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Early Silurian mafic–ultramafic and granitic plutonism in contemporaneous flysch, Magerøy, northern Norway: U–Pb ages and regional significance

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Abstract: The Caledonian Magerøy sequence comprises Earliest Silurian clastic metasedimentary rocks, which underwent folding and regional metamorphism and were intruded by a mafic–ultramafic complex and various granitic plutons. U–Pb ages of 438.2 ± 0.7 Ma for gabbro in the Honningsvåg Igneous Complex, 438.4 ± 0.9 Ma for an associated granite and 437.7 ± 1.6 Ma for the Finnvik granite coincide within error with the age of deposition inferred from fossils demonstrating a very rapid geological evolution. Plutons of peraluminous affinity are somewhat younger at 436.0 ± 1.0 Ma (Skarsvåg granite) and 434.5 ± 1.5 Ma (a granitic dyke in the Skarsvåg Nappe). The association of flysch deposition, folding and mafic–felsic magmatism suggests formation at a trench–ridge intersection. These Early Silurian events are the expression of a period of major magmatism in a variety of settings all along the Caledonides, probably reflecting rapid convergence and subduction during closure of the Iapetus Ocean. Re-evaluation of the palaeomagnetic signature of the Honningsvåg Igneous Complex indicates that at the time of formation the suite was located in an equatorial position, probably close to the Laurentian margin, and was subsequently translated southward by some 1350 km prior to and during emplacement onto the Baltic margin.

The development of collisional orogens commonly takes several tens of million years, and is punctuated by short-lived periods of intensive magmatic, deformational and metamorphic activity. These reflect specific stages of subduction, rotation, collision and/or extension controlled externally by large-scale plate motions and mantle convection, and internally, by progressive changes in the structure of the crust and lithosphere of the orogenic welt. Such major events are intercalated by periods of relative quiescence, or alternatively, by intense but only locally significant magmatic activity. Charting of these events and their variable expressions across an orogen provides important clues for understanding the overall process of crustal growth.

In the Scandinavian Caledonides Palaeozoic magmatism started about 500–480 Ma with the development of ophiolites and island arcs (Dunning & Pedersen 1988). Between 480 and 445 Ma magmatic activity occurred in continental arc settings of the Uppermost Allochthon and some mature island arcs of the Upper Allochthon (e.g. Nordgulen *et al*. 1993; Yoshinobu *et al*. 2002; Meyer *et al*. 2003; Tucker *et al*. 2004). A period of widespread magmatism between 445 and 435 Ma, mainly in the Upper Allochthon, coincided with the beginning of Scandian accretion and collisional processes (Fig. 1 and references therein). Subsequent high-pressure metamorphism, local formation of granite, and intense deformation during the main collisional stages at 425–400 Ma were followed by extension and exhumation concluding the orogeny between 400 and 370 Ma (Andersen 1998; Tucker *et al*. 2004). The event that occurred near the Ordovician–Silurian boundary (445–435 Ma; Fig. 1) is of special significance because it marks the last major episode of mantle-controlled magmatism during the closure of the oceanic basins. Thereafter, predominantly crustal processes accompanied the main collisional phase. In the Scandinavian Caledonides the events at the transition into the Silurian are recorded all along the orogen and formed such prominent rock suites as the Solund–Stavfjord ophiolite, the Røros volcanogenic massive sulphide deposit, the equally mineralized Sulitjelma and Råna layered intrusions and the Halti Igneous Complex, as well as felsic plutons such as the 447 ± 7 to 430 ± 7 Ma Bindal Batholith, the Hitra–Smøla and related intrusive rocks, the Bremanger Granitoid Complex, and the granites of Sunnhordland (Andersen & Jansen 1987; Dunning & Pedersen 1988; Fossen & Austrheim 1988; Nordgulen *et al*. 1993; Hansen *et al*. 2002; Andréasson *et al*. 2003; Tucker *et al*. 2004). With few potential exceptions (e.g. the Halti Complex) these plutons are intruded into rocks assigned to the Upper and Uppermost Allochthons. Pedersen *et al*. (1992) pointed to the Laurentian affinity of faunas and detrital zircon populations, which imply a development of the Late Ordovician–Early Silurian spreading complexes on the Laurentian margin of the narrowing Iapetus ocean. Roberts (2003), however, suggested an origin related to Baltica, and Andréasson *et al*. (2003) interpreted the Halti Complex to have formed on Baltic crust above a temporarily east-dipping subduction zone. Grenne *et al*. (1999) suggested that such complexes may have been formed on both margins during a transcurrent event accompanying the process of suturing of the two continental masses.

In this paper we contribute to the discussion with new critical evidence from the island of Magerøy in northernmost Norway. Our new precise ages, together with existing geological, palaeontological and palaeomagnetic evidence, help to constrain the

