A U–Pb zircon age for the Råna intrusion, N. Norway: New evidence of basic magmatism in the Scandinavian Caledonides in Early Silurian time

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Four morphologically distinctive zircon types from quartz-bearing gabbronorite in the Råna intrusion in the Narvik Nappe Complex yield coincident and concordant U–Pb analyses indicating a crystallization age of 437^{+1}_{-2} Ma. The intrusion, which consists of ultramafic and mafic cumulates derived from a high-MgO tholeiitic parental magma, was emplaced into argillaceous sediments within a probable marginal basin or back-arc setting prior to its tectonic emplacement onto the Baltoscandian Shield. The age of the Råna intrusion, together with other zircon ages from similar layered mafic intrusions and ophiolites in Norway, provide evidence for a distinct and possibly short-lived period of back-arc spreading and mafic plutonism in the upper part of the Upper Allochthon and in the Uppermost Allochthon of the Scandinavian Caledonides in Early Silurian time. The intrusion was emplaced during a period of regional crustal extension that post-dates the local D_1 deformational phase and pre-dates phases D_2–D_6. The main period of regional metamorphism (and D_{2-6}) in the Narvik Nappe Complex post-dates emplacement of the Råna intrusion, and it is concluded that these latest deformational phases are probably related to the medial Silurian Scandian orogeny and not the Cambrian–Early Ordovician (?) 'Finnmarkian' orogeny, as previously supposed.

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Introduction and geological setting

The Råna intrusion (Foslie 1941; Boyd & Mathiesen 1979; Barnes 1986, 1989) is a layered ultramafic-mafic intrusion located in the Narvik Nappe Complex in the Caledonides of N. Norway, roughly 20 km SW of Narvik (Figs. 1, 2). Attention has been focused on the intrusion largely because of its Ni–Cu mineralizations, particularly the Bruvann deposit, located in the northwestern part of the complex.

The geology of the Narvik Nappe Complex or parts thereof has been described by Foslie (1941), Gustavson (1974 and references therein) and more recently by Hodges (1982, 1985), Hodges & Royden (1984), Boyd (1983), Barker (1984, 1986a, b), Tull et al. (1985), Crowley (1983, 1985) and Crowley & Spear (1987). The work of several of these authors but especially Hodges (1982, 1985), Barker (1984) and Crowley (1985) has shown that the allochthonous units named the Rombak Group and the Narvik Group by Gustavson (1974 and references therein) consist of several nappes, all at middle to upper amphibolite facies metamorphic grade (Hodges 1982; Barker 1986a; Crowley & Spear 1987). This sequence of tectonic units is described as the Narvik Nappe Complex (Boyd & Søvegjarto 1983) (Fig. 1).

Certain geological units in the Narvik Nappe Complex can be traced to adjoining areas with confidence, whereas other units are only locally developed and not easily correlated with units in nearby areas. Table 1 shows a possible correlation scheme for the major tectonostratigraphic units defined in four separate studies. The Råna intrusion outcrops over an area of 70 km^2 in the uppermost part of the Narvik Nappe Complex of Boyd and Søvegjarto (1983), equivalent to the Kvernmo Nappe of Barker (1986a). A smaller, petrologically similar body lies 40 km to the SSW in the upper part of the Marko Nappe of Crowley & Spear (1987).

