Kyanite-grade metamorphism in the Evenes and Bogen Groups, Ofoten, North Norway

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Directly north of Ofotfjorden in northern Norway, pelitic schists within the Evenes and Bogen Groups contain the mineral assemblage garnet + biotite ± kyanite ± staurolite + white mica + quartz ± plagioclase. This assemblage implies metamorphic P-T minima of ~ 540°C and ~ 4.8 kb. The rocks are thus at a higher grade than suggested by previous reports, which placed them in the greenschist facies. This indicates that several metamorphic allochthons in Ofoten, including rocks of the Narvik, Evenes, Bogen, and Niingen Groups, are all at kyanite grade, supporting recent interpretations which on structural grounds concluded that the metamorphic peak outlasted stacking of these allochthons. A proposed correlation of the Evenes Group with the Middle Ordovician-Lower Silurian Balsfjord Supergroup implies that this stacking and associated kyanite-grade metamorphism are post-early Silurian and are related to the Scandian phase of the Caledonian orogeny.

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Our mapping, structural analysis, and petrographic studies in Ofoten have concentrated on the structural and metamorphic development of the Caledonian nappe stack. Figure 1 shows a preliminary interpretation of the tectonostratigraphic sequence in the Skånland area. Details of the lithologic sequence and petrography will be presented in a later paper (Steltenpohl in prep.). In this note we present field and petrographic observations regarding metamorphism of the Evenes and Bogen Groups, which may have major implications for the regional geology.

Tectonostratigraphic context

The Evenes Group and overlying Bogen Group contain a series of marbles and mica schists, with subordinate quartzites and metaconglomerates (Strand 1960). Gustavson (1966) included both the Evenes and Bogen Groups in his Salangen Group. However, two distinct lithologic assemblages, which correspond well to the Evenes and Bogen Groups of Strand (1960), are clearly present within the Salangen Group in the Skånland area. We thus use the earlier nomenclature here.

South of Ofotfjorden (Fig. 1), the base of the Evenes Group is marked by the Elvenes Conglomerate, which was deposited unconformably upon the schists, calc-schists, amphibolites, and ultramafic rocks of the Narvik Group, which are presently at kyanite grade (Foslie 1941, 1949, Gustavson 1966, 1972, Hodges 1982a, Tull et al. in press). The thrust beneath the Narvik Group (Gustavson 1966, 1974, Hodges 1982a) cuts structurally upward passing northward so that the entire Narvik group and the Elvenes conglomerate are missing north of Ofotfjord. In this northern area, the thrust places Evenes Group marbles upon 100–200 m of mica schist and marble, which we will call the 'basal' allochthon. The 'basal' allochthon directly overlies Precambrian granitic basement. Gustavson (1974) correlated the 'basal' allochthon with either the Narvik or Rombak Groups; we doubt that these rocks correlate with the Narvik Group, but are uncertain of their affinities pending more detailed study.

The contact between the Evenes and Bogen Groups is characterized by: 1) a lithologic break, from the marble-dominated Evenes Group which contains rare and minor mafic intrusions, to the calc-schist dominated Bogen Group which was intruded by numerous concordant granite sheets prior to most of the penetrative deformation; and 2) a zone of concentrated strain in which units in the underlying Evenes Group are transposed and locally truncated.

The contact could be either a thrust or a modified unconformity. A conglomerate present at or near the structural top of the Evenes Group