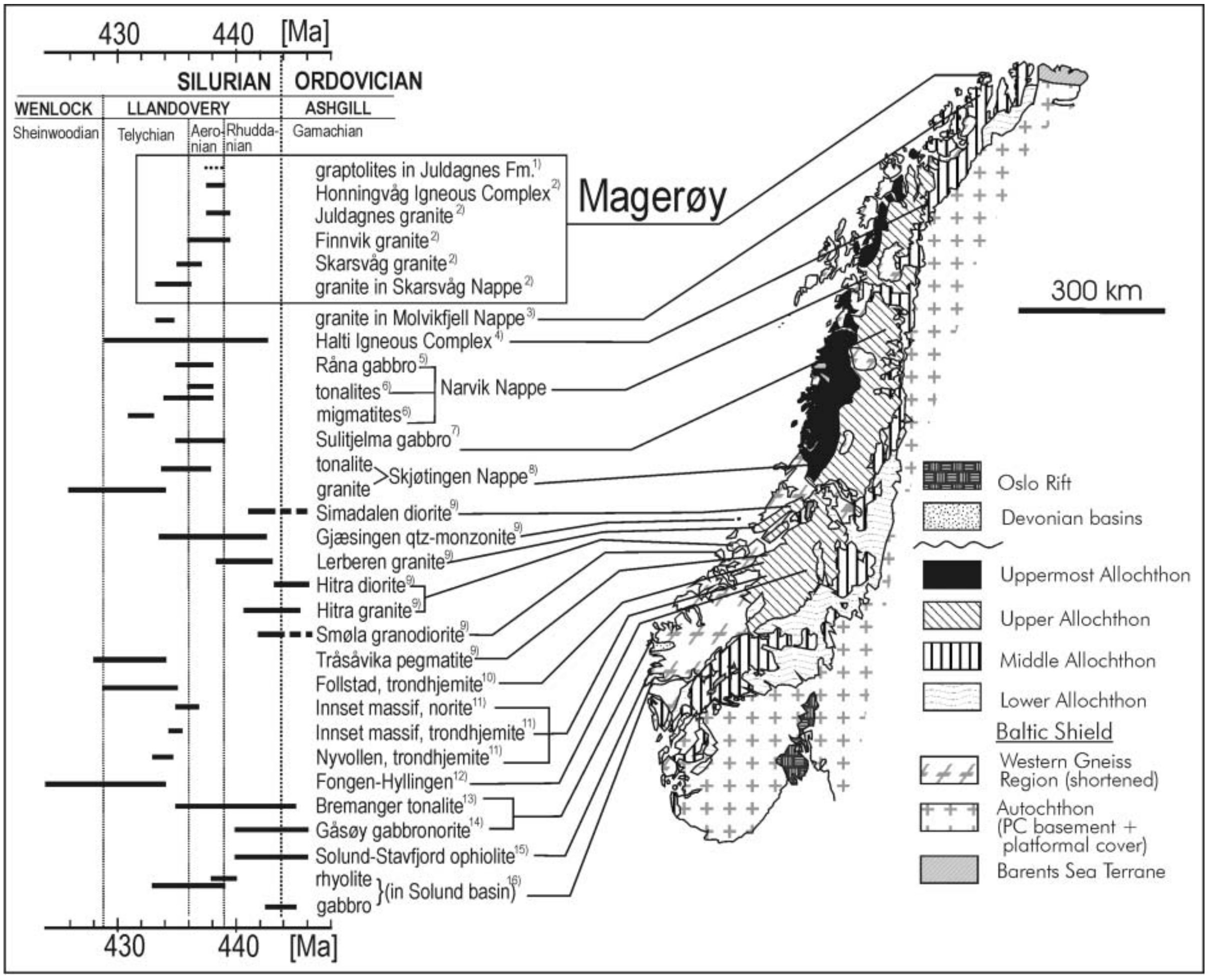

Fig. 1. Tectonic map of the Scandinavian Caledonides (after Gee *et al*. 1985) and ages for Early Silurian plutonic rocks of the Upper Allochthon (and Middle Allochthon?). In this tectonic map the Kalak Nappes of northern Norway are still assigned to the Middle Allochthon, which is inferred to represent the pre-Caledonian margin of Baltica. Recent data, however, indicate an exotic origin probably from the peri-Gondwanan realm. Time scale is based on the most recent compilation (Gradstein *et al*. 2004). Sources: (1) Krill *et al*. 1993; (2) this study; (3) Corfu *et al*. 2004; (4) Vaasjoki & Sipilä 2001; Andréasson *et al*. 2003; (5) Tucker *et al*. 1990; (6) Northrup 1997; (7) Pedersen *et al*. 1991; (8) Nordgulen *et al*. 2002; (9) Tucker *et al*. 2004; (10) Dunning & Grenne 2000; (11) Nilsen *et al*. 2003; (12) Wilson *et al*. 1983; (13) Hansen *et al*. 2002; (14) R. B. Pedersen, in Hansen *et al*. 2002; (15) Dunning & Pedersen 1988; (16) Hartz *et al*. 2002; F. Corfu, unpubl. data.

tectonic processes and contribute further arguments in favour of a Laurentian connection of these Early Silurian assemblages.

Geological setting

Geologically, the island of Magerøy is subdivided into the Gjesvær Migmatite Complex to the west and the metasedimentary and plutonic rocks of the Magerøy Nappe occupying the central and eastern parts of the island (Fig. 2; Andersen 1981). The interface between these two main geological elements is a zone of high strain, interpreted to be either a thrust (Ramsay & Sturt 1976) or a normal-sense extensional shear zone (Kjærsrud 1985).

The Magerøy Nappe consists of a metasedimentary succession deformed during two major folding events and intruded by gabbroic and granitic plutons. The metasedimentary succession, first described in an unpublished doctoral thesis by Curry (1975), has been subdivided into the basal Kjelvik Group, which consists of interbedded pelites and greywackes of turbiditic origin, and the overlying Nordvågen Group, composed largely of pelites and semipelites, but with local occurrences of conglomerate, limestone, quartzite and greywacke. The Nordvågen Group comprises the Sardnes and the interlayered Duksfjord formations and is capped by the Juldagnes Formation (Andersen 1981, 1984*a*). The sedimentological record has been interpreted (Andersen 1984*a*) as indicating two main depositional cycles, starting with a basinal environment for the Kjelsvik Group, gradually shallowing to a shelf facies represented by the Duksfjord Group. A second sedimentary cycle corresponds to a rapid deepening of the basin with the development of turbidites of the Juldagnes Formation, which is a typical flysch sequence probably formed during a period of convergence. Fossils indicating Early Silurian deposition have been found in both the Duksfjord (crinoids, pentamerides) and the Juldagnes Formation (ichnofauna and monograptides), whereas the age of the bottom units remains unconstrained (Henningsmoen 1961; Føyn 1967; Andersen 1984*a*; Krill *et al*. 1993).

A first phase of deformation (D_1) formed overturned to

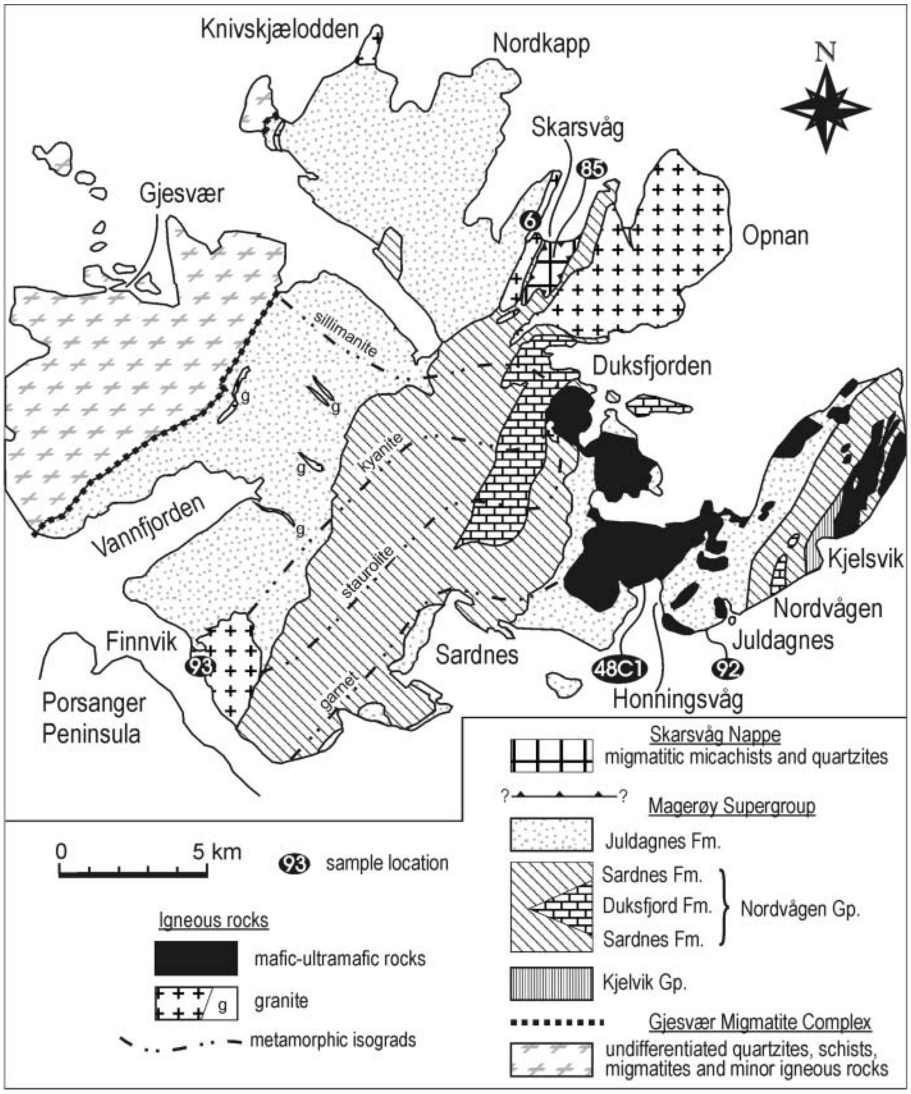

Fig. 2. Geological map of Magerøy showing the main geological elements and sample locations (48C1, Honningsvåg Igneous Complex; 92, Juldagnes granite; 93, Finnvik granite; 6, Skarsvåg granite; 85, granite dyke in Skarsvåg Nappe). Map modified from Andersen (1981).

