Late Cambrian U-Pb zircon age of a meta-trondhjemite from Ytterøya, Trondheimsfjorden, Central Norwegian Caledonides

DAVID ROBERTS & ROBERT D. TUCKER

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Zircon fractions extracted from one of several metatrondhjemite sheets interbanded with mafic volcanites in the Støren Nappe on the island of Ytterøya, Trondheimsfjorden, have yielded a U-Pb age of 495 ± 3 Ma. This is interpreted as the crystallisation age of this subvolcanic felsic intrusion. Field relationships indicate that the trondhjemite sheets are either broadly coeval with, or just slightly younger than the metabasaltic greenstones. The entire volcanosedimentary succession on the island, which includes local, thin, quartz keratophyres and rare phyllites, has participated in all the recorded Scandian deformation phases. A < 60 m-thick metalimestone is also present in one area. Based on comparisons with other U-Pb dated trondhjemitic sheets associated with metabasalts in this part of Central Norway, the Ytterøya greenstone pile thus appears to be one of the oldest metabasaltic units in the Trondheim Nappe Complex, with a minimum age of Late Cambrian.

David Roberts Norges geologiske undersøkelse, P.O. Box 3006-Lade, 7002 Trondheim, Norway; Robert D. Tucker, Department of Earth and Planetary Sciences, Washington University, 1 Brookings Drive, St. Louis, MO 63130-4899, USA.

Introduction

In the Caledonides of Central Norway, thick units of metamorphosed basaltic lavas, traditionally termed 'greenstones' in Scandinavia, constitute an important element of the geology. In relation to established Caledonide tectonostratigraphy, the greenstones occur almost exclusively within the higher parts of the Upper Allochthon (Roberts & Gee 1985), in the Köli Nappes. Geochemical studies on many of these greenstone units have indicated their accumulation in a variety of tectonic settings, but by and large they derive from ocean basin or island arc environments (Gale & Roberts 1972, 1974; Furnes et al. 1985). Some have been shown to form parts of dismembered or fragmented ophiolites (Grenne et al. 1980; Prestvik 1980; Heim et al. 1987).

Associated with the greenstones in some areas are felsic rock-types, either quartz keratophyres representative of metamorphosed rhyolites or dacites, or subvolcanic trondhjemites or plagiogranites. These have provided natural and ideal targets for U-Pb zircon age determinations, some results of which are referred to later in the 'Discussion' section. During a regional mapping programme of parts of the northern Trondheimsfjord district in the mid-1980s, one such prominent metatrondhjemite on the island of Ytterøya was sampled with a view to separating zircons for U-Pb dating. The results and implications of this study, which were registered earlier, informally, as an open-file Survey report (Roberts & Tucker 1995), form the basis of this short contribution.

Geology of Ytterøya

The geology of Ytterøya consists mainly of variably deformed, NE-dipping, schistose greenstones. These vary from dark, amphibole-rich varieties to paler green, chloritic schists, with common segregations of epidote. Good examples of pillow structure are comparatively rare. The succession is generally considered to form part of the Støren Nappe (one of the Köli Nappes), which in turn is part of the Trondheim Nappe Complex (Wolff 1979). Apart from a few sporadic quartz keratophyre layers, the general monotony of the greenstones is broken only by a 30–60 m-thick metalimestone occurring in the southwestern part of the island (Trønnes 1993), a small body of metagabbro in the northeast at Oterstein, and a prominent zone of layer-parallel plagiogranitic (trondhjemite) sheets in the northwest (Fig. 1). Ytterøya is also well known for the occurrence of a solitary lamprophyre dyke, which cuts the metalimestone (e.g. Carstens 1961; Mitchell & Roberts 1986; Torsvik et al. 1994).

Based on regional mapping and suggested lithostratigraphic correlation, the greenstones, as well as the metalimestone and metatrondhjemite sheets, have generally been considered to be of Ordovician age (Carstens 1961; Wolff 1979). The metalimestone, dipping at ca. 30° towards the NE/NNE, is banded and schistose, and at its base passes gradationally into schistose greenstones via transitional units of phyllite, banded tuff and thin ribs of limestone. The upper contact, on the other hand, has evidently been the locus of appreciably higher strains. Phyllonites and protomylonites are developed, and there

