is zoned, the olivine is mostly altered to iddingsite, and secondary biotite is present.

Analytical methods

The samples weighed about 250 grams each, and were crushed to 125–250 μ. Pyroxene and plagioclase were separated magnetically, and extraneous grains were removed by hand-picking under a binocular microscope. A whole-rock split of each sample was also analysed.

The analytical work was carried out at the laboratory of geochronology and isotope geology at the Mineralogical–Geological Museum, University of Oslo, following the procedure described by Mearns (1986). Mass-spectrometry was performed on a VG 354 5-collector solid-source instrument. Standard values are indistinguishable from those reported by Mearns (1986). Isochron calculations followed the procedure of York (1969) with uncorrelated x–y errors. $\lambda^{147}Sm = 6.54 \times 10^{-12}a^{-1}$ and $\lambda^{87}Rb = 1.42 \times 10^{-11}a^{-1}$ (Steiger & Jäger 1977) have been used in the age calculations, and previously published dates have been recalculated. The ε notation followed DePaolo & Wasserburg (1976a) using UR-values for Rb–Sr reported by DePaolo & Wasserburg (1976b) and CHUR-values for Sm–Nd reported by Jakobsen & Wasserburg (1984). Errors quoted are 2-sigma.

Fig. 2. Geological map and cross sections of eastern Magerøya by J. J. C. Geul (1958). The topographic base of the original map has been removed, and field locations A–M from the present study have been added. Some of the rocks shown as 'Eocambrian Formations' are now known to contain Silurian fossils.

Sm–Nd and Rb–Sr isotopic results

Complete isotopic results are presented in Table 1, and the data are plotted as standard isochron diagrams in Fig. 3.

For sample W2–22B from Skipsfjordtind, the plagioclase, clinopyroxene, and whole-rock fractions yield a Sm–Nd isochron with a date of 508 ± 18 Ma. The three-point isochron has an initial $^{143}Nd/^{144}Nd$ ratio of 0.51208 ± 2 (ε_{Nd} = 1.6 ± 1) and an MSWD of 1.3. The same fractions yield a Rb–Sr isochron with a date of 558 ± 91 Ma. The isochron has an initial $^{87}Sr/^{86}Sr$ ratio of 0.70488 ± 4 (ε_{Sr} = 14.8 ± 0.3) and an MSWD of 0.4.

For sample W2–18E from the town of Honningsvåg, the plagioclase, clinopyroxene, and whole-rock fractions yield a Sm–Nd isochron with a date of 475 ± 22 Ma. The isochron has an initial $^{143}Nd/^{144}Nd$ ratio of 0.51209 ± 2 (ε_{Nd} = 1.1 ± 0.2) and an MSWD of 1.3. The same three fractions yield a Rb–Sr isochron with a date of 468 ± 18 Ma. The initial $^{87}Sr/^{86}Sr$ ratio is 0.70416 ± 4 (ε_{Sr} = 3.0 ± 0.7), and the MSWD is 0.8.

If the six Sm–Nd analyses from both rocks are combined, they yield an apparent date of 499 ± 30 Ma. However, the high MSWD of 7.3 suggests that these two gabbro bodies did not have identical ages and initial $^{143}Nd/^{144}Nd$ ratios, and this errorchron date is not acceptable. The six Rb–Sr analyses cannot be combined, because the two gabbros clearly had different initial $^{87}Sr/^{86}Sr$ ratios (Fig. 3).

Robins et al. (1987) distinguished five major intrusions within the Honningsvåg Complex. The dated Skipsfjordtind sample was apparently from their intrustion 2, which consists of peridotitic, troctolitic, and gabbroic cumulates. The Sm–Nd age of 508 ± 18 Ma from sample W2–22B probably best represents the age of this intrusion. Sample W2–18E is from a part of the complex lying outside the area described by Robins et al. (1987). The intrusive age is probably best represented by the Sm–Nd date to be 475 ± 22 Ma. We consider these two dates to be more reliable than the Rb–Sr dates, which are apparently more easily disturbed by later tec-