recumbent folds. A second deformation phase (D_2) produced a large mainly upright north-trending synformal structure that controls the present regional orientation of foliation–layering (Andersen 1981). A Barrovian regional metamorphic gradient was initiated during D_1 and reached peak amphibolite-facies conditions after the end of D_1, but before D_2. There is a general increase in metamorphic grade from a chlorite zone in the SE through biotite, garnet, staurolite, kyanite and finally sillimanite zones in the NW (Fig. 2; Curry 1975; Andersen 1979, 1984*b*; Kjærsrud 1985). Retrogression accompanied late D_2 folding.

The relationships between structures, metamorphic assemblages and plutons show that emplacement of various plutons coincided with the later stages of D_1 and generally with the peak of metamorphism. The most important of these bodies is the Honningsvåg Igneous Complex, which comprises seven discrete nested intrusions of gabbroic to peridotitic composition derived by complex fractional crystallization of a parental olivine tholeiitic magma (Robins 1998). The complex is now tilted into a subvertical position, showing a sequence of younging to the SE in harmony with the younging direction in the sedimentary wall-rocks. The complex intruded during the final stages of D_1 deformation, as it cuts large-scale D_1 folds, which probably originated as mostly upright folds (Andersen 1981; Robins 1998), but it was tilted by 90° near the end of this event as the folds tightened and developed into recumbent structures (Torsvik *et al*. 1992). This is consistent with the reported local folding of gabbro in a D_1 syncline (Krill *et al*. 1993). Further moderate folding under brittle conditions also affected the complex during D_2 (Torsvik *et al*. 1992), at the same time as the metasediments responded to D_2 by folding and formation of a retrograde crenulation cleavage at greenschist-facies conditions (Andersen 1981).

The largest granitic plutons and smaller granitic, pegmatitic or quartz dykes occur all across the northwestern and northeastern parts of the nappe and were formed either synchronously with or after D_1 (Andersen 1979; Kjærsrud 1985). The Opnan and Skarsvåg quartz monzonitic to granitic plutons in the north are characterized by 1–2 cm twinned microcline phenocrysts in a medium-grained matrix (Kjærsrud 1985). Besides biotite there is muscovite, garnet and tourmaline, and, at least in the Skarsvåg quartz monzonite, monazite and xenotime. These are all indicative of a peraluminous composition for the granites. Peraluminous, kyanite-bearing granite dykes were also described from western Magerøy (Andersen 1979). The Skarsvåg pluton is distinctly foliated but the Opnan pluton locally appears to cut an early foliation, thus a late- to post-D_1 age has been proposed (Kjærsrud 1985). The Finnvik granite is mineralogically comparable with the Opnan and Skarsvåg granites, although it only rarely displays the porphyritic facies (Andersen *et al*. 1982). The Knivskjælodden granite west of Nordkapp is texturally comparable with the Finnvik granite (Kjærsrud 1985). The granitic, pegmatitic or quartz dykes have been separated by Kjærsrud (1985) into early and late generations. The early ones possess a distinct S_1 foliation and resemble mineralogically the main granite bodies; one good example is the long sheet aligned parallel to S_1 but also carrying an intensive S_1 fabric, located immediately east of the boundary to the underlying Gjesvær Complex. The later dykes may be up to 2 m wide and 1 km long and contain muscovite and garnet. In general, they show no evidence of ductile deformation and are oriented at a high angle to the regional NNE-trending foliation. These dykes were affected by the system of NW-trending brittle faults and fractures controlling the intrusion of Carboniferous mafic dykes (Roberts *et al*. 1991; Lippard & Prestvik 1997; Roberts *et al*. 2003).

To the east of Skarsvåg there is a sequence of rusty-weathering migmatitic mica schists with local quartzite horizons that are unlike the rocks elsewhere in the Magerøy Nappe. These rocks also rest on the Nordvågen Group rather than on the topmost Juldagnes Formation, as one could expect if the rusty schists were to be the youngest member of the stratigraphy (Andersen 1979; Kjærsrud 1985). The apparent implication is that the Juldagnes Formation has been tectonically excised and the Skarsvåg schists are an allochthonous unit. Kjærsrud (1985) argued that there is also a structural break with the preservation of structures that are distinct from and/or older than the Magerøy D_1. The base of the presumed nappe, however, is not distinguished by any clear mylonitic interface. Its origin may be related to that of the Storelv Schist of the Sørøy succession (Ramsay *et al*. 1985). Krill *et al*. (1988) reinterpreted the base of the nappe, placing it below the Skarsvåg and Opnan porphyritic granites, but this does not seem to be consistent with the fact that the western contact of the Skarsvåg granite interfingers with the Juldagnes Formation.

The Gjesvær Complex is dominated by migmatitic gneisses and banded metapsammites (Ramsay & Sturt 1976), with local calc-silicate gneisses and garnet amphibolites (Andersen 1979). A *c*. 300 m thick sheet of K-feldspar porphyritic granite gneiss occurs in the eastern part of the complex. The body is bounded on both sides by quartzite but marginal domains reveal the presence of very quartzite-like and of biotite-rich xenoliths, which probably represent the surrounding supracrustal rocks and thus indicate that the granite postdates the metasediments. The granite gneiss also contains sparse leucosome veins that probably reflect a younger remobilization. In approaching the top of the Gjesvær Complex the migmatitic rocks become strongly banded and mylonitic and quartzo-feldspathic veins are highly disrupted and stretched, as noted by Ramsay & Sturt (1976). Those workers attributed the mylonitization to overthrusting by the Magerøy Nappe, the alternative being that the Gjesvær Complex represents an original basement complex to the Magerøy sequence (Andersen 1979) and that the eastward-dipping boundary is a listric normal shear zone (Kjærsrud 1985).