The upper boundary of the Narvik Nappe Complex is marked by a thrust zone with discontinuous fragments of ophiolite overlain by conglomerate, partly derived from the ophiolitic material, and other sediments: (Bjerkvik Nappe of Boyd & Søvegjarto (1983) (Fig. 1), Gratangseidet Nappe of Barker (1986a)). This sequence is considered to represent the same tectonostratigraphic level as the Lyngen ophiolite and its supracrustal cover sequence, 130 km to the NE (Boyd 1983). The ophiolite fragments and overlying metasedimentary rocks are at a lower metamorphic grade, upper greenschist facies, and have a simpler tectonic history than the rocks of the underlying Narvik Nappe Complex (Boyd 1983; Barker 1986a). In the Narvik area, the age of the overlying metasedimentary rocks is not known but their correlatives overlying the Lyngen ophiolite contain Early Silurian corals (Bjørlykke & Olaussen 1981); the rocks in this succession are thought to extend in age from Lower Ashgill to mid-Llandovery (Bruton & Harper 1988). Boyd (1983) suggested, by analogy with models of Furnes et al. (1980), that ophiolite obduction and the amphibolite facies metamorphism in the Narvik Nappe Complex occurred during the late Cambrian–Early Ordovician (?) 'Finnmarkian' orogeny, and that the mid-Silurian Scandian orogeny caused deformation and lower grade metamorphism of the whole nappe stack. The age of these ophiolite complexes/fragments is not known with certainty but by analogy with supra-subduction zone ophiolites in S. Norway (Dunning & Pederson 1988; Pedersen et al. 1988) an Early to Middle Ordovician age (500–470 Ma) is inferred. Such an age, if correct, would preclude their tectonic emplacement in the Finnmarkian orogeny, now known to pre-date ca. 520 Ma (Pedersen et al. 1989).

Hodges (1982, 1985) has shown that the rocks of the Narvik Nappe Complex have experienced six deformation phases. Structural relationships

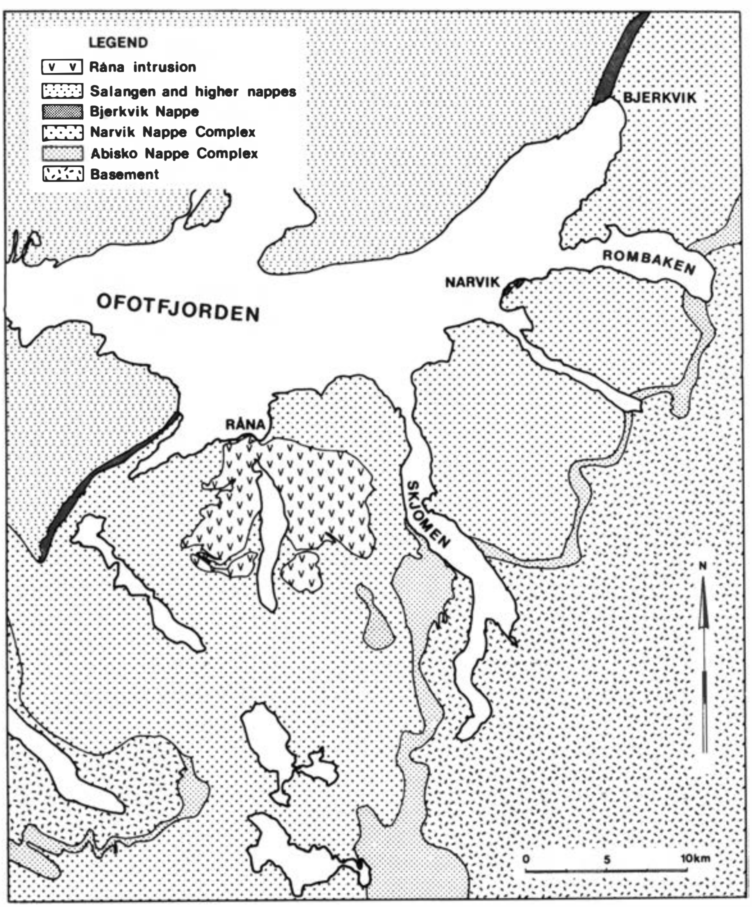

Fig. 1. Simplified geological map of the Ofoten area based on Gustavson (1974), Boyd & Søvegjarto (1983), Hodges (1985), and Boyd, Hodges, Steltenpohl & Søvegjarto (1986).

Table 1. Tectonostratigraphic correlations in the Ofoten area.