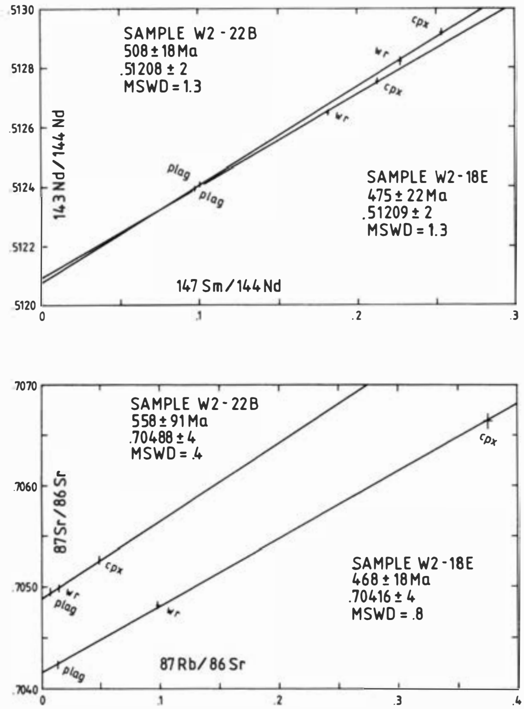

Fig. 3. Isochron diagrams for (a) Sm–Nd and (b) Rb–Sr results from the two samples of gabbro.

Table 1. Sm–Nd and Rb–Sr data

Sample/frac.	Sm[1]	Nd[1]	$^{147}Sm/^{144}Nd$[2]	$^{143}Nd/^{144}Nd$[4]	Rb[1]	Sr[1]	$^{87}Rb/^{86}Sr$[3]	$^{87}Sr/^{86}Sr$[4]
W2-22B plag	0.02	0.10	0.100568	0.512410 ± 10	1.00	391	0.00739	0.70495 ± 4
W2-22B cpx	1.46	3.52	0.252991	0.512921 ± 12	0.15	8.8	0.04841	0.70527 ± 4
W2-22B WR	1.14	3.06	0.227129	0.512823 ± 10	1.05	208	0.01462	0.70499 ± 4
W2-18E plag	0.32	1.98	0.097302	0.512395 ± 10	1.55	325	0.01378	0.70424 ± 4
W2-18E cpx	2.38	6.82	0.212600	0.512756 ± 10	2.52	19.5	0.37420	0.70664 ± 8
W2-18E WR	1.69	5.67	0.181137	0.512650 ± 5	6.72	200	0.09730	0.70488 ± 4

[1] ppm element
[2] error = ±0.25%
[3] error = ±0.5%
[4] 2σ errors, values applied to last digits of ratio.

tonothermal events. The regional metamorphic grade is only in the biotite zone, however, and the igneous minerals appear very fresh in thin-section.

The Honningsvåg Igneous Complex and adjacent metasediments

The new isotopic dates indicate a pre-Silurian age for the Honningsvåg Igneous Complex, in conflict with the interpretation that the rocks intrude fossiliferous Silurian strata. Therefore, two of us (AGK, JR) studied the available descriptions and spent several days on Magerøya checking critical relationship in the field. The results are discussed below, with emphasis on the contrasting interpretations.

Previous studies

The island of Magerøya has long been a goal for explorers and travellers because it is the northernmost landmass in Europe. Geologists had visited Magerøya, Honningsvåg, and Nordkapp well before most of the rest of Scandinavia, and Everest (1829, reproduced in Curry 1975) provided an excellent sketch map of the geology of the island.

Geul (1958) was the first to study the eastern part of Magerøya in detail, but his results were never properly published. He spent two months mapping the Honningsvåg Igneous Complex and the hornfelses, as well as the surrounding metasediments (Fig. 2). At the time of his mapping the metasediments were considered to be 'Eocambrian', because no fossils were known, and a diamictite ('tillite' in Fig. 2) at Duksfjord was shown by Holtedahl (1944) to be remarkably similar to the Late Precambrian tillites. Geul did not map the hornfelses as part of the 'Eocambrian' stratigraphy. He drew a thrust contact between gabbro and metasedimentary rocks at Kjelvik, where the contact was exposed (Fig. 2). Geul did not show that the gabbros intruded the 'Eocambrian' schists, but suggested that the Honningsvåg Igneous Complex was 'structurally predisposed', perhaps uplifted as a structural high, to come into contact with the nappes of isoclinally folded schists.

Geul's interpretations were greatly modified only one year after his work. During preparation of an excursion for the XXI International Geological Congress, crinoid stems were discovered in the metasediments, showing that the strata could not be Eocambrian (Holtedahl et al. 1960). Pentamerids and halysitids, definitive Silurian fossils, were found by one of us (JR) during the excursion itself (see Henningsmoen 1961; Føyn 1967). Holtedahl et al. (1960) and later Føyn (1967) discussed Geul's work and presented the central part of his map, showing the new fossil locations. The map did not extend to Kjelvik, where the thrust contact had been shown. Furthermore, in this simplified verion of the map, the hornfelses were not shown separately, as they are in Fig. 2, but were simply included within the 'gabbro complex', so that it appeared in the summary of Geul's conclusions (p. 211 in Føyn 1967) that Geul had reported contact metamorphism within the fossil-bearing rocks.