The age of the rocks on Magerøy has been the subject of some confusion, even though the discovery of Silurian fossils (Henningsmoen 1961) had long ago established the late Caledonian origin of the sequence, hence narrowing down considerably the potential ages of the intrusive bodies and of metamorphism. Rb–Sr whole-rock analyses by Andersen *et al*. (1982) provided identical ages of 411 ± 7 Ma for the Finnvik granite and 410 ± 28 Ma for migmatitic rocks of the Gjesvær Complex. The former was interpreted as the time of magmatic emplacement whereas the latter was taken to indicate isotopic resetting at peak metamorphic conditions, as the Gjesvær Complex was then assumed to be part of the Kalak Nappe and to have been metamorphosed during the Finnmarkian Orogeny (*c*. 500 Ma; Sturt *et al*. 1975; Ramsay & Sturt 1976). Field observations from the migmatites suggested that at least two generations of leucosome were present, and these were taken to indicate a polyphase high-grade tectonometamorphic history (Andersen 1979; Andersen *et al*. 1982). Dating of the Honningsvåg Igneous Complex by Krill *et al*. (1988) created much confusion regarding the age of the rocks in the Magerøy Nappe by yielding Sm–Nd isochron ages of 508 ± 18 and 475 ± 22 Ma and Rb–Sr isochron ages of 558 ± 91 and 468 ± 18 Ma from plagioclase, clinopyroxene and whole rock from two gabbro samples. The fact that these dates were older than the fossiliferous host-rocks was problematic and generated a heated debate (Andersen 1989; Krill & Rodgers 1989) that was eventually terminated by additional finds of Early Silurian graptolites inside the hornfelsed part of the contact metamorphic aureole near the base of the Honningsvåg Igneous Complex (Krill *et al*. 1993), thus confirming the original interpretation. The reason for the too-old Sm–Nd and Rb–Sr ages remains unexplained but analogous cases have been observed for the Halti Complex (Andréasson *et al*. 2003), and in plutons of the Seiland Igneous Province (Krogh & Elvevold 1990; Daly *et al*. 1991; Roberts *et al*. 2005).

Sample characteristics

Five samples were investigated in this study. Sample 48C1 represents a pegmatitic portion of intrusion 7 (and youngest) of the Honningsvåg Igneous Complex (Robins 1998). The pegmatite occurs both as diffuse pockets characterized by gradual grain-size coarsening of normal gabbro but also as discrete veins. Sample 92 represents a small granite body intruding metasedimentary rocks of the Juldagnes Formation between Honningsvåg and Nordvågen. The biotite- and hornblende-bearing granite exhibits graphic intergrowth of perthitic K-feldspar and quartz, consistent with high-level emplacement. Sample 93 represents the Finnvik granite, a biotite ± hornblende-bearing slightly porphyritic rock, which had originally been dated by the Rb–Sr method (Andersen *et al*. 1982). Sample 6 is a biotite- and muscovite-bearing K-feldspar porphyritic quartz monzonite representing the Skarsvåg pluton, whereas sample 85 was taken from a metre-wide dyke of medium-grained two-mica, tourmaline-bearing leucocratic granite in biotite–muscovite schists of the Skarsvåg Nappe.

U–Pb data

Analytical procedure

The U–Pb analyses were carried out by isotope dilution thermal ionization mass spectrometry (ID-TIMS) (Krogh 1973) on hand-picked and abraded (Krogh 1982) crystals of zircon, monazite and xenotime. Updates and details of the procedure have been given by Corfu (2004). The data have been plotted and the ages calculated using the Isoplot program (Ludwig 2003). Uncertainties represent 2σ.

Results

Pegmatitic gabbro, Honningsvåg Igneous Complex (48C1). The sample contains two distinct groups of zircons. One group comprises clear to very pale yellow, short prismatic crystals and the other one brown, translucent, short prismatic to equant crystals. The distinction is also reflected in the U content, which ranges from a few hundred parts per million in the clear grains to values between 6000 and 24 000 ppm in the brown ones, but with nearly equal Th/U between 0.64 in clear and about 0.5 in brown zircon (Table 1). In spite of the differences, U–Pb analyses of the two zircon types plot in a tight cluster near the concordia curve (Fig. 3). A discordia line anchored at 0 Ma has a mean square weighted deviation (MSWD) of 1.2 defining an intercept age of 438.2 ± 0.7 Ma. The strong variation in the characteristics of the zircon population probably reflects the differentiation process that led to the development of pegmatitic pockets in the gabbro, but the fact that the two zircon groups are indistinguishable in terms of age shows that this complex crystallization spanned a comparatively short period of time at 438.2 ± 0.7 Ma.

Granitic dyke adjacent to Honningsvåg Igneous Complex (92). The zircon population is dominated by clear to brown, sharp-edged crystals, varying from equant to very long prismatic, and dominated by {100} and {101} crystal faces. As in the gabbro there is a variation in U content from about 230 ppm in clear grains to about 4000 ppm in brown ones, but nearly equal Th/U at 0.6 to 0.5. The U–Pb data points plot close to the concordia curve, and a discordia line forced to pass through the data and 0 Ma has an MSWD of 0.7 and yields an age of 438.4 ± 0.9 Ma.

Finnvik granite (93). The zircon population in this sample is morphologically very similar to that in the granitic dyke near Honningsvåg, but the crystals tend to be clear, with moderately high amounts of U (300–500 ppm), somewhat lower Th/U (0.4) and more common inclusions of other minerals. Xenocrystic cores are not evident. The data range from concordant to about 4% discordant and a line anchored at 0 Ma has an MSWD of 1.9, yielding an upper intercept age of 437.7 ± 1.6 Ma.

Skarsvåg granite (6). The presence of well-developed zircon prisms without obvious evidence of having older cores made it possible to select good quality grains that provide concordant data points. This data cluster also includes the analysis of one xenotime crystal, together defining a concordia age of 435.6 $\pm$ 0.6 Ma (Fig. 3) or an upper intercept age of 435.1 ± 1.4 Ma for a line forced through 0 Ma. Two single grains of monazite provide reversely discordant data suggestive of initial ^{230}Th excess (Schärer 1984), thus the ^{207}Pb/^{235}U ages are preferred. Their average of 436.8 ± 1.3 Ma is slightly older than the zircon–xenotime age, but these ages overlap within error and can be integrated into a common age of 436.0 ± 1.0 Ma.

Granite dyke in Skarsvåg Nappe (85). The granite contains a relatively sparse zircon population, and it is evident that many of the crystals contain rounded xenocrystic cores. The newly grown crystals are generally short prismatic and have prominently developed {010} and {101} faces, and are brown to whitish. The analyses were carried out on five single zircon tips, broken away from the cores by squeezing with tweezers, and then mechanically abraded to isolate the most suitable parts of the grains. These tips contain over 1000 ppm U and have low Th/U. These characteristics and the morphology of the grains are very common for zircon grown in water-rich, minimum melt granites (e.g. Pupin 1980). The five analyses are 0–5% discordant and a regression line passing through 0 Ma has an MSWD of 1.5, yielding an upper intercept age of 434.8 ± 1.9 Ma. Monazite is a common accessory of this rock. Two single grains provide slightly reversely discordant data, again suggestive of an initial ^{230}Th excess and yielding an average ^{207}Pb/^{235}U age of 434.1 ± 0.6 Ma, which is identical to the zircon upper intercept age. A common age of 434.5 ± 1.5 Ma is derived from the incorporation of the two dates.