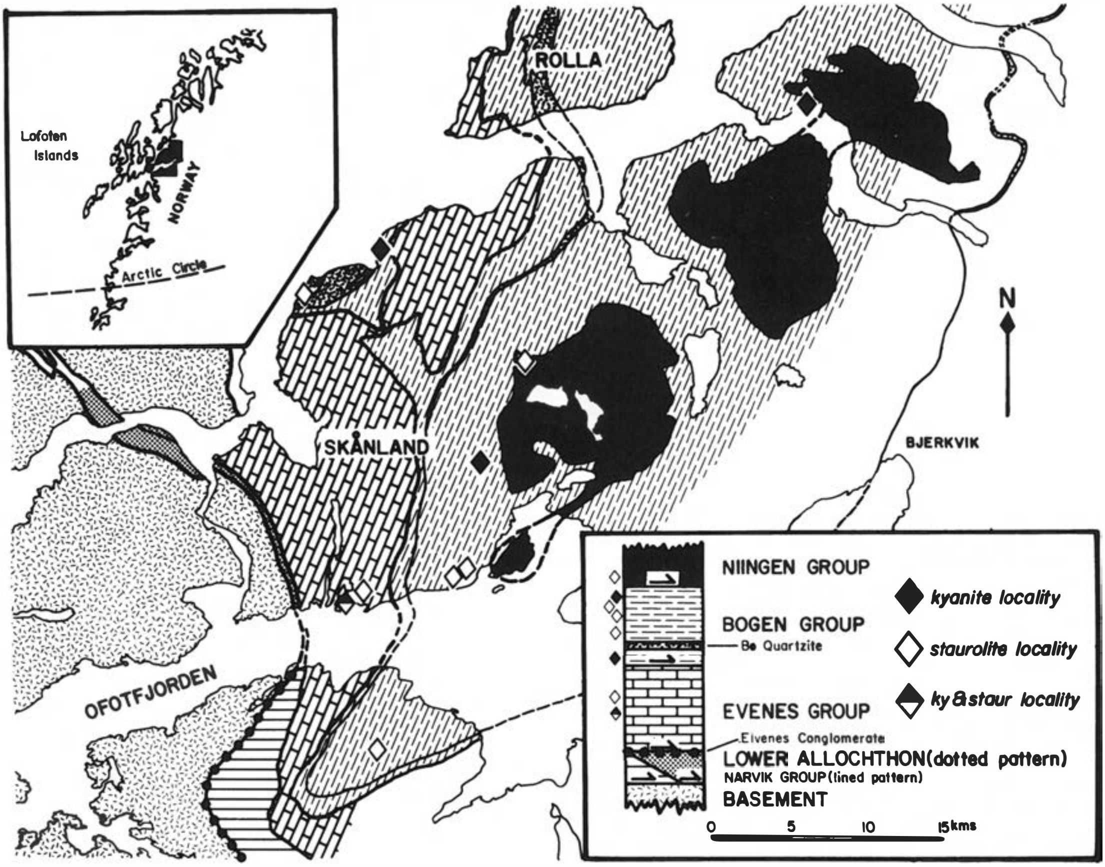


Figure 1. Tectonic map and simplified tectonostratigraphic column of the Skånland area, showing kyanite and staurolite localities. Tectonic units modified from Gustavson (1974).

suggests that the contact may be an inverted unconformity. The absence of granitic intrusions in the structurally lower Evenes Group could be interpreted to indicate that it was deposited upon the Bogen Group after intrusion of the granite sheets, and then the sequence was tectonically inverted. This would imply that the conglomerate at the top of the Evenes Group is equivalent to the Elvenes conglomerate at its base, and that a major structural repetition occurs within the Evenes Group. The lithologies of these two conglomerates are dissimilar, and we see no evidence for such a repetition. Further, interpretation of the contact as an unconformity implies that the Bogen Group is structurally equivalent to the Narvik Group, which it does not lithologically resemble. Combined with the presence of concentrated strain and local truncations of rock units at the contact, this leads us to favour the view that the Evenes and Bogen Groups are separate nappes which were thrust together.

The structurally highest nappe preserved in Ofoten comprises rocks of the Niingen Group, a scarcely studied lithologic assemblage broadly similar to the Narvik Group (Gustavson 1966). The contact between the Bogen Group and overlying Niingen Group is a low-dipping zone of intense foliation which separates contrasting suites of metasedimentary rocks. Intrusions in the Niingen Group are generally pegmatitic, while those in the Bogen Group are fine grained (Gustavson 1966, Steltenpohl in prep.). We recognize no retrograde metamorphism along this contact; mineral assemblages in the highly strained rocks at the contact are the same as those away from the thrust. No evidence of truncation or transposition of the principal metamorphic fabrics across this or the other probable nappe boundaries has been found in the Skånland area. If this contact reflects major tectonic juxtaposition, it would appear to predate the metamorphic peak.