The next work in the area was a detailed strain analysis of a conglomerate in the fossiliferous section (Ramsay & Sturt 1970). The nearby Honningsvåg Igneous Complex was not discussed, and no fragments of gabbro were found in the polymict conglomerate. A gravity survey of Magerøya showed the gabbro to extend to a depth of over 6 km beneath Skipsfjord (Lønne & Sellevoll 1975).

Curry (1975) studied the Honningsvåg Igneous Complex and surrounding rocks. Her map does not indicate areas of contact-metamorphism, but shows the rocks that Geul mapped as hornfelses to be part of the Silurian stratigraphy. She noted many similarities between the Seiland Igneous Complex and the Honningsvåg Complex. Both complexes contain highly fluid ultramafic and mafic magmas, and were considered to have intruded during phases of regional deformation and metamorphism. The Honningsvåg Complex appeared to differ mainly in its presumed age and in its lack of alkaline rocks. Curry's mapping has not been published, but most of the main features are shown in map compilations by Roberts (1981, 1985b, 1987).

Andersen (1981, 1984a, 1984b) combined his own work with the work of Curry to describe the structure, metamorphism, and stratigraphy of the metasedimentary rocks of Magerøya. The isograds on his map of regional metamorphism (Andersen 1984a) are truncated or deflected near the Honningsvåg Igneous Complex (more or less along the 'garnet isograd' of Geul, Fig. 2). Andersen (1984b) revised and formally established Curry's stratigraphic units. Again the hornfelses were included within the Silurian stratigraphy. The Scandian orogenic event was precisely dated on southern and western Magerøya. The synorogenic granite at Finnvik (Fig. 1) yielded a date of 411 ± 7 Ma, and migmatite near Gjesvær (Fig. 1), supposed to be Finnmarkian, yielded a Scandian Rb–Sr whole-rock isochron of 410 ± 28 Ma (Andersen et al. 1982). The Honningsvåg Igneous Complex was presumed to be of the same age. Rock descriptions and interpretations, up to and including this work, are well summarized in the description to the 1:250000 map-sheet Nordkapp (Roberts & Andersen 1985).

Robins et al. (1987) studied the igneous petrology of a large part of the Honningsvåg Complex. In the large gabbro body extending from Skipsfjorden toward Sardnes (Fig. 2), they mapped cumulate layers of peridotite, troctolite, and gabbro. Layering in the gabbro is mainly parallel to layering in the contact-metamorphosed turbidites. Both rock units strike NE–SW and dip steeply southeast, and in both the tops are to the east (Robins et al. 1987; Andersen 1981).

Ramsay & Sturt (1976), Andersen (1979), and Kjærsrud (1985) mapped the stratigraphy and structures of the western, southern, and northern parts of the island, respectively. These studies did not directly involve the Honningsvåg Igneous Complex, which is restricted to the eastern part of the island. Since the Silurian fossils were discovered in 1960, all authors have adopted the interpretation that the Honningsvåg Complex was Silurian and synorogenic because it appeared to intrude the fossil-bearing strata.

Our observations

In our field work on Magerøya, we found Geul's original map (Fig. 2) to be quite accurate and most useful for the critical relationships, and in the discussion below we describe our observations and the various interpretations with reference to his map. The metamorphic grade on Magerøya is lowest along the southeastern coast, east of Honningsvåg. According to both Geul (1958) and Andersen (1984a) the grade here is below the garnet isograd, and measurements of illite crystallinity showed the rocks to be in the anchizone (Bevins et al. 1986). Sedimentary structures are well preserved along the southern coast, and it was here, east of Nordvågen, that the fossils were first found. From our observations, the primary relations between the igneous and sedimentary rocks also appear to be best preserved here.

At Location C (UTM coordinates 35W MV 04695 78786), east of Kjelvik (Fig. 2), coarse-grained gabbro lies in tectonic contact above the low-grade sediments, as shown by Geul. The contact is irregular, dipping southeast. Abundant quartz lenses appear in the metasediments at the contact. These lenses show strong rodding, with lineations and fold axes plunging N175W,10SW. The gabbro is generally massive, but is foliated within about a meter of the contact. An irregular lens of sheared granite, about 2 m thick and 5 m long, is found at the contact. The granite interfingers in intrusive contact with the gabbro. It seems that the gabbro was more competent and resistant to deformation than the granite and sediments. Whether the contact represents a thrust, as shown by Geul (Fig. 2), or a normal fault, is unclear.