Discussion

Evolution of the Magerøy rocks

The most striking feature of the combined stratigraphic, structural and isotopic information is the temporal coincidence and rapidity of the various processes of sedimentation, deformation, metamorphism and plutonism. There are no direct age limits for the oldest unit, the Kjelvik Group (Fig. 2). The overlying Nordvågen Group (Duksfjord and Sardnes Formations) is constrained to an Early Silurian age by various types of fossils (Henningsmoen 1961; Andersen 1984*a*), whereas graptolites link the uppermost unit, the Juldagnes Formation, to Early Aeronian time (Krill *et al*. 1993), i.e. to the beginning of the period between 439 and 436 ($\pm$1.9) Ma based on the most recent time scale (Gradstein *et al*. 2004) (Fig. 1). Sedimentation and magmatism, and the intervening D_1 deformation and progressive metamorphism, were thus almost contemporaneous processes, indistinguishable in age within the present limits of uncertainty. The flysch-type deposits and the D_1 shortening are indicative of convergence and tectonic thickening, whereas the bimodal magmatic activity and rapid metamorphic evolution are more symptomatic of an extensional magmatic arc regime (Hildreth 1981; Bohlen 1987). The two processes are in principle at odds with each other, as crustal thickening generally implies a relatively cold geotherm with gradual and slow warming (e.g. England & Thompson 1984), in contrast to the hot geotherm associated with magma emplacement and extension. This situation is not unique; it is also observed in the Narvik Nappe (Northrup 1997), in older orogens (e.g. the Archaean Superior Province, Percival *et al*. (2004)) and in modern settings (Maeda & Kagami 1996), and is commonly explained by suprasubduction-zone spreading or arc splitting, or by invoking the collision of a spreading ridge with a trench.

Relations to the Skarsvåg Nappe and Hellefjord schists

The dated granite dyke intruding the schists of the Skarsvåg Nappe yields an age of 434.5 ± 1.5 Ma that is slightly younger than those of the Finnvik and Skarsvåg granites. This dyke could thus be related to the fairly widespread, undeformed, late granitic to pegmatitic dykes that cut the Magerøy supracrustal rocks. Only a pre-Silurian age would have been capable of proving the inferred allochthonous origin of the rocks. Granitic intrusions with an identical age also occur in the Hellefjord Formation on the Porsanger peninsula south of Magerøy (Figs 1 and 2) and coeval monazite has been identified in schists of the Storelv Group on Sørøy (Corfu *et al*. 2004). This could also support a correlation of the Skarsvåg Nappe with the Storelv schist as proposed by Andersen (1979) and Kjærsrud (1985).

Kirkland *et al*. (2005*b*) have dated granitic and volcaniclastic units in the Hellefjord schists on northeastern Sørøy and the Porsanger pensinsula at 438 ± 2–4 Ma, thus demonstrating that this unit is a direct correlative of the Magerøy sequence, an interpretation also supported by independent U–Pb data of Gerber *et al*. (2005).

Table 1. *U–Pb data for intrusive rocks, Magerøy*

Characteristics	Weight (μg)	U (ppm)	Th/U	Pbc (pg)	$^{206}Pb/^{204}Pb$*	$^{207}Pb/^{235}U$†	±2σ (abs)	$^{206}Pb/^{238}U$†	±2σ (abs)	ρ	$^{207}Pb/^{206}Pb$†	±2σ (abs)	$^{206}Pb/^{238}U$†	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$†	±2σ (abs)	D (%)
RJR-02-48C1, pegmatitic gabbro, Honningsvåg Igneous Complex (70°59′29.1″N, 25°55′54.6″E)																	
Z eu cl [50]	172	259	0.64	21.3	9175	0.5376	0.0015	0.07007	0.00018	0.95	0.05565	0.00005	436.6	436.8	438.3	1.9	0.4
Z eu cl [50] aliquot	–	259	0.64	24.5	7980	0.5366	0.0015	0.07000	0.00018	0.94	0.05560	0.00005	436.1	436.2	436.4	2.1	0.0
Z eu fr cl (in) [>20]	36	231	0.65	14.0	2607	0.5360	0.0015	0.06986	0.00016	0.81	0.05565	0.00009	435.3	435.8	438.2	3.5	0.7
Z eu b [1]	<1	>17000	0.51	1.6	45418	0.5385	0.0025	0.07022	0.00033	0.98	0.05562	0.00005	437.5	437.4	437.2	1.9	−0.1
Z eu b [1]	9	13750	0.51	11.9	45393	0.5371	0.0014	0.06997	0.00017	0.97	0.05567	0.00003	436.0	436.5	439.4	1.4	0.8
Z eu b [1]	7	6430	0.54	3.7	53704	0.5345	0.0017	0.06966	0.00022	0.96	0.05565	0.00005	434.1	434.8	438.6	2.0	1.1
Z eu b [1]	3	23800	0.49	0.9	343773	0.5336	0.0017	0.06956	0.00021	0.98	0.05564	0.00003	433.5	434.2	438.0	1.4	1.1
RJR-02-92, granite intruding Juldagnes Fm (70°58′27.4″N, 26°00′09.0″E)																	
Z eu lp fr cl, in [36]	29	232	0.48	5.6	5326	0.5380	0.0015	0.07007	0.00019	0.87	0.05569	0.00008	436.6	437.1	439.9	3.1	0.8
Z eu lp fr cl [12]	15	250	0.49	5.5	3009	0.5367	0.0022	0.06997	0.00026	0.75	0.05563	0.00015	436.0	436.2	437.7	6.1	0.4
Z eu eq-sp p-b [42]	31	3440	0.60	6.0	77558	0.5373	0.0019	0.07000	0.00023	0.98	0.05566	0.00004	436.2	436.6	439.0	1.6	0.7
Z eu eq-sp b [23]	14	3950	0.57	69.6	3477	0.5333	0.0015	0.06954	0.00016	0.91	0.05562	0.00006	433.4	434.0	437.2	2.6	0.9
Z eu eq-sp p-b [42]	18	3650	0.61	11.7	24353	0.5327	0.0017	0.06944	0.00021	0.98	0.05564	0.00004	432.8	433.6	438.0	1.5	1.2
RJR-02-93, Finnvik granite (70°58′03.5″N, 25°28′12.4″E)																	
Z eu lp-fr cl in [50]	29	416	0.41	20.7	2566	0.5344	0.0016	0.06974	0.00017	0.82	0.05557	0.00009	434.6	434.7	435.2	3.7	0.2
Z eu lp-fr cl (in) [32]	50	271	0.41	7.6	7784	0.5339	0.0022	0.06969	0.00026	0.94	0.05556	0.00008	434.3	434.4	434.8	3.2	0.1
Z eu tips cl (in) [60]	46	442	0.40	4.4	20166	0.5325	0.0014	0.06945	0.00016	0.95	0.05561	0.00004	432.8	433.5	437.0	1.8	1.0
Z eu lp (-fr) cl (in) [40]	43	418	0.40	5.0	15574	0.5329	0.0014	0.06945	0.00018	0.94	0.05566	0.00005	432.8	433.8	438.7	2.0	1.4
Z eu tips cl in [55]	98	330	0.37	13.9	10089	0.5314	0.0014	0.06925	0.00016	0.96	0.05565	0.00004	431.6	432.7	438.5	1.7	1.6
Z eu long tips cl [40]	41	458	0.37	18.5	4394	0.5300	0.0029	0.06885	0.00038	0.80	0.05583	0.00019	429.2	431.8	445.5	7.7	3.8
Z eu lp (-fr) cl (in) [11]	15	454	0.34	5.6	5159	0.5157	0.0014	0.06724	0.00017	0.85	0.05563	0.00008	419.5	422.3	437.7	3.2	4.3
C-04-6, Skarsvåg granite, Skarsvåg (71°06′53.4″N, 25°50′15.2″E)																	
Z eu lp-fr [25]	1	1700	0.23	2.0	3779	0.5337	0.0140	0.06967	0.00182	1.00	0.05556	0.00012	434.1	434.2	434.8	4.6	0.1
Z eu tip [10]	9	553	0.11	4.4	4958	0.5347	0.0020	0.06979	0.00021	0.88	0.05557	0.00010	434.9	434.9	435.1	3.9	0.1
Z eu lp [38]	15	527	0.19	4.2	8278	0.5358	0.0012	0.06994	0.00014	0.93	0.05557	0.00005	435.8	435.7	435.2	1.9	−0.1
X eu [1]	<1	>5600	0.16	1.7	14394	0.5363	0.0018	0.07001	0.00020	0.88	0.05556	0.00009	436.2	436.0	434.6	3.5	−0.4
M sb y [1]	<1	>3060	15.23	4.5	2978	0.5376	0.0024	0.07030	0.00028	0.86	0.05546	0.00013	438.0	436.8	430.7	5.2	−1.7
M sb y [1]	<1	>920	16.29	4.6	895	0.5373	0.0033	0.07054	0.00027	0.64	0.05524	0.00026	439.4	436.6	422	10	−4.3
RJR-02-85, granite dyke, Skarsvåg nappe, Øvre Langvatnet (71°06′04.0″N, 25°50′52.9″E)																	
Z eu tip p [1]	<1	>910	0.01	0.5	7993	0.5366	0.0029	0.07011	0.00035	0.91	0.05551	0.00013	436.8	436.1	432.8	5.0	−1.0
Z eu tip p [1]	<1	>2400	0.01	1.3	7786	0.5303	0.0017	0.06927	0.00019	0.82	0.05552	0.00010	431.8	432.0	433.3	4.1	0.4
Z eu tip p [1]	<1	>1240	0.00	0.9	6174	0.5256	0.0023	0.06853	0.00027	0.91	0.05563	0.00010	427.3	428.9	437.7	4.0	2.5
Z eu tip p [1]	<1	>2620	0.01	0.9	12733	0.5232	0.0025	0.06838	0.00031	0.91	0.05549	0.00011	426.4	427.3	432.1	4.3	1.4
Z eu tip p [1]	<1	>1830	0.01	1.4	5414	0.5122	0.0023	0.06678	0.00027	0.90	0.05563	0.00011	416.7	419.9	437.6	4.4	4.9
M eu flat-sp y [1]	2	15800	4.07	15.7	8807	0.5339	0.0014	0.06996	0.00016	0.95	0.05535	0.00004	435.9	434.4	426.5	1.7	−2.3
M eu flat-sp y [1]	<1	>31500	3.39	9.1	15212	0.5330	0.0013	0.06983	0.00015	0.95	0.05535	0.00004	435.1	433.8	426.6	1.7	−2.1