Gustavson (1966)		Boyd & Søvegjarto (1983), Boyd (1983)	Barker (1986a)	Crowley & Spear (1987)
Niingen Gp.		(Upper levels absent)	(Upper levels absent)	(Upper levels absent)
Bogen Gp.	Salangen Gp.	Salangen Nappe	Gratangen Nappe	
Evenes Gp.		Bjerkvik Nappe	Gratangseidet Nappe	
			Kvernmo Nappe	
Narvik Gp.		Narvik	Grønfjellet Nappe	Marko Nappe
		Nappe	Høgtind Nappe	
Rombak Gp.		Complex	Fossbakken Nappe	Langvatn Nappe
		Abisko Nappe		Storrit Complex
Storfjell Gp.		Complex	Basement	
		Basement		Basement
Autochthonous sediments				
Basement				

within and around the Råna intrusion indicate that its emplacement post-dates D_1, and pre-dates D_{2-6}. Shear zones cutting the noritic rocks contain assemblages bearing kyanite, zoisite, quartz and amphibole, indicating that regional metamorphism was later than cooling of the intrusion. A detailed P–T study of the mafic rocks on Tverrfjell (Fig. 2) (Barnes 1986; Barnes et al. 1988) has shown that the body was emplaced at a pressure of 2–4 kb and was subsequently buried to 9.5 ± 2 kb at a temperature of 655 ± 50°C. This is in good agreement with earlier evaluations of peak P–T conditions at this tectonostratigraphic level, ca. 8.5 kb and >680°C (Hodges & Royden 1984) and >7 kb and 625°C < T < 775°C (Crowley & Spear 1987). There is general agreement that the metamorphic peak pre-dated juxtaposition of the Narvik Nappe Complex and the underlying, lower grade Abisko Nappe Complex (Tull et al. 1985; Hodges 1985; Crowley & Spear 1987).

Roddick (1977) has suggested that mafic rocks from the Råna intrusion are ca. 400 Ma old on the basis of Rb/Sr whole rock and mineral data: this age was published in an abstract, without error estimates. Hodges (1982, 1985) presented K–Ar ages from three amphibole samples, two from rocks within the Narvik Nappe Complex and one from underlying orthogneissic basement. His data indicate a spread of ages from 436 to 463 Ma and, of several possible interpretations, Hodges (1985) believes that the ages are unrealistically old, reflecting the presence of excess argon; peak regional metamorphism and related deformation (D_2) probably occurred in Middle to Late Silurian time. Tilke et al. (1986) have published Ar–Ar data indicating that certain of the allochthonous units within this part of the Caledonides cooled through 500°C between 500 and 450 Ma, while others cooled through the same temperature between 435 and 425 Ma (abstract, not specifying which units). They state further that imbrication of the allochthonous package and underlying basement occurred between 425 and 385 Ma.

With the above points considered, a reliable age for the Råna intrusion would thus give:

(1) the time at which the host rocks to the intrusion were in an environment undergoing extension as implied by the emplacement of primitive mantle-derived magma at a depth of <12 km in the crust;

(2) a maximum age for the upper-amphibolite facies metamorphism in the Narvik Nappe Complex, and for five of its deformational phases;

