U–Pb zircon dating of felsic intrusions, Middle Köli Nappes, central Scandinavian Caledonides

STEFAN CLAESSON, MICHAEL B. STEPHENS & INGER KLINGSPOR

Claesson, S., Stephens, M. B. & Klingspor, I.: U–Pb zircon dating of felsic intrusions, Middle Köli Nappes, central Scandinavian Caledonides. *Norsk Geologisk Tidsskrift*, Vol. 67, pp. 89–97. Oslo 1987. ISSN 0029-196X.

U–Pb zircon data are presented for three metamorphosed trondhjemites from the Middle Köli Nappes in northern Jämtland and southern Västerbotten, Sweden. The analysed zircon fractions give concordant or practically concordant U–Pb ages defining three distinct age groups, one for each sample. The most precise ages are given by the $^{206}Pb/^{238}U$ ratios. The average ages are 492 ± 1 Ma and 476 ± 1 Ma for two metamorphosed trondhjemites in the Stekenjokk Quartz-Keratophyre, and 440 ± 2 Ma for a dyke-like body in the Blåsjö Phyllite. It is argued that the first of these ages and, due to the possibility of minor post-crystallization Pb-loss, less confidently even the other two reflect the times of emplacement of the intrusions. Furthermore, it is considered that the first age lies close to the age of the volcanic activity in the Stekenjokk Quartz-Keratophyre which is, thus, most likely to be Tremadoc. The pre-Silurian age of these intrusions and their host rocks confirms earlier suggestions that there exists a major tectonic break in the lower part of the Köli sequence. The felsic igneous activity is considered to belong to a prolonged period of rifting. This overlapped in time with and succeeded the waning stages of an island arc development which was active probably during the Tremadoc.

S. Claesson & I. Klingspor, Laboratoriet för isotopgeologi, Naturhistoriska riksmuseet, S-104 05 Stockholm, Sweden; M. B. Stephens, Sveriges geologiska undersökning, Box 670, S–751 28 Uppsala, Sweden.

The Köli Nappes (Stephens & Gee 1985, p. 957) in the central Scandinavian Caledonides are composed of metamorphosed sedimentary, volcanic and intrusive rocks which formed in various submarine tectonic environments predominantly during closure of the Iapetus Ocean. Stratigraphic and geochemical evidence suggest that these environments are represented by segments of ocean floor, rifted ensimatic arcs, and marginal basins (Roberts et al. 1984; Stephens et al. 1985). These various rock complexes are preserved both in different internal thrust slices and at different stratigraphical levels in an individual slice. The Köli Nappes thus comprise a complex of geological terranes (Stephens & Gee 1985, and in press). Palaeontological evidence suggests that some terranes are likely to have formed at large distances from each other, including sites both outboard of the continent Baltica as well as proximal to the continent Laurentia (Gee 1975; Bruton & Bockelie 1980; Bruton & Harper 1985; Stephens & Gee 1985). Although there is evidence for early-stage collisional events in some of the Köli Nappes, accretion of the various terranes both to each other and to the continent Baltica was not completed until final closure of Iapetus during the Silurian-Devonian (Stephens & Gee 1985, and in press).

A better understanding of the early Caledonian evolution of these exotic Köli terranes is essential not only for reconstruction of the plate boundary interaction which helped to produce this part of the Caledonian mountain belt, but also as a guide in future mineral resource analysis. Detailed models for this evolution have been suggested and, in some cases, differ markedly from each other (compare, for example, Roberts et al. 1985 and Stephens & Gee 1985). In order to evaluate the relevance of these models, more constraints are required. As pointed out by Stephens & Gee (1985), more data on the age of the various units are essential.