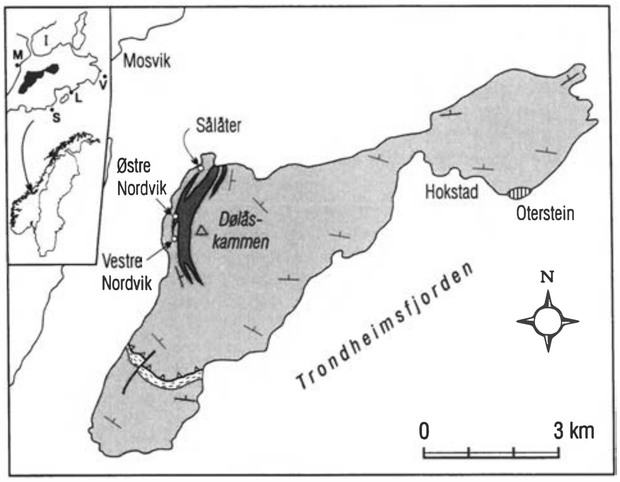

Fig. 1. Simplified geological map of Ytterøya showing the location of the metatrondhjemite (dark grey ornament) near the farms Vestre and Östre Nordvik. The metalimestone mentioned in the text, ca. 3 km south of vestre Nordvik, is indicated by the dashed line ornament. The upper contact to this limestone unit is shown as a thrust. The remainder of Ytterøya (pale grey ornament) is underlain mostly by schistose greenstones (metabasalts) with minor keratophyres. The orientation of the compositional banding/foliation is shown by the strike-and-dip symbols. The small area on the coast at Oterstein (vertical lined ornament) is underlain by metagabbro. Letters in the inset map: I – Inderøya; L – Levanger; M – Mosvik; S – Skogn; V – Verdal.

are shear bands indicating a contractional oblique-slip movement. This contact is interpreted as a thrust of unknown magnitude. Calc-phyllites, dark-grey phyllites, greenschists, tuffs and thin bands of metalimestone occur above the contact, eventually passing up into greenstones. Unlike several other carbonates in the Støren Nappe, for example, those in the Hølonda, Meldal and Tautra areas, no body fossils or microfossil remains have yet been found in the Ytterøya limestone. An upper isotopic constraint on the age of the mafic volcanites, and limestone, is set by the lamprophyre dyke, which is either Devonian or, more likely, Permian in age (cf. Torsvik et al. 1994). However, the supracrustal rocks of Ytterøya are considered to have been deformed and metamorphosed during the *Scandian* phase of the Caledonian orogeny, in Late Silurian to possibly Early Devonian time.

The geochemistry of the Ytterøya greenstones is the topic of an ongoing study. Although the analytical data have not yet been fully assessed, preliminary work has shown that the volcanites carry many of the chemical attributes of ocean-floor basalts (D. Roberts, unpubl. data).

The metatrondhjemite

Field relationships

The trondhjemite, or rather a series of trondhjemite sheets, is exposed along and to the west and north of the ridge Dølåskammen (Fig. 1). It is well exposed east of the farms Vestre and Østre Nordvik along and adjacent to road-cuts where the samples were collected (see below). In the road-cuts and steep ridge slope above the road it occurs as sheets or sills varying from 30 cm to 4 m in thickness, lying within or subparallel to the banding in the greenstone (Fig. 2). Higher up, sheets of up to 9 m in thickness are encountered. Further north, the trondhjemite sheets are also present in the vicinity, and to the east, of the farm Sålåter.

The NE- to E-dipping, medium- to coarse-grained trondhjemite is quite strongly foliated. The repetitious sheet-like nature of the rock, alternating with schistose greenstone on a variety of scales, is a characteristic feature. Almost all of the individual sheets or sills contain thin layers, lenses or stringers of greenstone (Fig. 2). The impression, therefore, is that we are probably dealing with a felsic, subvolcanic, sheeted sill type of emplacement, either broadly coeval with or, more likely, just slightly younger than the effusion of the basaltic lavas. Along the coast ca. 500 m north of the farm Østre Nordvik, the greenstone carries intercalations of a white, banded to laminated, fine-grained quartz keratophyre.