West of Kjelvik, at Location D (670781), the contact between the low-grade schist and the hornfelses is not exposed, but it is marked by a small creek. As shown by the strike and dip symbols of Geul (Fig. 2), there is a small angular discordance between the schistosity of the low-grade metasediments and the bedding of the nearby hornfelses. The hornfelses are not schistose, but form blocky outcrops. They ring like porcelain when hit with a hammer, and break with a conchoidal fracture. The argillaceous hornfelses have small porphyroblasts of cordierite. The hornfelses include white psammite and muscovite-bearing quartzite, which are unlike the fine-grained dark turbidites southeast of the contact. The contact here is apparently a steep northwest-dipping fault.

West of Nordvågen, at Location E (642753), a high-angle fault striking about N60E and probably dipping steeply northwest separates gabbro and hornfels on the north from low-grade sediments on the south (Fig. 4). Both the hornfelses and the low-grade sediments are well-bedded turbidites and lithologically they are similar, but the hornfelses are cut by a large gabbro body and contain numerous thin sills of gabbro; locally they appear to have melted somewhat. The bedding in the hornfelses is oriented about N160E,30SW, while bedding south of the fault in the low-grade sediments is about N30E,45NW. The fault contact is not exposed, but in a small outcrop in a gravel quarry near the contact, white granite is exposed in contact with gabbro.

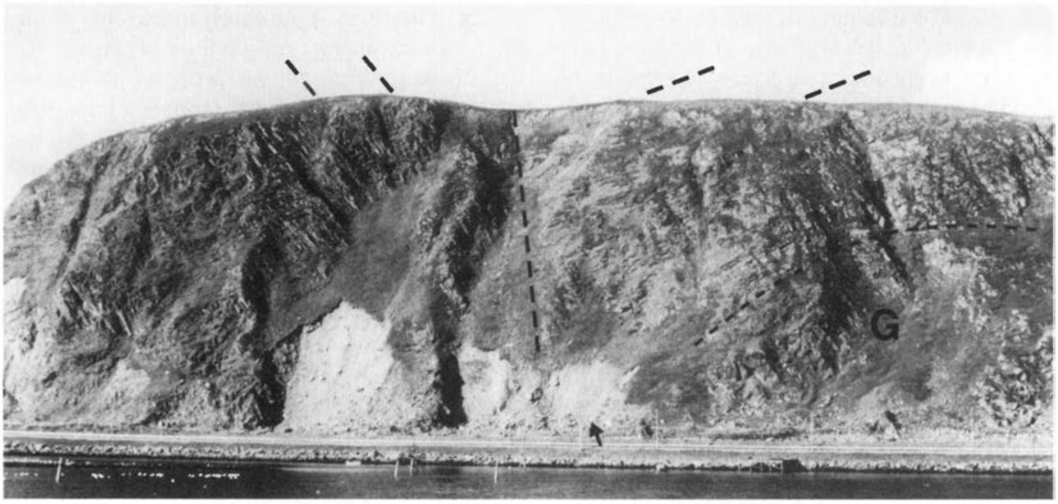

Fig. 4. Location E in Fig. 2, view west across the bay at Nordvågen. High-angle fault separates gabbro (G) and contact-metamorphosed turbidites from low-grade metamorphosed turbidites. Arrow points to small granite outcrop, not visible in photograph.

At Location F (638750), along the same contact about 500 m to the southwest, bedding in both the hornfelses and the low-grade sediments dips steeply west. Geul mapped a thick granite dike along the contact (Fig. 2). The granite follows the fault contact up the steep hillside and clearly cuts the low-grade sediments. The contact between Locations E and F is straighter than mapped by Geul (Fig. 2). The hornfelses west of the contact contain many sills of gabbro, while none were found in the granite or the low-grade sediments east of the granite.

At Location G (591785), on the west side of the gabbro massif, the contact dips steeply east beneath very coarse-grained gabbro. Geul (1958) thought that the metasediments here were not contact metamorphosed, and he mapped them as part of his Eocambrian sequence. Within the nearest few meters of the gabbro contact, however, the sediments are thoroughly melted, as pointed out by Roberts & Andersen (1985, p. 38) in an area about 1.5 km farther north. The metasediments along the western side of the gabbro here are apparently part of the gabbro/hornfels complex, although little other evidence of contact metamorphism is visible in the field.

Also at Location H (601829), southwest of Kamøyvær, the sediments show contact melting near the gabbro contact, although they too were mapped as schists by Geul. There are clearly more hornfelses near the gabbro bodies than are shown in Fig. 2.