Prograde metamorphism

Nine occurrences of kyanite and/or staurolite have been located in the Evenes and Bogen Groups (see Fig. 1 for geographic and tectonostratigraphic locations). The mineral assemblages are (Fig. 2a):

1) Kyanite + garnet + biotite
2) Staurolite + garnet + biotite
3) Kyanite + staurolite + garnet + biotite

The rocks also contain quartz, white mica, and plagioclase. In the idealized pelitic system (Thompson 1957), assemblages 1 and 2 are divariant, while assemblage 3 is univariant. It is likely that the actual variances are higher due to significant amounts of CaO and MnO, although assemblage 3 alternatively may indicate internal buffering of f_{H_2O} (Rumble 1978, Hodges & Spear 1982). The absence of staurolite in assemblage 1 implies metamorphic P and T above the intersection of the quasi-univariant reactions:

staurolite + muscovite + quartz
= kyanite + garnet + biotite + H_2O (1)
kyanite = sillimanite (2)

This intersection was placed by Carmichael (1978) at 540°C and 4.8 kb, based on experimental calibrations and field observations. If we assume that additional components have stabilized staurolite in assemblages 2 and 3, then assemblage 1 is probably the most reliable indicator of grade because it more closely approaches the simplified systems used in experimental calibration. In this case, Carmichael's (1978) P-T values for the intersection of the univariant equilibria are *minima* for the metamorphic conditions of the rocks. The presence of staurolite in some assemblages probably indicates that this temperature is not greatly exceeded, but pressures as high as 9–10 kb are not excluded. Petrological studies in progress will better quantify the metamorphic conditions.

Retrograde metamorphism

Retrograde metamorphism is common but erratically developed in the Skånland area. Retrogression is strongest in rocks affected by late fold-phases which post-date the metamorphic peak (F_2, F_3 of Gustavson 1972, F_3, F_4 of Bartley 1981, in press, and Steltenpohl 1983, in prep.). Retrograde metamorphism does not appear to be restricted to or concentrated at any particular structural level. In some retrograded samples, greenschist-facies mineral assemblages replace amphibolite-facies minerals along late-stage spaced cleavage planes (Fig. 2b). The typical retrograde mineral assemblage in pelites is

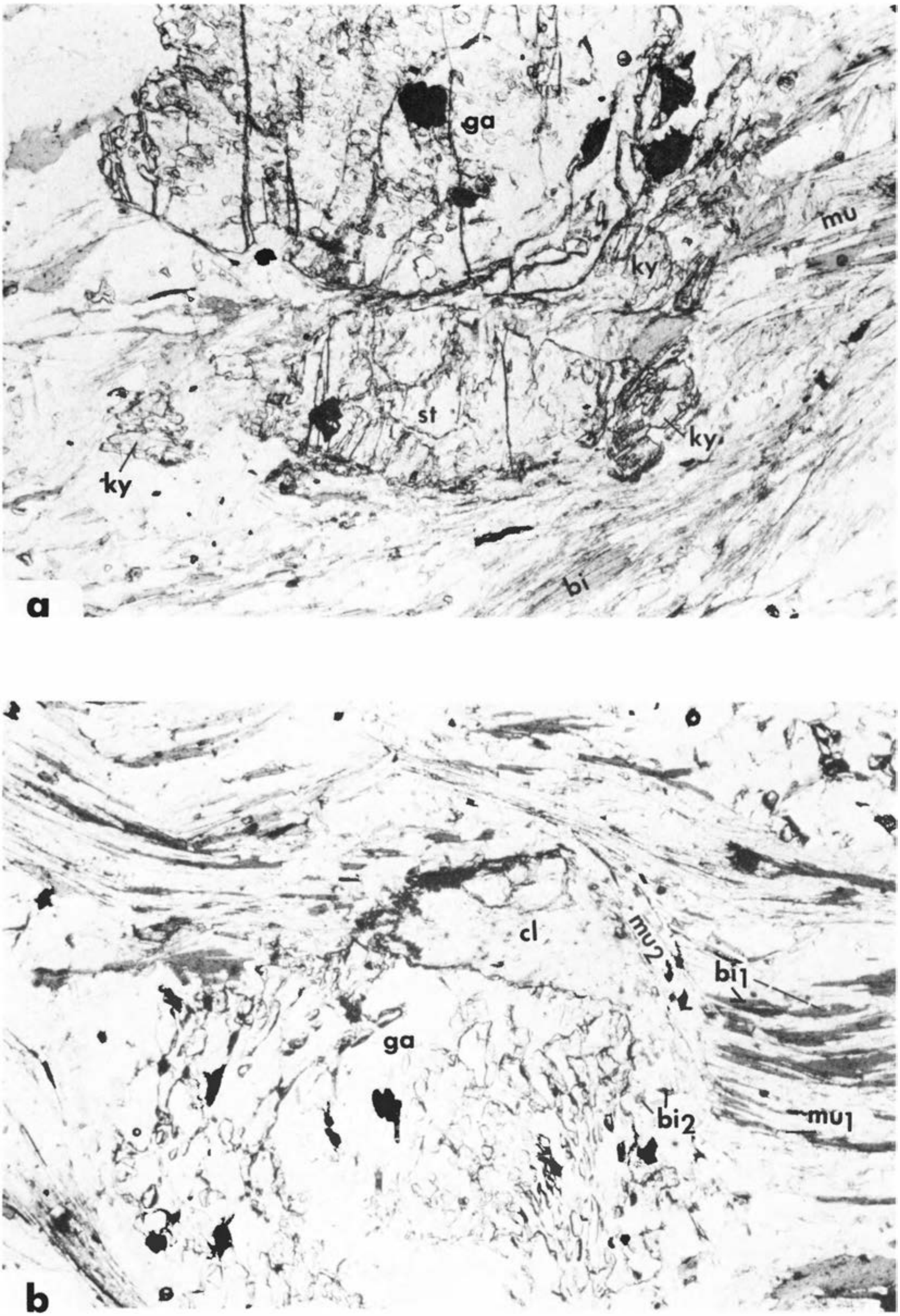
chlorite + biotite ± white mica ± epidote
± quartz.