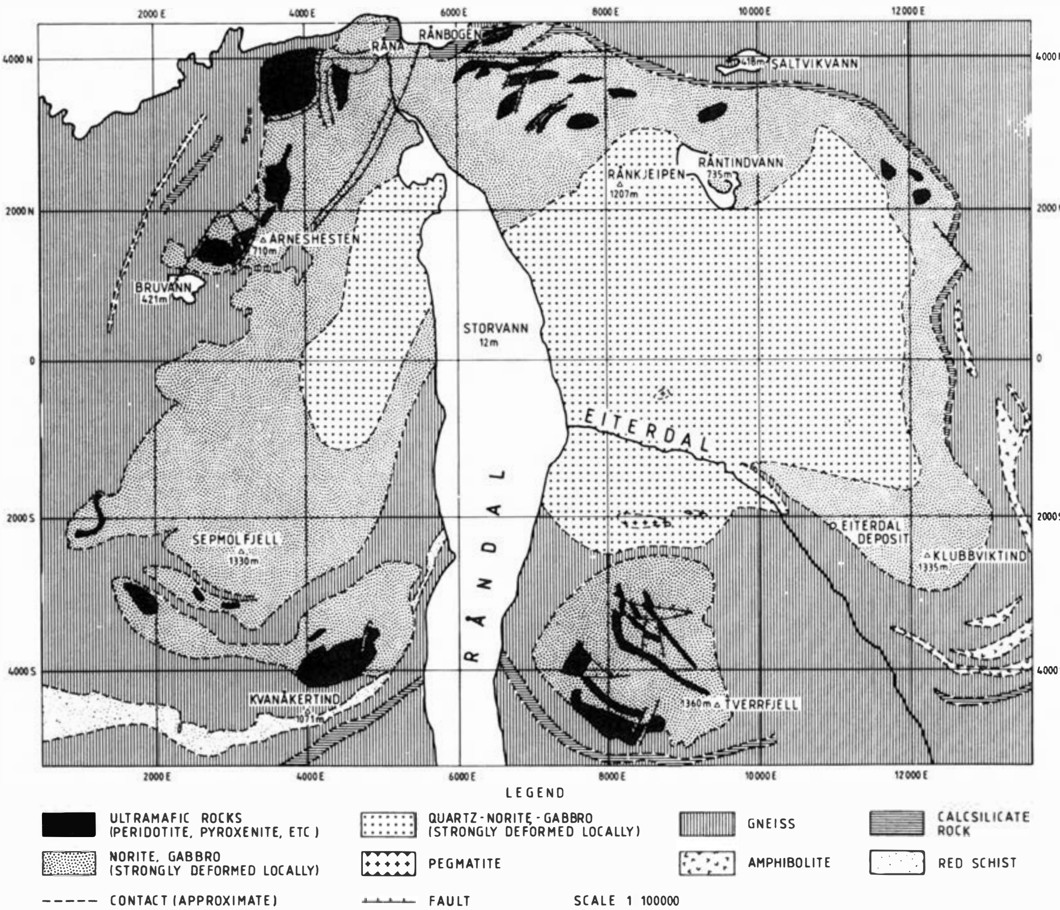

Fig. 2. Simplified geological map of the Råna area (Boyd & Mathiesen 1979). The coordinates are in metres.

(3) a maximum age for the juxtaposition of the Narvik Nappe Complex with its over- and underlying allochthons;
(4) a minimum age for the D_1 event.

The Råna intrusion and description of the zircons

The major rock types in the Råna intrusion show a roughly concentric distribution (Fig. 2), with the following somewhat idealized sequence in the most complete sections:

- quartz-gabbronorite core (>1000 m at its thickest): ultramafics absent
- gabbronorite zone (300–2000 m): ultramafics and quartz-bearing varieties subordinate
- ultramafic zone (0–800 m): gabbronorite subordinate
- norite (<50 m)

The dimensions given are approximations of the thicknesses normal to the contacts between the zones based on the exposed section and on drillcore information from the Bruvann area. Surface mapping and gravity data (Sindre & Boyd 1977) indicate that the body has the form of an inverted cone with an axis plunging NW with a plunge which is shallow in the SE but which steepens northwestwards. The gravity data also indicate that the proportion of ultramafic rocks increases with depth in the northern part of the intrusion. The form of the body and its internal structures reflect the effects of folding, local thrusting, shearing and faulting in D_{2-6}. Gross forms of layering are found in several parts of the intrusion but well-developed layering at scales below 100 m is found only in the Tverrfjell outlier in the southeastern part of the body (Boyd & Mathiesen 1979; Barnes 1986, 1989).

Zircons were found in quartz-bearing gabbronorite (sample 1120B 867A, coordinates 4100E 1491N) within the gabbronorite zone (Fig. 2), 400 m NW of the quartz-gabbronorite core. The rock is a weakly to non-laminated plagioclase–orthopyroxene–clinopyroxene mesocumulate with postcumulus biotite, quartz, zircon (clearly visible in thin section) and opaque minerals and secondary actinolite, cummingtonite and clinozoisite. The weak lamination is defined by laths of plagioclase and pyroxene up to 4 mm long. Adcumulus growth is shown commonly by plagioclase and locally by the pyroxenes: postcumulus minerals constitute less than 15% of the mode. The primary texture and mineralogy of the rock are well preserved, less than 10% of the mode consisting of secondary minerals.