The rocks east of the mapped granite of Location I (582833) are also partially melted hornfelses, and the granite separates these contact-metamorphosed rocks from regionally metamorphosed rocks to the west. An apophysis of the granite extends to the north and intrudes the gabbro northeast of Geul's presumed fault line. On the eastern side of the granite, the hornfelses are relatively massive. They are characteristically spotted, and garnets are present locally. On the western side, the rocks are typical regional-metamorphic schists, with staurolite, kyanite, and abundant garnet. One outcrop of contact-metamorphosed rock and a few outcrops of gabbro were also found on the western edge of the granite.

Geul's garnet isograd extends southward from the 'tail' of this granite (Fig. 2). Along the road south of the granite, this isograd line separates spotted hornfelses with well-preserved bedding from strongly foliated schists. The hornfelses are also locally foliated, and we could not always distinguish them from the schists. We did not attempt to follow the contact between schists and hornfelses across the rugged terrain to the south, but we think that the 'garnet isograd' represents the tectonic contact from the tail of the granite to near the coast at Sardnes. Geul showed this isograd as a probable fault on his cross-section III (Fig. 2) and on aerial photos it forms a clear lineament along which structures appear to be deflected and truncated. The lineament swings east near the coast, not west as does the garnet isograd.

Summary of our interpretations

Fault contacts appear to separate the gabbros and contact-metamorphosed rocks from the fossiliferous sediments. The faults mostly dip under the gabbro complex, but it is not clear whether the gabbro complex lay over or under the fossiliferous metasediments before the folding and high-angle faulting. In any case, the gabbro/hornfels complex appears to form a fault-bounded tectonic block, which we refer to as the Honningsvåg unit to distinguish it from the fossiliferous Magerøy sequence. The new dates show that the sediments of the Honningsvåg unit are not younger than Late Cambrian, while some of the rocks of the Magerøy sequence must be as young as Early Silurian.

Sedimentary structures are well preserved in the hornfelses. The sediments of the Honningsvåg unit apparently were not regionally deformed and metamorphosed until after intrusion and contact metamorphism, and we consider the Honningsvåg Igneous Complex to be pre-orogenic. Regional-metamorphic minerals and textures are well developed in the Magerøy sequence but poorly developed in the hornfelses of the Honningsvåg unit. The unit probably was tectonically emplaced against the schists before the climax of regional metamorphism, but the hornfelses were more resistant to recrystallization and penetrative deformation.

The stratigraphy and structure of central and western Magerøya

Previous studies

The hornfelses have been presumed to be stratigraphically continuous with the fossiliferous Magerøy sequence, and all these sedimentary rocks form the so-called Magerøy Supergroup (Andersen 1984). The Magerøy Nappe has been defined to include the Magerøy Supergroup together with the Honningsvåg Igneous Complex (Andersen 1981). This nappe has been interpreted to lie above significantly older rocks of the Finnmarkian nappes on western Magerøya. In the discussion below, we propose alternative stratigraphic and structural interpretations that are not consistent with the terms Magerøy Supergroup and Magerøy Nappe. We use these terms only to discuss the previous interpretations.

The Magerøy Supergroup was defined to include three main stratigraphic units, from bottom to top – the Kjelvik Group, the Nordvåg Group, and the Juldagnes Formation (Andersen 1984). Both the lower (Kjelvik) and upper (Juldagnes) units are characterized by monotonous turbidites with abundant greywacke and lesser amounts of pelitic rock. The middle unit (Nordvåg) is by far the most distinctive, with mappable conglomerates, calcite-marbles, dolomite-marbles, quartzites, and diamictites. These rocks are best displayed in the cores of the large-scale Duksfjord and Sardnes synforms, which are shown in Geul's cross-sections II and III, respectively (Fig. 2). The Sardnes synform is one of the prominent folds of the island of Magerøya (Andersen 1981).

According to the previous interpretation (Fig. 3 in Andersen 1981), the rocks of the Magerøy Supergroup in central Magerøya are inverted beneath an early polycline, or mushroom-shaped pair of anticlines, now mostly eroded away. Following the presumed inversion, the rocks were thrust-emplaced above the Finnmarkian-deformed rocks, and refolded by younger folds such as the Sardnes synform. Because of the inversion, the youngest strata (Juldagnes Fm.) are not found in the core of the Sardnes synform, but in two early synclines flanking the mushroom fold. One of these areas of the Juldagnes Fm. is to the east of the Sardnes synform, and one area is to the west, and they are never in contact.

Our observations

The area east and southeast of the Sardnes synform includes the best preserved and most typical rocks of the Juldagnes Fm. (Andersen 1984b). As shown by Andersen, the contact between greywacke-dominated turbidites of the Juldagnes Fm. on the east, and conglomerate and other distinctive rock types of the Nordvåg Gp. on the west follows more or less the garnet isograd of Geul (Fig. 2). Most of these Juldagnes rocks were apparently contact-metamorphosed by the

Honningsvåg gabbros, however (see Locations G and I above), and we now consider them to be part of the Honningsvåg unit and not the Magerøy sequence.