Other samples contain these retrograde phases without development of a late-stage cleavage.

It is unclear whether garnet was stable during the retrograde metamorphism. In many samples, garnet is partly replaced by chlorite; however, this may only reflect a shift in the stable garnet composition during cooling. Some garnets show inclusion-free overgrowths over 'snowball' cores (Gustavson 1966, Juve 1967, Steltenpohl 1983). In similar garnets from the Narvik Group, electron microprobe analyses suggest that rims grew during cooling and may relate to retrogression (Hodges 1982b).

Discussion

The metamorphic map of southern Troms and Ofoten by Gustavson (1966) shows the bulk of the Salangen Group (i.e., the Evenes and Bogen Groups) to be within the garnet zone of the greenschist facies. Part of the Salangen Group on Rolla (see Fig. 1 for location) is shown to be within the staurolite and kyanite zones (amphibolite facies), as is the overlying Niingen Group. Gustavson (1966) shows a 'thrust plane (?)' which places kyanite-grade Niingen Group rocks upon garnet-grade Salangen Group rocks, which implies a metamorphic inversion at the contact. Gustavson (1966, p. 131) noted that the absence of kyanite in the Salangen Group might reflect high CaO content rather than a difference in metamorphic grade, but he placed the Salangen Group rocks in the garnet zone for the purposes of the map. The present work extends the kyanite/staurolite zones from Rolla southward throughout the Evenes and Bogen group rocks of the western limb of the Ofoten synform (Fig. 1). There appears to be no difference in metamor-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phic grade between the Niingen Group and underlying rocks.

All of the non-retrograde mineral assemblages we have observed in the Evenes and Bogen Groups are consistent with kyanite-grade metamorphism. The usual pelitic assemblage is garnet + biotite + white mica + quartz ± plagioclase, which is a stable assemblage at metamorphic grades from the garnet zone up through the sillimanite zone. Recent studies in western Ofoten have failed to find field or petrographic evidence for post-metamorphic structural breaks between the high-grade cover units. The structural histories of the nappes from the metamorphic peak onward are indistinguishable (Bartley 1981, in press, Tull et al. in press, Hodges, 1982a, in prep., Steltenpohl in prep.). Prior to the metamorphic peak, different cover units may have had different histories. However, later deformation and kyanite-grade metamorphism have made evidence for early deformation sparse and ambiguous.