Age-constraining fossils have been found only at a few localities in the Köli Nappes (Bruton et al. 1985; Bassett 1985), which is why a general dating programme has to rely on radiometric methods. We consider felsic high-level intrusions commonly occurring in volcanic complexes to be the most suitable rock type for this purpose. Previous studies (Claesson et al. 1983 and unpublished material) indicate that the Rb–Sr systems in these rocks are disturbed. This is probably due

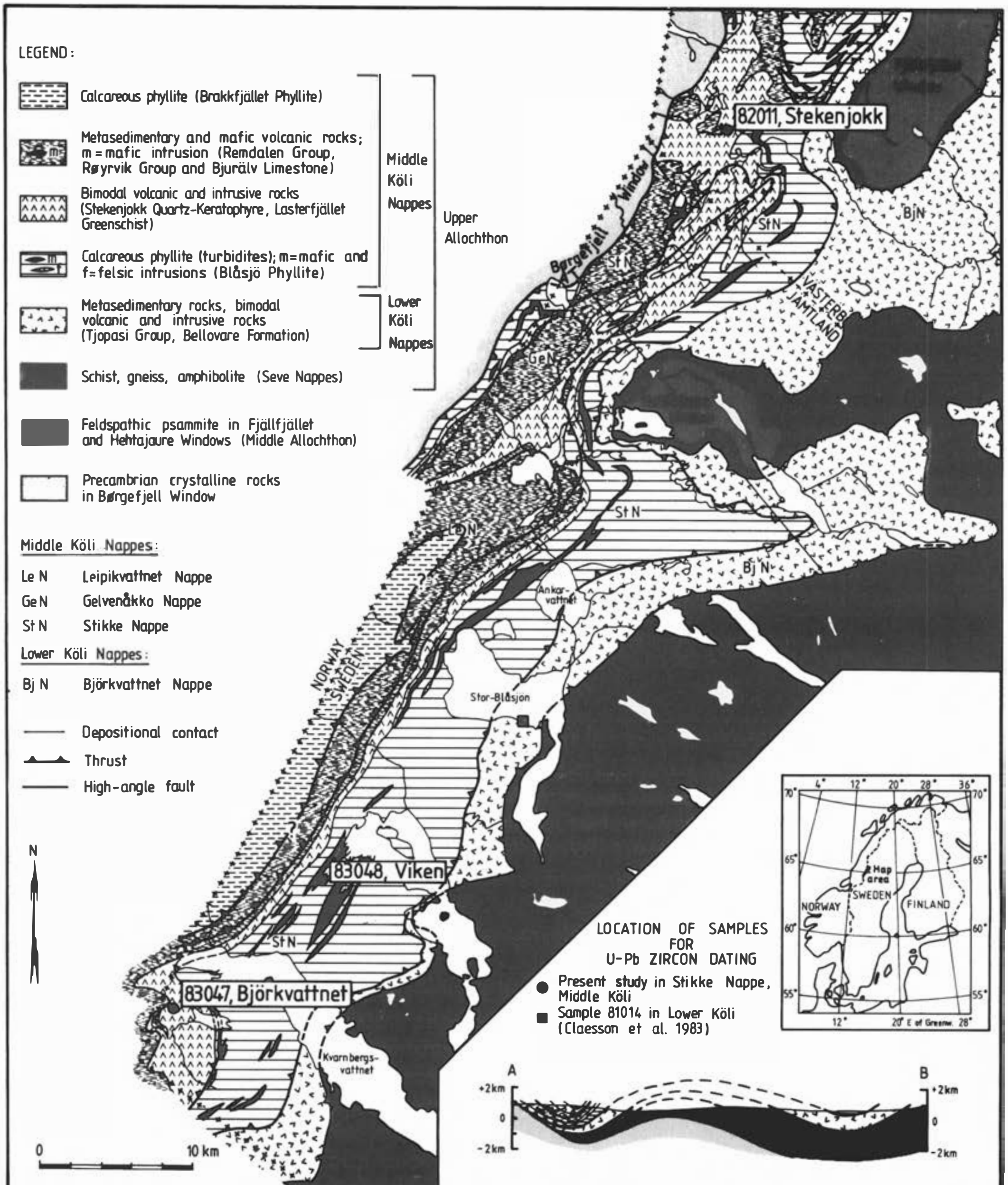

Fig. 1. Geological map of northern Jämtland and southern Västerbotten, Sweden, showing locations of samples for U–Pb zircon dating (geological base redrawn after Zachrisson 1969 and Stephens 1982).