Abundant way-up indicators in these well-preserved Juldagnes turbidites show that the rocks face eastward (Andersen 1981, 1984), as do the nearby cumulate-layered gabbros (Robins et al. 1987). The Juldagnes rocks were though to be continuous with the schists of the Sardnes synform, and since the hornfelses preserve the best sedimentary structures and clearly face eastward away from the synform, they contributed to the interpretation that the stratigraphic units within the synform were inverted on a regional scale. We exclude these eastward-facing rocks from the Magerøy sequence, and contend that they no longer support the interpretation that the stratigraphy is regionally inverted.

As previously mentioned, greywackes west of the Sardnes synform lie structurally beneath the Nordvåg Gp. and have been interpreted to represent the Juldagnes Fm. that is stratigraphically above. The interpretation of regional inversion in this area has been supported by bedding–cleavage relationships (Andersen 1981), but in multiply deformed rocks such relationships may be deceptive, and sedimentary structures are more reliable. Several conglomerates were mapped by Andersen (1979, see Roberts 1981), and among these rocks we found unequivocal way-up indicators showing that the strata are not inverted west of the Sardnes synform. At Location J (556822), where the rocks dip steeply east into the Sardnes synform, two separate beds of conglomeratic turbidites each show sharp basal contacts and grade upward to the east. At Location K (512840), the beds dip more shallowly to the east, and again, separate conglomerate beds clearly show sharp bases and grade upward to the east. Location K is near the contact between the Nordvåg Gp. and Juldagnes Fm. (see Roberts 1981), and probably represents the regional facing direction of the strata. Andersen (Fig. 3, 1984) noted that conglomerates in central Magerøya commonly show reverse grading. If the sequence is normal, as we suggest, these reverse-graded conglomerates are normal graded.

Summary of our interpretations

We consider most of the Juldagnes Fm. of eastern Magerøya to belong to the Honningsvåg unit, and exclude these parts from the top of the Magerøy sequence. The turbidites of the Nordvåg Gp. also contain abundant greywacke (Andersen 1984b), and the Juldagnes greywackes near the coast at Nordvågen and at Sardnes, which we include in the Magerøy sequence, could be incorporated into the Nordvåg Gp.

Judging from the way-up data, the Duksfjord and Sardnes symforms are true synclines, the interpretation of two early synclines on either side is not needed, and no mushroom fold exists. If the sequence is normal, the greywacke-rich turbidites (Juldagnes Fm.) west of the Sardnes synform lie stratigraphically beneath the Nordvåg Gp. They may be equivalent to the greywackes of the underlying Kjelvik Gp., which previously has only been recognized in southeastern Magerøya (Andersen 1984).

The Nordvåg Gp. includes the diagnostic Silurian fossils and we now think that it lies stratigraphically above the other rocks of the Magerøy sequence. Thus only in the very highest stratigraphic levels, in the cores of the deep Sardnes and Duksfjord synclines and along the southeast coast, are the distinctive dolomites, limestones, quartzites, and diamictites preserved. Remarkably similar rocks and fossils are found in the Balsfjord Group, 300 km to the southwest (Bjørlykke & Olaussen 1981; Bergh & Andresen 1985). There, too a Silurian tillite-like diamictite occurs near the top of the sequence.

The greywackes of western Magerøya and the greywacke hornfelses of the Honningsvåg unit have been correlated (the Juldagnes Fm. of Andersen 1981, 1984). Although we now think that there is an important structural break between them, this correlation may be retained. The way-up indicators show that the greywackes of western Magerøya are stratigraphically older than the fossilferous Nordvåg Group. The isotopic dates show that the greywackes of the Honningsvåg unit are pre-Early Ordovician, also older than the Nordvåg Group. These interpretations are in agreement, and support Geul's suggestion that the greywackes and gabbros of the Honningsvåg unit were structurally uplifted from a deeper level.

The tectonostratigraphic position of the Magerøy sequence

Previous studies and interpretations

The Magerøy Nappe and the Skarsvåg Nappe, which overlies it to the northeast (Fig. 1), are generally recognized to be Scandian thrust nappes. In existing tectonostratigraphic schemes, these are the highest nappes, representing the only erosional remnants of the Upper Allochthon in Finnmark. All of the lower nappes have been considered to be of Finnmarkian age. These include the rocks of Gjesvær on western Magerøya, which are part of the large Kalak Nappe Complex representing the Middle Allochthon in Finnmark (Roberts & Gee 1985; Roberts 1985).