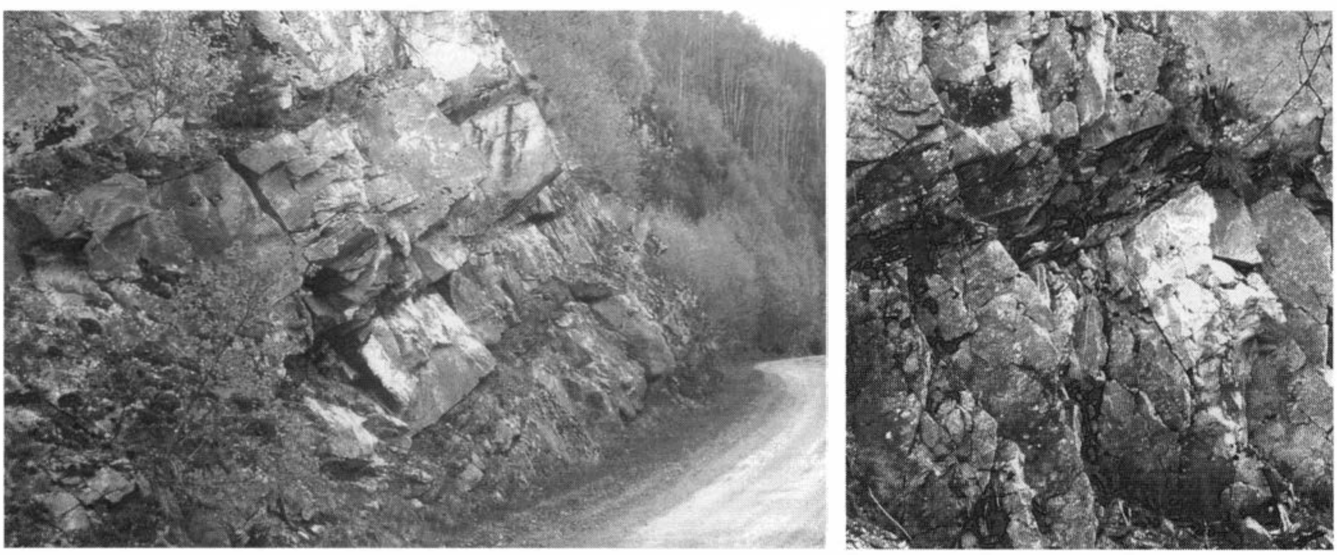

Fig. 2. Left: The sample locality along the road near Vestre Nordvik farm; metatrondhjemite sheets with intercalated schistose greenstone (metabasalt). *Right*: A close-up of part of the same road-cut outcrop; hammer for scale, bottom right.

Fig. 3. Field sketch showing a thin sheet of metatrondhjemite within schistose greenstone, deformed by an early (F1), flattened subisoclinal fold. The regional schistosity (S1) lies parallel to the axial plane of this fold. The fold axis plunges at 10° towards 121°.

Field evidence, from several localities, indicates that the entire greenstone-trondhjemite package or association has clearly participated in all the Caledonian deformation phases recognised in this area. Examples are to be seen along the coast of flattened, isoclinal, SE-plunging folds deforming thinner bands or sheets of trondhjemite or, in some cases, keratophyre (Fig. 3). These folds carry the pervasive regional schistosity as an axial planar fabric, and this schistosity is itself deformed, in some localities, by upright second-phase or flat-lying third-phase folds. An even younger deformation phase is reflected in the development of kink bands.

Petrography and geochemistry

The greyish-white metatrondhjemite carries a pronounced foliation. Quartz and plagioclase (ca. An_{14}) are the principal minerals, with minor amounts of K-feldspar, muscovite, biotite and clinozoisite, and accessory apatite, zircon, sphene and chlorite. The texture is, in general, characterised by lensoid clusters of fine-grained, recrystallised, highly strained quartz, and of coarser grained plagioclase, which is partly saussuritised and carries aggregates of clinozoisite. In some thin-sections, intergrowths of quartz and plagioclase in the mesostasis form a vermicular and graphic texture. The lensoid mineral clusters, which, together with the micas, define the foliation, are up to 2 cm in length.

A sample taken from exactly the same outcrop as the material collected for the U-Pb zircon study was analysed for major and minor elements at NGU, Trondheim. Care was taken to break the sample into small pieces on the outcrop in order to check for the possible presence of xenoliths. The analytical data and CIPW norms are presented in Table 1. On a plot of normative An-Ab-Or (not shown), the Nordvik trondhjemite falls almost in the centre of the trondhjemite field.