We thus believe that the Narvik, Evenes, Bogen, and Niingen Groups were metamorphosed together at kyanite grade, during or directly following any tectonic stacking. The new kyanite localities strongly support this interpretation. We support the suggestion made by Gustavson (1966) that the common absence of kyanite and staurolite in the Evenes and Bogen Groups reflects bulk composition rather than metamorphic grade.

A further implication of this interpretation regards the timing of kyanite-grade regional metamorphism of the allochthons. The Silurian final phase of the Scandinavian Caledonide orogen has been termed the Scandian phase by Gee (1975). However, the metamorphic peak in the high-grade Caledonian nappes of Finnmark occurred during the Cambro-Ordovician Finnmarkian phase of the Caledonian orogeny (Sturt et al. 1978). The Lyngen ophiolite nappe, located approximately 100 km north of Ofoten, was emplaced and metamorphosed during the Finnmarkian. The Lyngen nappe is unconformably overlain by the greenschist facies Balsfjord Supergroup (Minsaas 1981, Minsaas & Sturt 1981, Binns & Matthews 1981), which contains Middle Ordovician to Lower Silurian fossils. Parts of the Balsfjord Supergroup can be directly correlated southward with the Lower Silurian Sagelvvatn Group (Bjørlykke & Olaussen 1981). Boyd (1983) recently recognized low-grade metasedimentary rocks at Bjerkvik (see Fig. 1 for location), which are generally similar to the Sagelvvatn Group and may be a southward continuation into Ofoten of the low-grade Silurian rocks.

Detailed study of the lithostratigraphy of the Evenes Group (Steltenpohl & Tull in prep.) supports the correlation proposed by Binns (1978) of the Evenes Group with Silurian rocks of the Balsfjord Supergroup. The correlation cannot be proven until the area between Sagelvvatn and Ofoten has been mapped in more detail. However, if this correlation is correct, then the stacking and metamorphism of the kyanite-grade allochthons in Ofoten must be post-early Silurian, rather than Finnmarkian. This requires major post-early Silurian transport of this composite allochthon after the metamorphic peak, in order to juxtapose the composite kyanite-grade allochthon with low-grade Silurian rocks. Pre-Silurian, perhaps Finnmarkian, deformation may have affected the Narvik Group, which contains dismembered ophiolites (Hodges 1982a, in prep., Boyd 1983, P. Crowley, pers. commun.) possibly lated to the Lyngen ophiolite. However, it appears that in Ofoten, Finnmarkian structures, if present, have been virtually obliterated by post-early Silurian events.

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Figure 2. Photomicrographs of Evenes Group schists.
a. Kyanite (ky) + staurolite (st) + garnet (ga) + biotite (bi) + muscovite (mu) in a pelitic schist of the Evenes Group. Long dimension of photo is 5 mm.
b. Retrograde features in Evenes Group pelitic schist. The prograde assemblage is garnet (ga) + biotite (bi_1) + muscovite (mu_1). The retrograde assemblage is chlorite (cl) + biotite (bi_2) + muscovite (mu_2). Micas mu_1 and bi_1 define the prominent lepidoblastic foliation which is slightly inclined to the right of the photo. A late-stage spaced cleavage, steeply inclined in the photo, crenulates the earlier foliation and truncates the right-hand side of the garnet porphyroblast, with resulting formation of chlorite. Long dimension of the photo is 5 mm.

References

Bartley, J. M. 1981: *Structural geology, metamorphism, and Rb/Sr geochronology of east Hinnøy, north Norway*. Unpubl. Ph. D. dissertation, Massachusetts Institute of Technology, Cambridge, USA, 263 pp.

Bartley, J. M. in press: Caledonian structural geology and tectonics, east Hinnøy, north Norway. *Nor. geol. unders.*

Binns, R. E. 1978: Caledonian nappe correlation and orogenic history in Scandinavia north of lat 67°N. *Geol. Soc. Am. Bull. 89,* 1475–1490.

Binns, R. E. & Matthews, D. W. 1981: Stratigraphy and structure of the Ordovician-Silurian Balsfjord Supergroup, Troms, North Norway. *Nor. geol. unders. 365,* 39–54.