Four distinctive types of zircon were handpicked for U–Pb analysis (Table 2): (a) clear trapezohedral grains with length to width ratios of 3:1; (b) dark brown (high U) fragments of skeletal grains; (c) clear needle-like prisms; (d) clear stubby, doubly terminated prisms. All clear prismatic grains had well-developed pyramidal faces including (101) and (211), and none showed evidence of metamorphic rounding or resorption, or new zircon overgrowths.

Application of U–Pb zircon dating to mafic rocks

The U–Pb dating method has the inherent advantage of being based on two distinct parent-daughter decay schemes, each characterized by independent and non-equal decay rates. This allows for discrimination between open and closed system behaviour and, thus, between reliable and unreliable ages. Application of this method to zircon, which normally contains varying amounts of U but essentially no initial Pb, allows for determination of high precision ages essentially independent of an assumed initial Pb composition. Moreover, the refractory nature of zircon preserves morphological characteristics that are helpful in discriminating between primary, magmatic zircon and inherited, xenocrystic zircon. The principal problem with zircon dating of mafic rocks is that zircon is commonly a very minor constituent (if not altogether absent), thus making the technical requirements for extraction and measurement of minute amounts of radiogenic-Pb very exacting.

Over the past five years, many problems inherent in analysing ultra-small zircon samples have been eliminated by:

(1) reduction of the amount of contaminant Pb introduced during zircon dissolution and chemical extraction (Krogh 1973);
(2) preparation of high-purity ^{205}Pb tracer solution (Parrish & Krogh 1987); and
(3) an increase in ion-detection sensitivity through the use of high-transmission, extended focusing mass spectrometers.

This paper reports a U–Pb zircon age from the differentiated portion of a layered mafic-ultramafic intrusion that is based on replicate analyses of sub-milligram size zircon fractions separated from a hand-specimen sample weighing less than 3 kg. The results demonstrate that technical improvements in mass spectrometry and chemical extraction facilities now make it possible to obtain high precision and meaningful ages for rock types previously assumed to be devoid of reliable geochronometers, and that such ages can routinely be obtained from very small quantities of zircon-bearing samples.

Analytical methods

All fractions were strongly abraded to eliminate the effects of secondary, surface correlated Pb-loss (Krogh 1982). After washing in distilled water, hot 6N nitric acid, and distilled acetone, zircon fractions were weighed in teflon bombs with a mixed ^{205}Pb–^{235}U spike (Krogh & Davis 1975) and dissolved in hydrofluoric and nitric acids according to the procedure of Krogh (1973). Lead and uranium were eluted in 0.10 ml anion exchange columns; total Pb and U blanks for this procedure were less than 10 and 1 pg, respectively, as estimated by periodic blank determinations and calculated common-Pb levels presented in Table 2. Isotopic ratios were measured on a VG 453 thermal ionization mass spectrometer, corrected for mass fractionation of 0.1% per atomic mass unit established by periodic runs of NBS 981 and U 500 standards. Error analysis follows the recommendations of Ludwig

Table 2. U–Pb zircon data from the Råna intrusion.

No.	Fractions	Concentrations			Atomic ratios					Age (Ma)
	Properties	Wt. [mg]	U [ppm] (2)	Pb common [pg] (3)	$^{206}Pb/^{204}Pb$ (4)	$^{207}Pb/^{206}Pb$ (5)	$^{208}Pb/^{206}Pb$ (5)	$^{206}Pb/^{238}U$ (6)	$^{207}Pb/^{235}U$ (6)	$^{207}Pb/^{206}Pb$ (6)
	Quartz gabbronorite [1120B-867]									
a	Zircon ONM,-100+200,cl,tr,A	0.402	393	15	45,001	0.05568	0.11067	0.06985	0.5354	436
b	Zircon ONM,-100+200,b,s,A	0.136	2310	3	457,770	0.05562	0.09859	0.06994	0.5363	437
c	Zircon ONM,-100+200,pr,n,A	0.356	315	15	32,103	0.05574	0.12402	0.06975	0.5348	437
d	Zircon ONM,-100+200,cl,st,A	0.158	543	14	26,189	0.05578	0.02693	0.06955	0.5336	438