The low content of Al_2O_3 and high ytterbium (Table 1) are features typical of oceanic trondhjemites, as compared, for example, with the high-alumina/low-Yb trondhjemites which characterise mature continental margin situations (Arth 1979; Size 1979; Roberts & Sundvoll 1996). On the other hand, the K_2O content is somewhat higher than most, but not all, oceanic trondhjemites. Some trace element features, for example a Rb:Sr ratio of 0.09, a La_N/Lu_N of 3.6, and a modest enrichment in LREE, could suggest that the Nordvik metatrondhjemite might not be strictly cogenetic with the metabasalts, but these features can equally well be attributed to processes of fractional crystallisation.

U-Pb zircon dating

Approximately 50 kg of fresh sample material were collected for this isotopic study from what was, in 1987, a comparatively newly blasted road outcrop close to the farm Vestre Nordvik (UTM 600065 707460, zone 32, blue grid 3-NOR edition, 1:50,000 map-sheet 'Verran' 1622 I). The sample of metatrondhjemite was pulverised and sieved to a fine powder (<70 microns) and separated into mineral constituents by standard techniques of heavy-liquid and magnetic mineral purification.

Two fractions of high-quality prismatic zircon, of probable igneous origin, were selected and analysed by the isotopic dilution method following techniques developed by Krogh (1973, 1982) and outlined in Tucker et al. (1990) using a ^{205}Pb-^{235}U enriched tracer solution purified by Parrish & Krogh (1987). Both fractions of zircon are concordant within analytical uncertainty (Fig. 4, Table 2), and the weighted average $^{207}Pb/^{206}Pb$ age of 495 ± 3 is taken as the time of crystallisation of the trondhjemite protolith.

Discussion

Bearing in mind the field relationship between the trondhjemite sheets and their host metabasalt, the 495 ± 3 Ma crystallisation age of the metatrondhjemite (Fig. 4) can also be taken as the minimum age of this part of the mafic volcanic pile and its associated rocks. In the revised subdivision of the Cambrian and Ordovician Systems of Tucker & McKerrow (1995), this age would correspond exactly with the Cambrian-Ordovician boundary; in the chronology of these authors, the base of the Ordovician (Tremadoc) is put at 495 Ma. More

Table 1. Major and trace element contents (wt.% and ppm, respectively) and CIPW norms for the metatrondhjemite from the road-cut close to Vestre Nordvik farm.

Elements, wt.%		CIPW norms		Trace elements, ppm			
SiO_2	74.59	q	37.9	Zr	123	La	14.7
Al_2O_3	12.82	c	1.1	Y	27	Ce	32.7
TiO_2	0.21	or	6.3	Sr	175	Nd	15.1
FeO	0.97	ab	41.5	Rb	16	Sm	3.3
Fe_2O_3	0.92	an	6.9	Zn	11	Eu	0.6
MgO	0.50	di	–	Cu	6	Tb	0.55
CaO	2.44	hy	1.9	Ni	5	Yb	3.08
Na_2O	4.91	mt	1.3	Cr	5	Lu	0.42
K_2O	1.06	hm	–	Ba	150	Sc	5.6
MnO	0.03	il	0.4	Nb	5	Hf	3.38
P_2O_5	0.05	ap	0.1	V	20	Ta	0.17
Co_2	0.77					Th	4.5
H_2O^+	1.09					U	1.4
H_2O^-	0.01						

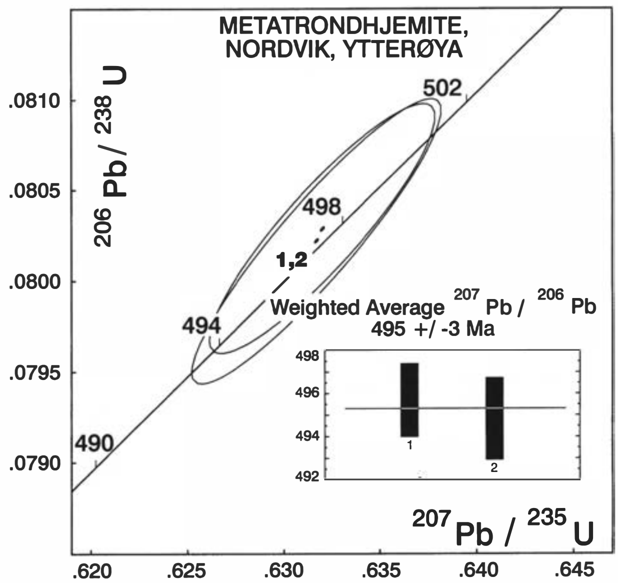

Fig. 4. U-Pb concordia diagram of zircon analyses (1, 2; Table 2) from the Nordvik metatrondhjemite on Ytterøya.