Bjørlykke, A. & Olaussen, S. 1981: Silurian sediments, volcanics, and mineral deposits in the Sagelvvatn area, Troms, North Norway: *Nor. geol. unders. 365,* 1–38.

Boyd, R. 1983: The Lillevik dike complex, Narvik: geochemistry and tectonic implications of a probable ophiolite fragment in the Caledonides of the Ofoten region, N. Norway: *Nor. Geol. Tidsskr. 63,* 39 – 54.

Carmichael, D. 1978: Metamorphic bathozones and bathograds: a measure of the depth of post-metamorphic uplift and erosion on a regional scale. *Am. J. Sci. 278,* 769–797.

Foslie, S. 1941: Tysfjords geologi. *Nor. geol. unders. 149,* 298 pp.

Foslie, S. 1949: Håfjellsmulden i Ofoten og dens sedimentære jern-mangan-malmer. *Nor. geol. unders. 174,* 129 pp.

Gee, D. G. 1975: A tectonic for the central part of the Scandinavian Caledonides. *Am. J. Sci. 275-A,* 468–515.

Gustavson, M. 1966: The Caledonian mountain chain of the southern Troms and Ofoten areas. Part I. Basement rocks and Caledonian metasediments. *Nor. geol. unders. 239,* 162 pp.

Gustavson, M. 1972: The Caledonjan mountain chain of the southern Troms and Ofoten areas. Part III. Structures and structural history. *Nor. geol. unders. 283,* 56 pp.

Gustavson, M. 1974: Bergrunnskart "Narvik", 1:250000. *Nor. geol. unders.,* Trondheim.

Hodges, K. V. 1982a: *Tectonic evolution of the Aefjord-Sitas area, Norway-Sweden*. Unpubl. Ph. D. dissertation, Massachusetts Institute of Technology, Cambridge, USA, 192 pp.

Hodges, K. V. 1982b: The use of geothermometry and geobarometry to constrain the uplift history of a portion of the Scandinavian Caledonides. *Geol. Soc. Am. Abstracts with Programs 14,* 516.

Hodges, K. V. & Spear, F. S. 1982: Geothermometry, geobarometry and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire. *Am. Mineral. 67,* 1118–1134.

Juve, G. 1967: Zinc and lead deposits in the Håfjell syncline, Ofoten, northern Norway. *Nor. geol. unders. 244,* 54 pp.

Minsaas, O. 1981: *Lyngenhalvøyas geologi, med spesiell vekt på den sedimentologiske utvikling av de Ordovisisk-Siluriske klastiske sekvenser som overligger Lyngen gabbro kompleks*. Unpubl. cand. real. thesis. University of Bergen, 295 pp.

Minsaas, O. & Sturt, B. A. 1981: The Ordovician clastic sequence immediately overlying the Lyngen gabbro complex and its environmental significance. *Terra Cognita 1* (Uppsala Caledonide Symposium abstracts), 59–60.

Rumble, D. III 1978: Mineralogy, petrology, and oxygen isotopic geochemistry of the Clough formation, Black Mountain, western New Hampshire, U.S.A. *J. Petrol. 19,* 317–340.

Steltenpohl, M. G. 1983: *The structure and stratigraphy of the Ofoten synform, North Norway*. Unpubl. M. S. thesis, University of Alabama, Tuscaloosa, USA, 108 pp.

Strand, T. 1960: Cambro-Silurian deposits outside the Oslo region, Geology of Norway. *Nor. geol. unders. 208,* 151–169.

Sturt, B. A., Pringle, I. R. & Ramsay, D. M. 1978: The Finnmarkian phase of the Caledonian orogeny. *J. geol. Soc. London 135,* 597–610.

Thompson, J. B., Jr. 1957: The graphical analysis of mineral assemblages in pelitic schists. *Am. Mineral. 42,* 842–858.

Tull, J. F., Bartley, J. M., Hodges, K. V., Andresen, A., Steltenpohl, M. G., & White, J. M. in press: The Caledonides in the Ofoten region (68°–69°), North Norway: key aspects of tectonic evolution. *In* Gee, D. G., and Sturt, B. A., (eds.), *The Caledonide Orogen – Scandinavia and Related Areas*. New York, Wiley-Interscience Publishers.