(1) NM, M = non-magnetic, magnetic at indicated degree of tilt of Frantz isodynamic separator (at 1.6A and 0° slope); 100, 200 = size in mesh; b = brown; cl = clear; pr = prismatic; n = needles; s = shards; st = stubby prismatic; tr = trapezohedra.
(2) Concentrations are known to ±1–2% for sample weights between 1.0 and 0.1 mg.
(3) Corrected for 0.117 mole fraction of common Pb in the ^{205}Pb spike.
(4) Measured ratio relative to total radiogenic Pb.
(5) Corrected for fractionation and blank; U blank = 1 pg; Pb blank = 10 pg; Pb and U fractionation correction = 0.1%/amu (±0.05%).
(6) Corrected for fractionation, spike, blank, and initial common Pb; error for zircon is estimated at 0.50% for Pb/U and 0.1% for $^{207}Pb/^{206}Pb$ at the 2-sigma level (errors are estimated from replicate analyses).

(1980), and errors for $^{207}Pb/^{206}Pb$ and U/Pb are cited at the 2-sigma level (Table 2). Decay constants used to calculate ages are from Steiger & Jäger (1977).

Discussion

Three of the four zircon fractions analysed are concordant within analytical uncertainty, whereas the fourth, fraction d (Table 2), is 1% discordant (Fig. 3). Moreover, all fractions overlap within limits of analytical uncertainty yielding a mean $^{207}Pb/^{206}Pb$ age of 436.9^{+1}_{-2} Ma, which is taken as the age of emplacement of the Råna intrusion. As the analysed fractions were free of resorbed faces and exhibited no range to younger ages (despite a difference of a factor of 7 in U levels), no information could be gained on the age(s) of other Caledonian events in the area. The well-faceted prismatic appearance of many grains suggest that the part of the intrusion from which this sample was collected was effectively shielded from recrystallization during subsequent orogenic events.

The emplacement age of 437 ± 2 Ma indicates that the regional metamorphism in the uppermost part of the Narvik Complex must have occurred after that time and probably during the Silurian Scandian orogeny. This supports the conclusions of Hodges (1985).

The emplacement age of the Råna intrusion falls within the Early Silurian (Llandovery) according to the time-scale of Tucker et al. (1990) or at about the Ordovician–Silurian time boundary, set at ca. 435 Ma by McKerrow et al. (1985). The intrusion thus appears to have been emplaced at a depth of ca. 6–10 km at approximately the same time as sedimentary rocks overlying ophiolitic fragments in Nordland and Troms were being deposited. This fact, and the contrast in metamorphic grade between the supraophiolite rocks and the Narvik Nappe Complex itself, imply that their subsequent juxaposition was a Scandian or post-Scandian event. The above results are thus compatible with the conclusions of Tilke et al. (1986), that the whole nappe pile was assembled and emplaced onto Rombak window basement post-425 Ma.

Timing of basic magmatism in the Caledonides

The U/Pb zircon age of the Råna intrusion is close to, or overlaps, the U–Pb zircon ages of two other major mafic-ultramafic intrusive complexes further south in the Upper/Uppermost Allochthons of the Scandinavian Caledonides, the Artfjäll layered intrusion (434 ± 5 Ma) (Senior et al., in Otten 1983) and the Fongen–Hyllingen layered intrusion (426^{+8}_{-2} Ma) (Wilson et al. 1983) (Table 3). Further examples of basic magmatism of roughly similar age are Llandovery volcanites of MORB (−WPB) affinity in the Broken Formation of the L. Köli Nappe (Stephens et al.