to alteration processes during pre-deformational, sub-seafloor metamorphism, involving large element redistributions related to spilitization (Stephens 1980a). However, the U–Pb systems in zircons investigated by Claesson et al. (1983) were unaffected by this alteration and provided a precise age, inferred to be the time of intrusion. U–Pb zircon dating thus appeared to be the most reliable technique for future studies. In this paper, U–Pb zircon ages for three metamorphosed

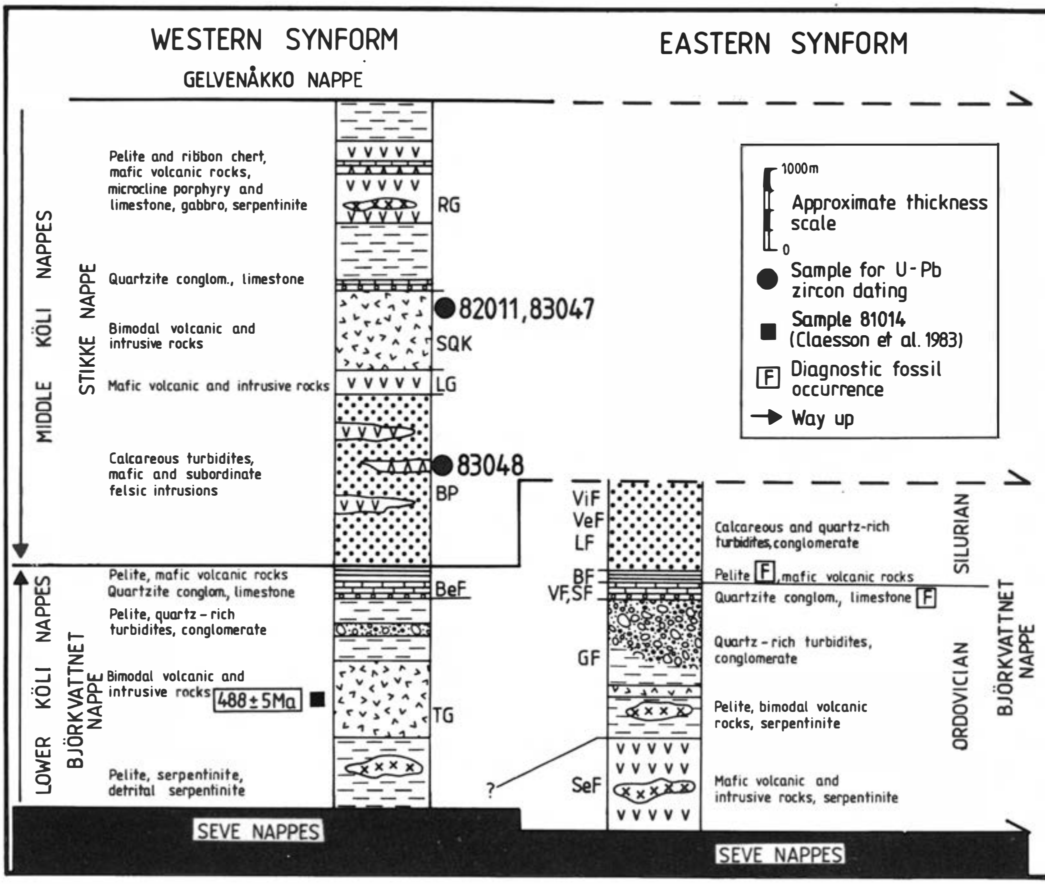

Fig. 2. Stratigraphy within the Björkvattnet (Lower Köli) and Stikke (Middle Köli) Nappes and approximate locations of samples for U–Pb zircon dating (stratigraphy redrawn after Stephens 1982). SeF, GF, VF, SF, BF, LF VeF, ViF, TG, BeF = Seima, Gilliks, Vojtja, Slätdal, Broken, Lövfjäll, Vesken and Virisen Formations, Tjopasi Group, and Bellovare Formation, respectively, in the Björkvattnet Nappe; BP, LG, SQK and RG = Blåsjö Phyllite, Lasterfjället Greenschist, Stekenjokk Quartz-Keratophyre and Remdalen Group, respectively, in the Stikke Nappe.