recent refinements, however, based on U-Pb dating of zircons from an ash bed in fossiliferous uppermost Cambrian strata from North Wales, are now showing that the Cambrian-Ordovician boundary is probably as young as at least 490 Ma (Davidek et al., 1998). In addition, other new zircon dating (Landing et al., in press) places the base of the Upper Cambrian at ca. 500 Ma. These data clearly indicate that the Nordvik metatrondhjemite is of Late Cambrian age; it follows that the metabasaltic greenstones are at least of this age, and may conceivably extend down into the Middle Cambrian.

In the Central Norwegian Caledonides, and more specifically within the Trondheim Nappe Complex, several U-Pb zircon dates have been reported either in the literature or as 'personal communications'. Within the Støren Nappe, zircon ages of 493 ± 10 and 487 ± 5 Ma have been obtained from plagiogranite dykes in the Løkken Ophiolite, and 480 ± 4 Ma for similar rocks in the Vassfjell Ophiolite (Dunning 1987 and pers. comm. 1990; Sturt & Roberts 1991). In the SE Trondheim Region, a trondhjemite at Folldal has yielded a U-Pb zircon age of 488 ± 2 Ma (Bjerkgård & Bjørlykke 1994). Further north, across the Grong-Olden Culmination, an albite-trondhjemite in the Köli rocks of the Gjersvik Nappe has a given a zircon age of 483 ± 4 Ma (Kullerud et al. 1988). Both these bodies are intimately associated with mafic volcanite sequences.

The 495 ± 3 Ma date from Ytterøya is, thus, with one exception (the 493 Ma date from Løkken), just slightly older than other reported plagiogranites/trondhjemites cutting inferred broadly coeval or slightly older metabasalts. This could mean that the Ytterøya mafic volcanites – and trondhjemite sheets – are genuinely slightly older than most other Early Palaeozoic mafic volcanites in this region; or alternatively, it could be that we have fortuitously dated just a slightly older part of a thick, volcanic/subvolcanic accumulation of wide-ranging extent which also covered a wide span in time, i.e. some 10–15 million years. Volcanism spanning such a time range, or an even longer time interval, is known from e.g. the Karmøy-Bømlo region of SW Norway (Pedersen 1992) as well as from the Gjersvik Nappe (Kullerud et al. 1988; Roberts & Tucker 1991).

Another U-Pb zircon date which is of interest here is that from a minor trondhjemite intrusion in the high-level gabbro/dolerite dyke unit of the Leka Ophiolite Complex, 497 ± 2 Ma (Dunning & Pedersen 1988). In terms of actual age, this is identical, within a reasonable margin of error, to the age reported here from the Ytterøya metatrondhjemite. However, the Leka zircon age derives from the lower and inferred older, subvolcanic part of the Leka ophiolite, i.e. the higher, pillowed basalt member of the same ophiolite complex should, or may presumably, have an age younger than 497 Ma.

A topic of more regional significance arising from the U-Pb age of the trondhjemite and, in consequence, the Cambrian age for the metabasalts on Ytterøya, is whether or not there is any evidence for an early Caledonian deformational event in this northern part of the Støren Nappe *sensu lato*. In the type area of this nappe, in the SW Trondheim Region, biostratigraphic constraints point to

Table 2. U-Pb zircon analyses, Nordvik metatrondhjemite, Ytterøya.

Fractions		Concentrations					Atomic ratios				Age [Ma]
No.	Properties[1]	Wt. [μg][2]	Pb rad [ppm][2]	U [ppm][2]	Pb com [pg][3]	Th/U	$^{207}Pb/^{204}Pb$[5]	$^{207}Pb/^{206}Pb$[6]	$^{206}Pb/^{238}U$[6]	$^{207}Pb/^{235}U$[6]	$^{207}Pb/^{206}Pb$[6]
1	+100–150, c, cl, sp, A	35	11.9	141	4	0.525	342	0.05711 ± 9	0.08022 ± 32	0.6317 ± 27	495.7
2	+100–150, c, cl, cr, p, A	41	15.1	176	4	0.556	478	0.05709 ± 10	0.08029 ± 28	0.6320 ± 24	494.8

[1] gr denotes number of zircon grains analysed (e.g. 1). All other analyses are multigrain fractions selected from non-paramagnetic separates at 0° tilt at full magnetic field in Frantz Magnetic Separator; 100, 150 = size in mesh (150 mesh = 70 μm); c = colourless; cl = clear; cr = cracked; sp = short prismatic; p = prismatic; A = grains air-abraded (following Krogh 1982).