The rocks of the Kalak Nappe Complex are well known from Sørøya and the mainland south of Magerøya (Porsangerhalvøya). A consistent transgressive stratigraphy is recognized within these nappes (Ramsay 1971; Gayer et al. 1985). Precambrian migmatitic gneisses form the base of the sequence. Above lies a thick cover of the Klubben Psammite Group, with the basal unconformity and basal conglomerate locally preserved (Ramsay et al. 1979). The Klubben Psammite grades upward into pelitic rocks of the muscovite-rich Storelv Schist Group or the biotite-rich Kokelv Schist Group. These are overlain by the thin or absent Falkenes Marble and Aafjord Schist Groups, and then the thicker Hellefjord Schist Group. The rocks of the Hellefjord Schist Group on Sørøya are well described and interpreted as turbidites (Roberts 1968a, 1968b).

Repetitions and disturbances of this stratigraphy allow recognition of the individual nappes of the Kalak Nappe Complex (Ramsay et al. 1985; Gayer et al. 1985). Unequivocal fossils are not known from any of the rocks, but the lower psammites are thought to be Late Precambrian and the upper turbidites are thought to be older than the Late Cambrian Finnmarkian event. There have been no attempts to correlate any of the rocks of the Finnmarkian Kalak Nappe Complex with those of the Scandian Magerøy Nappe, because they have not been thought to overlap in age. Scandian isotopic dates suggest that some of the rocks of the Kalak Nappe Complex were strongly heated during the Scandian event (Andersen et al. 1982), but in a detailed structural and metamorphic study of the Kalak Nappe Complex south of Magerøya, only one major event could be recognized (Gayer et al. 1985).

The western, basal contact of the Magerøy Nappe is interpreted as a profound tectonic discordance, with the Silurian rocks separated by mylonites from the underlying psammites (Ramsay & Sturt 1976). At the contact, the highest unit of the Magerøy Supergroup (Juldagnes Fm.) has been interpreted to lie above the lowest unit of the Finnmarkian-deformed stratigraphy (Klubben Psammite Group), with the intermediate units tectonically removed (Roberts & Andersen 1985). From our observations of way-up indicators, however (Locations J and K, described above), we interpret this structurally lowest part of the Magerøy sequence to be stratigraphically low as well.

The Skarsvåg Nappe, overlying the Magerøy Nappe to the northeast contains high-grade schists and gneisses that most resemble the Kokelv or Storelv Schist Group (Kjærsrud 1985). It has been generally presumed that they are rocks of the Kalak Nappe Complex that were involved in the Scandian thrusting. The Skarsvåg Nappe lies in a double synform plunging northeast, with axes parallel to the Duksfjord and Sardnes synforms. Geul (Fig. 2, cross-section I) interpreted the granitic rocks on each side of the synform to be continuous at dept. Andersen (1981), Kjærsrud (1985), and Roberts & Andersen (1985) did not consider the granites to be related to each other or to the Skarsvåg Nappe, and placed the thrust contact above the granites, within the schists. Their descriptions show, however, that the two granitic rocks are very simlar, as they are both porphyritic tourmaline-bearing adamellites. The metasedimentary rocks of the Skarsvåg Nappe also contain tourmaline (Kjærsrud 1985).

Our observations and interpretations

The base of the Magerøy sequence is marked by several meters of highly strained rocks and mylonites, as described by Ramsay & Sturt (1976). Psammites of the Klubben Psammite Group underlie the contact, but within the sheared contact zone we noted semipelitic schists, with garnet, muscovite, and K-feldspar. These rocks resemble those of the Storelv Schist Group, which may have been considerably thicker before the intensive shearing.

On the island of Hjelmsøya, west of Magerøya, turbidites of the Hellefjord Schist Group overlie a thin zone of Storelv Schist and then Klubben Psammite (Fig. 1). We could not visit this island but the geology has been described by Ramsay et al. (1979). The map pattern and rock descriptions are similar to Magerøya, if the lower part of the Magerøy sequence (the Juldagnes Fm.) is equivalent to the Hellefjord Schist Group. Mylonites have not been reported on Hjelmsøya, but the contact between the Hellefjord Schist Group and the Storelv Schist Group is not exposed (Ramsay et al. 1979), presumably because the rocks at the contact weather easily.

On the nearby island of Havøya, the western contact of the Hellefjord Schist also weathers easily, but where it is exposed at the head of Garpviken (159795), it is a zone of mylonites. Ramsay et al. (1985) mapped the contact as a major thrust. The turbidites, semipelites, and psammites are overturned, as on the southern tip of Hjelmsøya (Ramsay et al. 1979), but otherwise we think that the rock types and high-strain textures are strikingly similar to those at the base of the Magerøy sequence. Thus, both the Magerøy sequence and the Hellefjord Schist Group are, locally at least, bounded beneath by mylonitic thrust contacts.