Z, zircon; X, xenotime; M, monazite; eu, euhedral; sb, subhedral; eq, equant; sp, short prismatic (l/w = 2–4); lp, long prismatic (l/w >4); fr, fragment; cl, colourless; b, brown; y, yellow; p, pink; op, opaque; in, inclusions; [*n*], number of grains in fraction. Weight and concentrations are known to better than 10%, except for those near and below the *c.* 1 μg limit of resolution of the balance. The Th/U model ratio is inferred from 208/206 ratio and age of sample. Pbc is the total common Pb in sample (initial + blank). D, degree of discordancy.

*Raw data corrected for fractionation and blank.

†Corrected for fractionation, spike, blank and initial common Pb; error calculated by propagating the main sources of uncertainty.

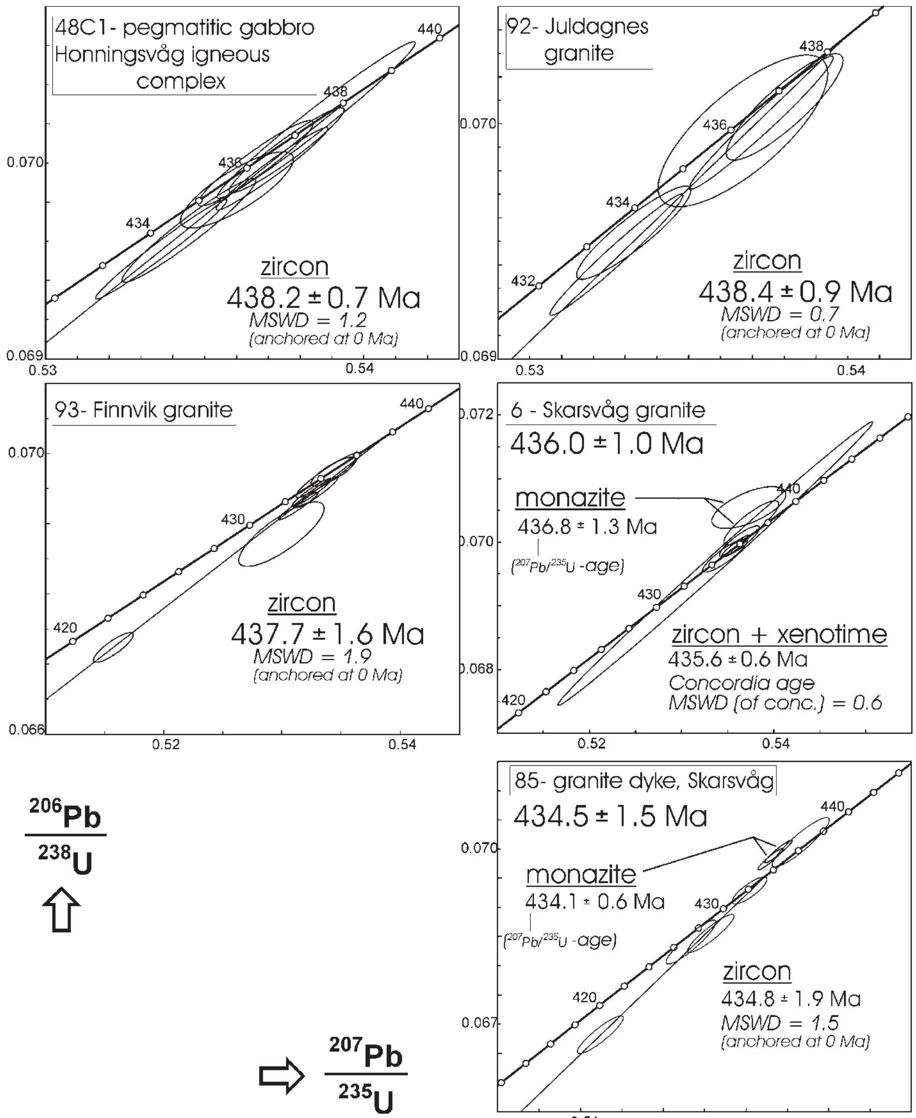

Fig. 3. Concordia diagram with U–Pb data for zircon, monazite and xenotime of mafic and felsic intrusions of Magerøy. Uncertainties ellipses represent 2σ.