[2] Concentrations are known to ±30% for sample weights of about 20 μg and ±50% for samples ÿ 5 μg.

[3] Corrected for 0.0215 mole fraction common-Pb in the ^{205}Pb-^{235}U spike.

[4] Calculated Th/U ratio assuming that all ^{208}Pb in excess of blank, common-Pb, and spike is radiogenic (ÿ $^{232}Th = 4.9475 \times 10^{-11}$ y^{-1}).

[5] Measured, uncorrected ratio.

[6] Ratio corrected for fractionation, spike, blank, and initial common-Pb (at the determined age from Stacey & Kramers (1975)). Pb and U fractionation correction = 0.1%/amu (±0.14%); U blank = 0.5 pg, Pb blank ÿ 10 pg. Absolute uncertainties (2ÿ) in the Pb/U and $^{207}Pb/^{206}Pb$ ratios calculated following Ludwig (1980). U and Pb half-lives and isotopic abundance ratios from Jaffey et al. (1971).

a probable Early Ordovician event (syn- to post-Tremadoc/pre-Mid or Late Arenig) which also involved ophiolite obduction (Sturt & Roberts 1991). On Ytterøya, although the critical faunal constraints are lacking, the earliest foliation in the rocks does appear to be of a regional nature, as on the mainland, and is thus inferred to be a Scandian structure. Thus, by inference, there is no evidence available at present, on Ytterøya alone, for an Early Ordovician event. Timing of Ordovician tectonothermal events within the exotic, outboard terranes represented by the Köli Nappes, however, is known to be quite variable (Halls & Roberts 1988; Stephens & Gee 1989; Stephens et al. 1993) and even the Støren Nappe, or Støren-Steinkjer terrane (Roberts 1988), may ultimately prove to be composed of segments with differing deformation histories. Should this be the case, then this would warrant a revision of the tectonostratigraphic nomenclature for this part of the Trondheim Region.

The barren Ytterøya limestone has been reported to be correlative with metalimestones occurring to the northeast and east on Inderøya, near Levanger and along the Verdal valley (Fig. 1, inset), and an Ordovician age inferred (Wolff 1979). Faunal proof, however, is lacking. As a tectonic contact separates the Ytterøya limestone from the metatrondhjemite/metabasalt association discussed here, an Ordovician age is still possible. The alternative, i.e. a Late Cambrian age for the Ytterøya limestone, is not inconceivable. Geochemical data do, in fact, indicate that the Ytterøya limestone has a markedly higher FeO content and higher Fe/Mg ratio than other limestones in this district (Trønnes 1993). In a more regional context, the oldest parts of some lithostratigraphic successions in the Middle Köli Nappes in Sweden also contain limestones (e.g. Remdalen Group), and these now appear to be of latest Cambrian age (accepting the revised time-scale of Davidek et al., 1998) based on a U-Pb zircon date of 492 ± 1 Ma from a trondhjemite at Stekenjokk (Claesson et al. 1988). This would confirm an earlier suggestion (Stephens 1986, p.27) of a possible Late Cambrian age for parts of the Remdalen Group succession.

Conclusions

Two fractions of zircon extracted from a metatrondhjemite sheet interbanded with mafic volcanites on the island of Ytterøya in Trondheimsfjord, Central Norway, have yielded a U-Pb age of 495 ± 3 Ma, interpreted as the crystallisation age of the subvolcanic felsic intrusion. This is also the minimum age of the host metabasaltic greenstones.

By comparison with other trondhjemite/plagiogranite sheets and dykes associated with metabasalts from this part of Central Norway which have been dated by the U-Pb method, the Ytterøya greenstone pile appears to be one of the oldest volcanic units in the Trondheim Nappe Complex. As the base of the Ordovician System is now reported to be placed at 490 Ma, the Nordvik metatrondhjemite is accordingly of Late Cambrian age. The metabasaltic greenstones are also at least of this age, and may conceivably extend down into the Middle Cambrian.

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