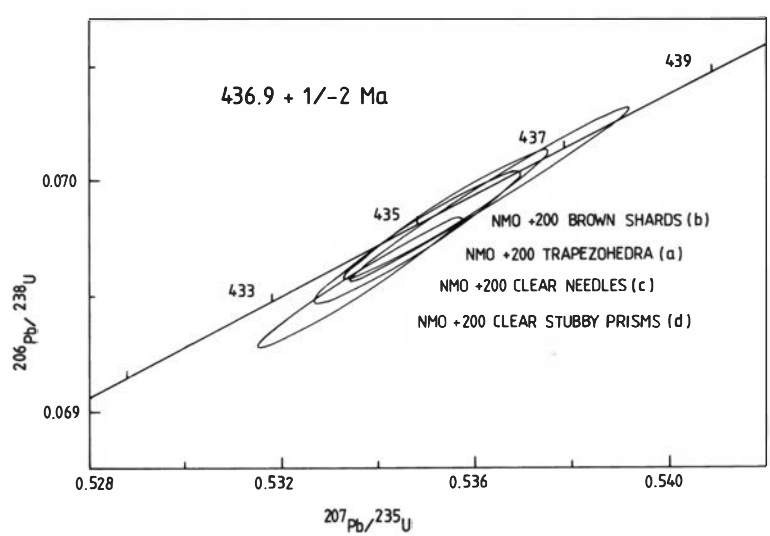

Fig. 3. Concordia diagram showing zircon data from Råna. The letters a–d refer to the description in the text and to Table 2.

Table 3. Caledonian basic intrusives and volcanic rocks of Ashgill–Llandovery age.

Magmatic event	Age	Dating method	Source
SCANDINAVIA			
Råna layered intrusion	436.9^{+1}_{-2}	U/Pb zircon	This paper
Artfjäll layered intrusion	434 ± 5	U/Pb zircon	Senior et al., in Otten 1983
Fongen–Hyllingen layered intrusion	426^{+8}_{-2}	U/Pb zircon	Wilson et al. 1983
Mosjøen gabbro	420 ± 8	Rb/Sr whole rock	Tørudbakken & Mickelson 1986
Broken Formation volcanites	Llandovery	corals	Stephens et al. 1985
Balsfjord volcanites	L. Silurian	corals	Bjørlykke & Olaussen 1981
Solund ophiolite	443 ± 3	U/Pb zircon	Dunning & Pedersen 1988
Sulitjelma gabbro	437 ± 2	U/Pb zircon	Pedersen et al. (in press)
APPALACHIANS			
Rainy Lake gabbro	438 ± 8	U/Pb zircon	Whalen et al. 1987
Main Gut mafic pluton	431 ± 2	U/Pb zircon	Dunning et al. 1988
Boogie Lake mafic pluton	435^{+5}_{-2}	U/Pb zircon	Dunning et al. 1988
Pocomoonshire gabbro	423 ± 24	K/Ar hornblende	Westermann 1973

1985) and the Mosjøen gabbro (Tørudbakken & Mickelson 1986). The age is also close to that of the Solund ophiolite (Table 3), reported by Dunning & Pedersen (1988), who also quote U/Pb ages for two basic complexes in Newfoundland (Main Gut and Boogie Lake) which are broadly Early Silurian in age. Even more recent U/Pb zircon dating has shown that the Sulitjelma ophiolite (Fig. 4) is also Early Silurian (Pedersen et al. in press).

Most of the data reported by Dunning & Pedersen (1988) relate to ophiolites in the Scandinavian Caledonides formed in Tremadoc/Arenig times which, they point out, have ages similar to U–Pb zircon ages from ophiolites in Newfoundland and Scotland. Also this period has seen contemporaneous development of ophiolitic crust and emplacement of layered mafic intrusions, e.g. in Aberdeenshire (Pankhurst 1970), in N. Norway (Krill et al., 1988), Connemara (Jagger et al. 1988) and Maryland (Shaw & Wasserburg 1984). Furthermore, the Early Ordovician ophiolite ages in the Scandinavian Caledonides (489–497 Ma (Pedersen et al., 1988)) overlap in time with U–Pb zircon ages (Claesson et al. 1983, 1988) of felsic rocks in biomodal volcanic sequences (in the Scandinavian Caledonides) linked to ensimatic rifted-arc systems.