Revised interpretation of the magnetic signature of the Honningsvåg Igneous Complex

In a palaeomagnetic study of the Honningsvåg Igneous Complex (Torsvik *et al*. 1992), a dual-polarity magnetic signature was interpreted as postdating emplacement of the Magerøy Nappe (late D_1) and linked to remanence acquisition during post-D_1 uplift at *c*. 410 Ma. The age estimate and interpretation was based on Rb–Sr ages from the Finnvik granite and the Gjæsvær migmatite, and the observation that the Honningsvåg Igneous Complex pole position plotted in the vicinity of Siluro-Devonian poles from Baltica, Scotland and North America. Given that the first reliable and high-precision dating of the Honningsvåg Igneous Complex now provides Early Silurian (Llandovery) ages (438.2 ± 0.7 Ma and 438.4 ± 0.9 Ma) and an improved definition of the Baltic apparent polar wander (APW) path, the original interpretation by Torsvik *et al*. (1992) requires modifications.

Figure 4a shows the Honningsvåg Igneous Complex pole together with the most updated Baltic APW path from the Ordovician to the Devonian (400 Ma), and a combined Baltica–Scotland–North America (Laurussia) path from the Silurian to the Carboniferous (updated from Torsvik *et al*. 1996). If our earlier assumption that the Honningsvåg Igneous Complex pole is secondary and post-Magerøy Nappe emplacement (post-D_1 with minor D_2 modification; see Torsvik *et al*. 1992) was correct, then the Honningsvåg Igneous Complex pole should fall on the Baltica APW path. However, the Honningsvåg Igneous Complex pole does not fall directly on any parts of the Baltic (or Laurussian) APW path. Post-acquisition clockwise rotation on a vertical axis (e.g. linked to D_2) would bring the Honningsvåg Igneous Complex pole to an APW segment that is older than the actual age of the complex (*c*. 438 Ma), and counterclockwise rotation marginally improves a fit with the Siluro-Devonian corner of the Baltic APW path. A post-D_1 remagnetization age of *c*. 410 Ma as advocated by Torsvik *et al*. (1992) would also imply a latitudinal position for the Honningsvåg Igneous Complex some 2500 km south of its present position (Fig. 4c); this appears palaeogeographically impossible as the complex would be located in southern England–Central Europe after Iapetus closure. A *c*. 400 Ma remagnetization age would also position the Honningsvåg Igneous Complex too far south in relation to Baltica and we do not consider a model with large-scale post-410–400 Ma dextral lateral movements plus easterly thrusting seriously. Therefore, alternative models are necessary.

The magmatic layering in the Honningsvåg Igneous Complex

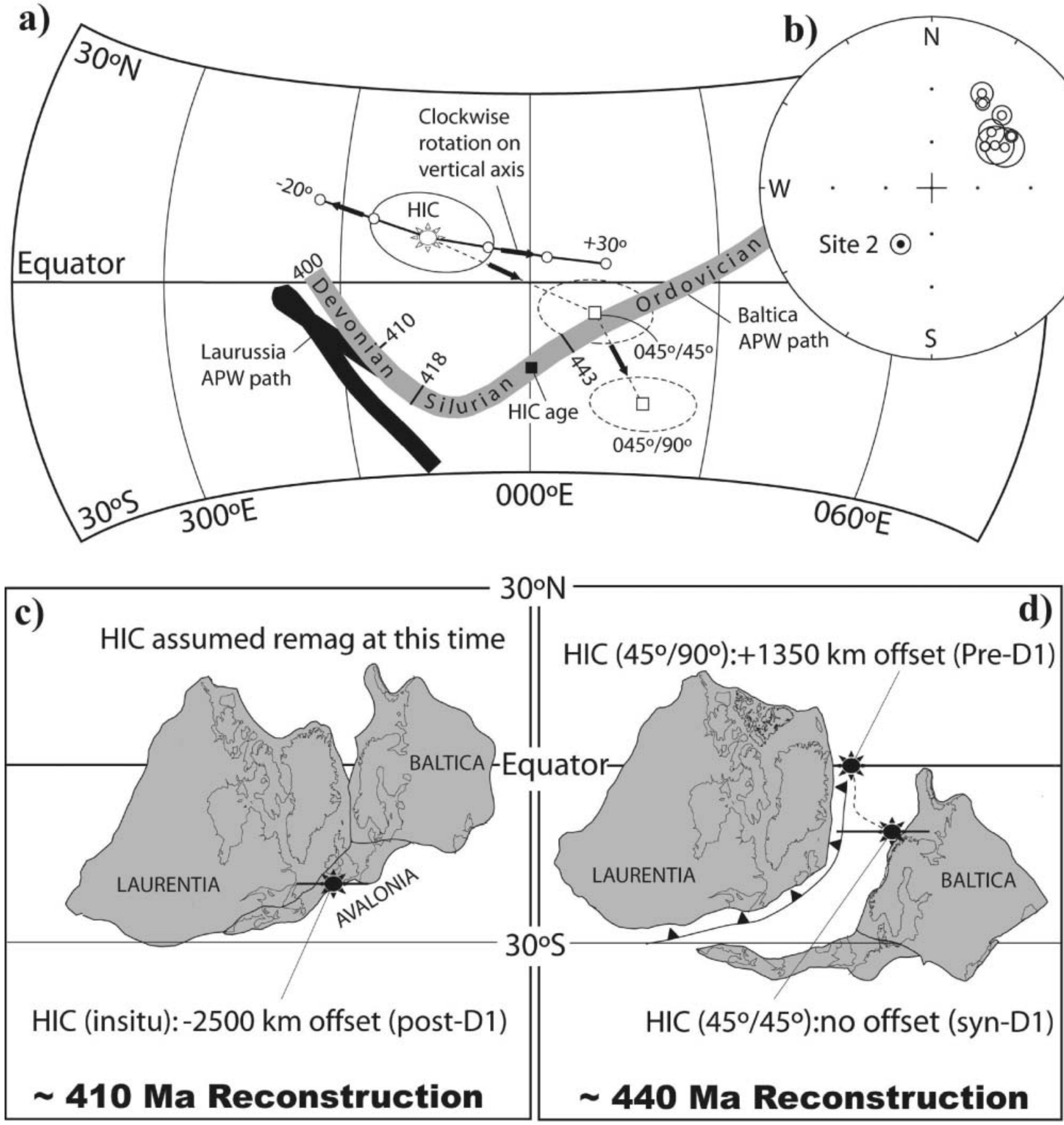

Fig. 4. (**a**) Apparent polar wander (APW) paths for Baltica (Torsvik & Rehnström 2003) and Laurussia (updated from Torsvik *et al*. 1996) shown together with the pole position for the Honningsvåg Igneous Complex (HIC) (Torsvik *et al*. 1992). The Honningsvåg Igneous Complex pole is shown with dp/dm confidence ellipses (semi-axis of the 95% confidence ellipse around the virtual geomagnetic pole). Clockwise and counterclockwise rotation on a vertical axis is shown in 10° steps (○). Example on correcting the Honningsvåg Igneous Complex pole for magmatic layering (i.e. primary or syn-D_1) shows 50% (45°) and 100% (90°) corrections (□). (**b**) Site mean directions from the Honningsvåg Igneous Complex (Torsvik *et al*. 1992) shown with α_{95} confidence circles. Site 2 corresponds to intrusion 3 of Robins (1998). (**c**) Devonian reconstruction (*c*. 410 Ma) showing the palaeogeographical implication of interpreting the Honningsvåg Igneous Complex pole as a Devonian *in situ* remagnetization. (**d**) Preferred Early Silurian (*c*. 438 Ma) reconstructions where the Honningsvåg Igneous Complex pole is interpreted as primary or syn-D_1, which will indicate a position near or to the NW of Baltica.