There are no marker horizons or distinctive stratigraphic units within the lower parts of the Magerøy sequence or the Hellefjord Schist Group, and no metavolcanites are known. In several places, however, thin sills of biotite-hornblende granitic gneiss (Roberts 1968a) and adamellitic gneiss (Gayer et al. 1985) have been mapped in the lower part of the Hellefjord Schist Group (granitic gneisses, Fig. 1). Such granitic sills have been mapped also in the lower part of the Magerøy sequence (Andersen 1981; Kjærsrud 1985), and our reconnaissance observations extend the known length of the thickest sill by about a kilometer (Fig. 1). We have briefly compared the turbidites and granitic sills on Magerøya and on Porsangerhalvøya east of Snøfjorden, and we think that they may be both stratigraphically and tectonostratigraphically equivalent. The rocks east of Snøfjorden are part of the Molvikfjell Nappe, which lies in a broad synform at the very top of the 'Finnmarkian' Kalak Nappe Complex (Gayer et al. 1985). The Magerøya Nappe lies in a broad synform at the very bottom of the 'Scandian' nappe sequence. Thus the previous interpretations placed the Magerøy Nappe directly above the Molvikfjell Nappe, although these nappes are never in contact. We think that the Magerøy Nappe is not above, but is equivalent to the Molvikfjell Nappe. Correlation of these nappes would not modify the tectonostratigraphy, but would include the Silurian Magerøy sequence as an integral part of the Kalak Nappe Complex, and suggest that the Kalak nappes were stacked during the Scandian event.

The top of the Magerøy sequence is cut off by the basal thrust contact of the Skarsvåg Nappe, but because of strong deformation and high-grade metamorphism, there is no well-defined thrust contact. The thrust contact must be inferred on lithologic grounds.

The Skarsvåg and Opnan adamellites are very similar lithologically. They are rather dark, biotite-rich rocks, containing K-feldspar porphyroclasts of various sizes, and muscovite and garnet. Texturally, the Skarsvåg adamellite is more sheared than the Opnan adamellite. At Location L (573873), the rocks are mostly covered by the lake and Quaternary deposits, but within the limits of exposure, the Opnan and Skarsvåg adamellites appear to be continuous on the surface. At Location M (576899) the adamellites are extensively interlayered with the coarse-grained and migmatitic rocks of the Skarsvåg Nappe. These rocks are coarse-grained biotite-rich pelites, which do not resemble the fine-grained and layered rocks of the Magerøy sequence. We prefer to follow the suggestion from Geul's cross-section I (Fig. 2) and place a thrust contact beneath the adamellites, thus including them in the Skarsvåg Nappe (Fig. 1).

Concluding remarks

Our working hypothesis, that the Scandian and Finnmarkian orogenic phases in Finnmark represent a single phase, appears to be still workable. It has successfully predicted that the Honningsvåg gabbros would yield pre-Silurian isotopic dates, and that they could be tectonically separated from the Silurian fossiliferous succession. We agree that most of the geological data currently available can be made to fit either this hypothesis or the dichotomous Finnmarkian–Scandian model. Further tests of the alternative interpretations could include isotopic and structural dating of the various adamellites, stratigraphic comparisons of the turbiditic sequences on Sørøya and Magerøya, and study of the contact between Seiland gabbro and Hellefjord schists on Sørøya.

Since deposition of the Magerøy sequence extended continuously upward into the Silurian, none of these rocks could have been affected by a Finnmarkian orogenic event. We are confident that the lower part of the Magerøy sequence is stratigraphically and structurally equivalent to the Hellefjord Schist Group. Thus we attribute the thrusting, regional metamorphism, and large-scale folding of the Hellefjord Schist Group and the other groups of the Sørøy stratigraphy to the Scandian phase of orogenesis.

The Honningsvåg tectonic unit may represent marine sediments and mafic intrusions of Early Ordovician oceanic crust. The turbidites of the Hellefjord Schist Group on Sørøya also contain lenses of metagabbro (Roberts 1968a), and may reflect the same environment. Roberts (1968a) suggested that these metagabbros are related to the Storelv Gabbro of the Seiland Igneous Complex. Their age is not well constrained, but the youngest, presumably Early Ordovician, rocks of the Seiland Complex are mafic dikes (Fig. 2 in Robins & Gardner 1975). Thus there may be a link between the Honningsvåg gabbros and the younger mafic rocks of the Seiland Complex, while the older rocks and ductile structures of the Seiland Complex may represent an earlier stage of continental rifting.

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