trondhjemitic intrusions in the Köli Nappes of northern Jämtland and southern Västerbotten, Sweden are presented. The paper is written by the first two authors and most of the laboratory work was carried out by the third.

Structural and stratigraphic scenario

The trondhjemitic intrusions dated in this study occur within a major synform (Western Synform of Zachrisson 1969) which, in its northern part, lies between the Fjällfjället and Hehtajaure Windows in the east and the Børgefjell Window in the west (Fig. 1). The rocks within this synform comprise a volcano-sedimentary complex with both mafic and felsic minor intrusions, all of which have suffered polyphase deformation, thrust nappe transport, and both pre- and syn-deformational low-grade metamorphism. Early studies recognized several internal thrust sheets in this Köli complex which caused repetition of some of the stratigraphic units (Lower Köli unit, and Gelvenåkko and Leipikvattnet Nappes of Zachrisson 1969). However, the structural sequence downwards from the base of the Gelvenåkko Nappe to the top of the sub-Köli tectonostratigraphic units (Seve Nappes or Middle Allochthon), as exposed in the windows, was considered to be stratigraphically continuous and right-way up (Zachrisson 1964, 1969; Figs. 1 and 2). The only reliable time constraint when this stratigraphy was established concerned the shallow-water quartzite conglomerate, quartzite and limestone of the Bellovare Formation (Fig. 2). This was correlated eastwards over the Fjällfjället Window (Zachrisson 1969 and Fig. 2) with the Upper Ordovician Vojtja and Slätdal Formations occurring in the classic Björkvattnet–Virisen area in the Eastern Synform (Kulling 1933; Stephens 1977). The upper part of the succession – Blåsjö Phyllite up to and including the Remdalen Group – was thus assumed to be Silurian.

Subsequent work, using both the regional geological relationships (Sjöstrand 1978; Stephens 1982) and detailed studies of major massive sulphide deposits (Juve 1977; Sunblad 1980; Zachrisson 1982, 1984), indicated that the upper part of the succession was inverted and separated by an internal Köli thrust from essentially the Bellovare Formation and Tjopasi Group beneath; the thrust sheets were referred to as the Stikke and Björkvattnet Nappes, respectively (Stephens 1982 and Fig. 2). Although stratigraphic links are apparent between the lithological units in the Stikke and higher nappes, referred to collectively as the Middle Köli, they are lacking between the Stikke and Björkvattnet or Lower Köli Nappes (Zachrisson 1969; Stephens 1980b; Stephens & Gee 1985). Both the Lower and the Middle Köli successions are thought to include segments of rifted ensimatic arcs which were buried beneath clastic rocks deposited in marginal basins (Stephens 1980b, 1982 and unpublished material). However, the stratigraphic contrasts suggest that they are derived from separate terranes (Virisen and Gjersvik terranes, respectively, of Stephens & Gee, in press) which evolved at a significant distance from each other, evidence for accretion emerging only in the Silurian (Stephens & Gee 1985, and in press). An Ordovician age was inferred for the succession in the Stikke Nappe (Stephens 1982). More specifically, a Tremadoc age was argued for a black phyllite horizon near the stratigraphic top (structural base) of the Stekenjokk Quartz-Keratophyre (Sundblad & Gee 1985). This was based on its distinctive chemical signature including high contents of U, Mo and especially V.