is nearly vertical, trending *c*. 045, and younging to the SE. The magnetic polarity of the two sites (2 and 6) representing intrusion 3 of Robins (1998) differs from that of the bulk of the Honningsvåg Igneous Complex (intrusions 1, 4 and 7 of Robins (1998)) (Fig. 4b). The two polarities are antipodal (Fig. 4b) and it is theoretically possible to advocate that the magnetization in the Honningsvåg Igneous Complex is primary and was subsequently affected by tilting of the complex and eastward nappe translation onto Baltica. The pole position would therefore be expected to show no resemblance to that of Baltica. Restoring the magmatic layering to the horizontal yields a palaeolatitude near the equator, suggesting that the Honningsvåg Igneous Complex formed *c*. 1350 km north of its present position (longitude is unconstrained) at around 438 Ma (Fig. 4d). We can also partially restore the magmatic layering (assuming a syn-D_1 magnetic signature in a dual-polarity field), for example by 50% unfolding–tilting, and this will suggest a palaeoposition just north of its present position during D_1. We therefore interpret the magnetization signature of the Honningsvåg Igneous Complex as primary or syn-D_1, and conclude that the complex probably formed NW of Baltica, perhaps in a position near NE Greenland.

Early Silurian tectonic and magmatic activity along the Caledonides

As shown in Figure 1, the Early Silurian plutonism recorded in Magerøy was part of a widespread tectonomagmatic activity seen all along the Caledonides but in settings that range from contractional to extensional.

The closest analogue to Magerøy seems to be the Narvik Nappe Complex, where a sequence of various metasedimentary rocks with local mafic and ultramafic rocks, interpreted as an accretionary complex, were intruded by mafic and felsic plutons and dykes at 436–437 Ma and subsequently migmatized at about 432 Ma (Tucker *et al*. 1990; Andresen & Steltenpohl 1994; Northrup 1997). The intrusive activity postdates D_1 deformation and was followed by a multiphase deformational history. By contrast, the Solund–Stavfjord ophiolite in southern Norway developed in a spreading environment, presumably in a back-arc basin opening on older Palaeozoic arc crust that was eroded and accreted onto Laurentia (Furnes *et al*. 1990; Pedersen *et al*. 1992; Pedersen & Dunning 1993). The coeval Bremanger tonalite and Gåsøy gabbronorite (Fig. 1) probably reflect associated arc magmatism (Hansen *et al*. 2002) whereas a back-arc setting has been suggested for the Sulitjelma Igneous Complex (Fig. 1; Pedersen *et al*. 1991). Intrusion of trondhjemitic to gabbroic plutons in the Trondheim region has been related to transtensional tectonic processes, a general interpretation used for most other Early Silurian sedimentary–basaltic assemblages in the Upper Allochthon. In most cases there are strong geological as well as faunal and/or isotopic arguments supporting an outboard Baltica and possibly Laurentian affinity of these marginal basins (Stephens & Gee 1989; Pedersen *et al*. 1992; Andersen & Andresen 1994). An apparent exception is the Halti Complex, which was placed by Andréasson *et al*. (2003) into a Baltic setting. The critical link for this interpretation is the presence of mafic dykes in the underlying nappe, a correlative of the Kalak Nappe system. The latter has long been considered to represent a slice of Baltic basement and Neoproterozoic cover, but new data show instead that this is an exotic terrane of probable peri-Gondwanan affinity (Corfu *et al*. 2004). The Gjesvær Migmatite Complex, the potential basement to the Magerøy sequence, contains Grenvillian intrusions (Corfu *et al*. 2005), suggesting a provenance similar to that of terranes in East Greenland and Svalbard rather than Baltica. Sveconorwegian plutons have also been documented in more easterly domains of the Kalak Nappe Complex (Kirkland *et al*. 2005*a*). Hence the presence of inherited zircon of Sveconorwegian age in the Halti plagiogranites (Andréasson *et al*. 2003) could be indicative of a similar relationship. Moreover, the contacts between the Halti Complex and its present basement are highly tectonized and thus the postulation of an original intrusive contact appears speculative.

We thus see no reason to support the notion of an Early Silurian eastward-dipping subduction geometry, preferring instead that of an arc system related to subduction towards and underneath the Laurentian margin, but perhaps also involving intraoceanic microcontinental fragments of peri-Gonwanan derivation (parts of the subsequent Kalak Nappe system). The intensive magmatic activity at this time was probably related to rapid subduction during the final closing of the oceanic basin(s) intervening between Laurentia and Baltica. The variations in setting and stress regime observed for these Early Silurian intrusive rocks is analogous to the situation existing along the northern Pacific margin in the Late Cretaceous, where contrasting tectonic styles developed between areas under extension and those under concurrent contraction, apparently dependent on changes in mechanical coupling between the converging plates (Rubin *et al*. 1995).

Conclusions

The U–Pb zircon ages of *c*. 438 Ma for pegmatitic gabbro of the Honningsvåg Igneous Complex, the associated Juldagnes granite and the Finnvik granite are identical within error to the age of deposition of the host turbidites inferred from graptolites (Krill *et al*. 1993), demonstrating that deposition of the flysch, deformation and magmatism were part of a related and very rapid set of processes. The apparent contradiction between the low thermal regime typical of accretionary prisms and the high thermal regime implied by the mafic–ultramafic and granitic intrusions can probably be explained by invoking ridge subduction. Regional metamorphism outlasted D_1 deformation and there may be a relation between the more protacted metamorphic activity and formation of the 436 Ma Skarsvåg granite and the 434.5 Ma granitic dyke in the Skarsvåg Nappe, both of which have a mineralogy suggesting a peraluminous character and postdate the early intrusions by 1–4 Ma. The palaeomagnetic characteristics of the Honningsvåg Igneous Complex can be reinterpreted in light of the present U–Pb ages to indicate formation of the sequence at a latitude near the equator with subsequence southward translation and eventual thrusting on the Kalak Nappes of Finnmark. It remains uncertain whether the Gjesvær Migmatite Complex to the west was the original basement to the Magerøy succession (with subsequence normal faulting along the interface), or whether the two were unrelated at the time of deposition. The presence of a Sveconorwegian–Grenvillian element in the Gjesvær Complex (Corfu *et al*. 2005) could accommodate a common derivation of Gjesvær and Magerøy from the Laurentian margin, as Grenvillian granitic activity is recorded within terranes of East Greenland and Svalbard. The Early Silurian events recorded in Magerøy are a common feature in nappes all along the orogen and probably reflect increased subduction along the northern Laurentian margin during the closing stages of the Iapetus Ocean.

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