Collectively, the age information and regional geological relationships allow us to draw the following conclusions:

(1) Basic intrusive activity in the Caledonide belt occurred in generally short-lived episodes but with a wide distribution along the strike length of the orogen and, in Scandinavia, restricted tectonostratigraphically to the part of the Upper Allochthon above the Seve, and to the Uppermost Allochthon. Two such episodes are now apparent: one from ca. 500–470 Ma represented by mafic intrusions in Maryland, Connemara, Aberdeenshire and N. Norway and another from ca. 443–420 Ma (see Table 3).

(2) Basic intrusive activity and generation of ophiolitic crust may have occurred roughly contemporaneously. It is our view that the Råna intrusion was emplaced into a terrane undergoing active crustal extension, perhaps in a back-arc or marginal basic setting, but that the extension in that setting ceased before true ophiolitic crust could form.

A similar suggestion has been made for layered intrusions in Aberdeenshire (Wright 1976) and elsewhere (Dewey & Shackleton 1984), and for the Broken Formation volcanics (Stephens et al. 1985) and Artfjäll layered mafic intrusion (Otten 1983) in Sweden. The latter intrusive complexes should probably be regarded as intraorogenic rather than as synorogenic. Their differences with contemporaneous ophiolites (e.g. Solund–Stavfjorden) and ophiolite-like complexes (e.g. Sulitjelma) may be due solely to the duration and linear extension of the spreading event.

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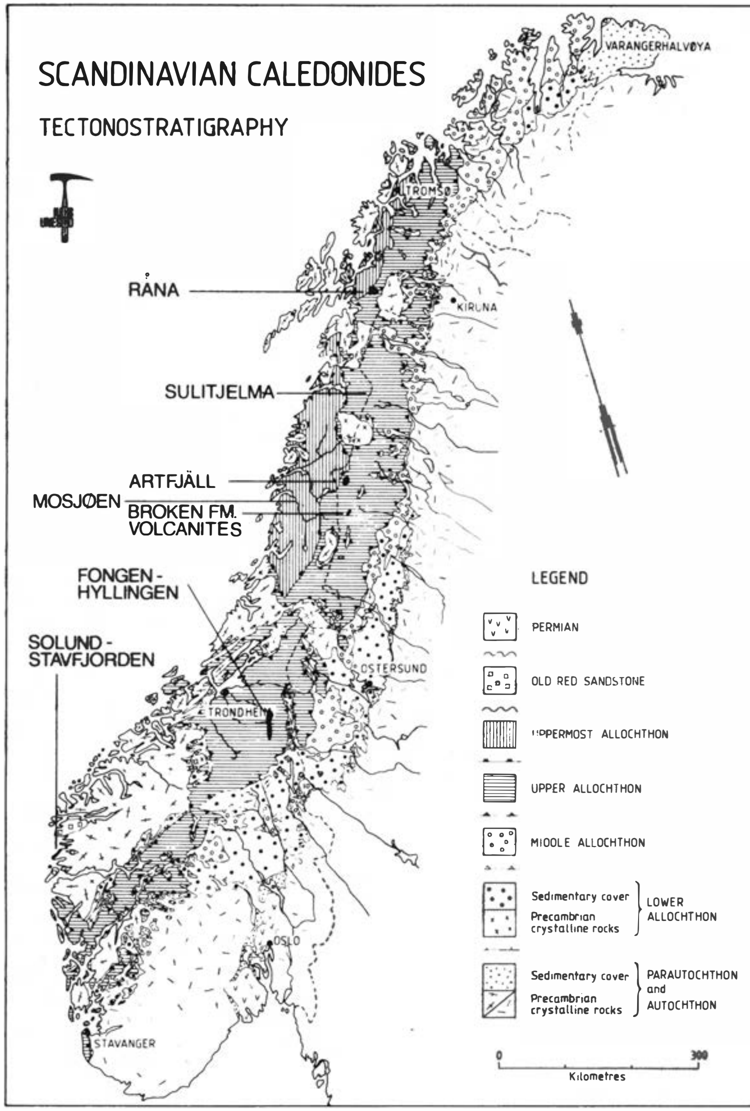

Fig. 4. Location of mafic complexes (black ornament) in the Scandinavian Caledonides mentioned in the text (base map from Roberts & Gee 1985).

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