The previous U–Pb zircon dating (Claesson et al. 1983) concerned a metamorphosed trondhjemitic intrusion situated within the bimodal volcanic and intrusive rocks of the Tjopasi Group in the Lower Köli (Figs. 1 and 2). An emplacement age of 488 ± 5 Ma was obtained which, together with the late Ordovician age for the Bellovare Formation, confirmed the right-way up character of the volcano-sedimentary sequence in the lower Köli. This paper now directs attention to metamorphosed trondhjemitic intrusions in the Stikke Nappe of the Middle Köli. This work aims primarily to test the new structural and stratigraphic model now proposed for these Köli Nappes. The results should also provide tighter constraints on the timing of rifted ensimatic arc and marginal basin development as represented in the Middle Köli.

Description of whole-rock samples and zircons

Zircons for this study were separated from large (c. 100 kg), fresh samples of metamorphosed trondhjemite. Two samples were collected from blasted outcrop material, one in the Stekenjokk Quartz-Keratophyre at Björkvattnet (sample no. 83047) and the other in the Blåsjö Phyllite at Viken (83048). The third sample (82011) was collected from material in five drillholes which transect the Stekenjokk Quartz-Keratophyre in its stratigraphic position beneath (structural position above) the Levi massive sulphide deposit, approximately 3 km northwest of Stekenjokk. Sample locations and stratigraphic positions are shown in Figs. 1 and 2, respectively.

Sample 83047 from Björkvattnet was taken from a massive to weakly foliated albite trondhjemite, c. 100 m thick, which can be traced for 4 km along strike in the stratigraphically lower part of the Stekenjokk Quartz-Keratophyre. The main minerals are albite and quartz, the former 1 mm long and sericitized, with minor contents of chlorite, epidote, calcite and Fe–Ti minerals (see Fig. 8b in Stephens 1982). Sample 82011 is typical of the coarse-grained, massive and homogeneous albite trondhjemites, up to c. 50 m thick, which are conspicuous in the Levi drillholes near the stratigraphic base of the Stekenjokk Quartz-Keratophyre (Zachrisson 1984). In this lithology, sericitized albite megacrysts, up to 2 mm across and generally displaying the effects of intense deformation, merge into a finer matrix containing recrystallized albite and quartz with scattered chlorite grains, and thin, discontinuous seams of white mica, chlorite and epidote. The strain-induced recrystallization gives the rock a pseudo-porphyritic appearance in thin-section. The coarse grain size and homogeneity of the samples from Björkvattnet and Stekenjokk suggest a high-level intrusive origin. Nevertheless, on the basis of major- and trace-element geochemical data (Stephens 1982), an intimate petrological relationship between these and other high-level intrusions and the porphyritic felsic volcanites which dominate the Stekenjokk Quartz-Keratophyre is apparent.

Sample 83048 from Viken was taken from an albite trondhjemite which is in sharp contact with and structurally above calcareous phyllite of the Blåsjö Phyllite. The trondhjemite shows a chilled margin relationship along this boundary. The upper contact of the felsic body, which is probably only a few metres thick, is not exposed. In this sample, relict, poorly preserved megacrysts of albite and aggregates of strain-free quartz, both up to 1 mm across, are enclosed in a fine- and even-grained matrix of albite and quartz with subordinate white mica, chlorite, clinozoisite and opaque minerals. This body belongs to a suite of high-level mafic and subordinate felsic intrusions which characterize the Blåsjö Phyllite. These intrusions are pre-deformational and concordant with bedding and the regional foliation in the metasedimentary rocks which are interpreted as a calcareous turbidite complex (Sjöstrand 1978) of distal affinity. The mafic bodies contain relict, coarse-grained hornblende inferred to have formed during pre-deformational, sub-seafloor metamorphism. It is tentatively suggested that this bimodal suite intruded into a relatively wet and poorly consolidated turbidite complex in a basinal environment.

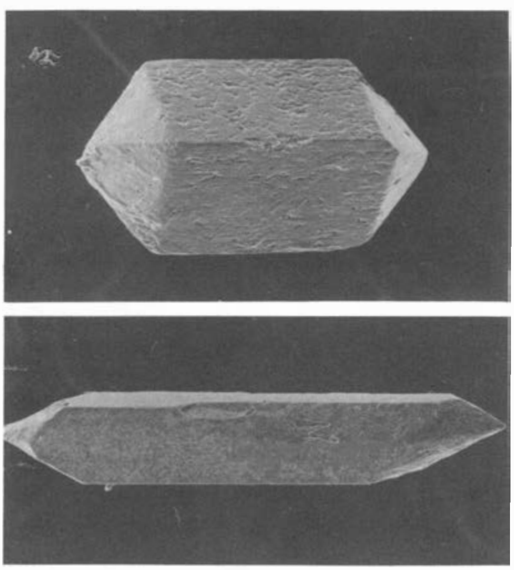

Fig. 3. SEM photographs showing typical appearances of analysed crystals. A (*top*). 200 µm long crystal from sample 83047, Björkvattnet. This morphology is typical also for zircons from sample 82011, Stekenjokk, although more irregularly shaped crystals are slightly more common in sample 82011. B (*bottom*). 190 µm long crystal from sample 83048, Viken.

The Björkvattnet zircons (83047) are typically stubby (100) prisms with short, pointed pyramidal terminations (Fig. 3a). They are half-transparent and reddish brown in colour. The Stekenjokk zircons (82011) are similar to 83047, but irregularly shaped crystals are slightly more common in this sample. Some of the pyramids are blunt, and the prisms are not only of (100) type, but all have (100) > (110). The zircons from Viken (83048) are different from those in the previous two samples. They are developed as elongate, colourless and transparent (100) prisms terminated with pyramids where more acute (211) types dominate over (101). A typical crystal is shown in Fig. 3b. None of the investigated zircon fractions contained any optically identifiable cores.

Analytical details and results

All zircons are non-magnetic in a Frantz isodynamic magnetic separator. Before analysis they were divided into size fractions, as many as the available amount of material from each of the sample allowed (Table 1). The chemical preparation was carried out using standard techniques, essentially following Krogh (1973). The total Pb blank contamination was 2 ng. The U was measured on an AVCO 901-A mass spectrometer, and Pb isotope ratios were determined on a Finnigan MAT 261 mass spectrometer equipped with a multicollector for masses 204, 206, 207, and 208. Measured Pb ratios were corrected for 0.12%/amu mass fractionation, as determined from replicate analyses of the NBS Pb standards 981 and 982, and U was corrected for 0.10%/amu mass fractionation. For two zircon fractions, 83047 90–106 µm and 106–150 µm, the Pb isotopic composition was measured with an electron multiplier. $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$ and $^{207}Pb/^{206}Pb$ ratios were calculated according to Ludwig (1980). The following initial Pb composition was used: $^{206}Pb/^{204}Pb = 18.0$, $^{207}Pb/^{204}Pb = 15.5$, $^{208}Pb/^{204}Pb = 37.7$. This is the composition given by Sundblad & Stephens (1983) for the massive Stekenjokk-

Table 1. Analytical U–Pb data.

Sample Size fraction	U ppm	Pb_{rad} ppm	Pb_{init} ppm	Atom ratios[a] $^{206}Pb/^{204}Pb$	Atom ratios[a] $^{206}Pb/^{208}Pb$	Atom ratios[b] $^{206}Pb/^{238}U$	Atom ratios[b] $^{207}Pb/^{235}U$	Atom ratios[b] $^{207}Pb/^{206}Pb$	Ages (Ma) $^{206}Pb/^{238}U$	Ages (Ma) $^{207}Pb/^{235}U$	Ages (Ma) $^{207}Pb/^{206}Pb$
82011											
Map-sheet 23E Sipmeke, 722530/143530											
60–74 μm	602	53	0.1	>20000	4.7	0.0793 (4)	0.622 (5)	0.0569 (4)	492	491	486
90–106 μm	665	58	0.5	6800	4.4	0.0794 (2)	0.630 (4)	0.0575 (3)	493	496	512
106–150 μm	761	68	0.4	9700	4.1	0.0794 (3)	0.623 (25)	0.0569 (21)	493	491	486
83047											
Map-sheet 22E Frostviken, 716890/139915											
45–60 μm	748	70	0.1	>20000	2.7	0.0764 (2)	0.603 (7)	0.0573 (6)	475	479	501
60–74 μm	595	55	0.1	>20000	2.8	0.0767 (2)	0.611 (7)	0.0579 (6)	476	484	524
74–90 μm	615	57	0.1	>20000	2.9	0.0767 (4)	0.610 (19)	0.0577 (17)	476	483	518
90–106 μm[c]	751	68	0.4	9800	3.0	0.0755 (4)	0.596 (9)	0.0572 (8)	469	474	500
106–150 μm[c]	635	56	0.8	4100	3.2	0.0756 (3)	0.594 (16)	0.0570 (14)	470	473	492
83048											
Map-sheet 22E Frostviken, 717690/140885											
74–106 μm	167	13	0.1	7000	3.9	0.0702 (4)	0.559 (23)	0.0578 (22)	438	451	521
106–210 μm	89	7	0.2	2400	4.5	0.0709 (21)	0.552 (28)	0.0564 (22)	442	446	470

Numbers within parentheses indicate 2σ precision in last decimal(s).
[a]Corrected for blank Pb.
[b]Corrected for blank and initial Pb.
[c]Pb isotopic composition measured with an electron multiplier as detector.

Levi sulphide deposit, situated in the Stekenjokk Quartz-Keratophyre from which sample 82011 was collected. The decay constants recommended by Steiger & Jäger (1977) were used in the age calculations. Results are given in Table 1 and plotted in a concordia diagram in Fig. 4.

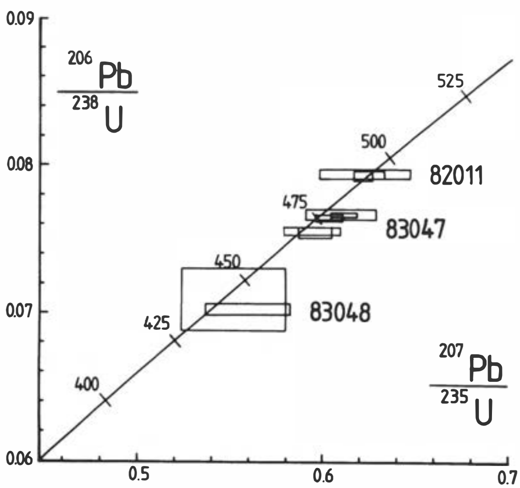

Fig. 4. Concordia diagram showing all analysed zircon fractions. Isotopic ratios are given in Table 1.

The analytical uncertainty for some fractions is rather large. This is mainly due to small sample size, especially for the fraction 83048, 106–210 μm from Viken, which had a total Pb amount of only 15 ng. It can be seen in Table 1 and Fig. 4 that the $^{206}Pb/^{238}U$ ratios are more precisely determined than $^{207}Pb/^{235}U$. This is because the isotopes in the former ratio are more abundant. For this reason, the $^{206}Pb/^{238}U$ ratio is also considered more reliable.

The U concentration in the Björkvattnet (83047) and Stekenjokk (82011) zircons are similar, 600–750 ppm, but their $^{206}Pb/^{208}Pb$ ratios are different (Table 1). This suggests that the magmas from which they crystallized had different U/Th ratios. The two analysed zircon fractions from Viken (83048) are much lower in U, about 90 and 170ppm (Table 1).

Only one of the 10 analysed fractions, 83047 60–74 μm is discordant within the estimated analytical precision (Fig. 4). The fractions fall into three well-defined age groups, one for each sample, with $^{206}Pb/^{238}U$ ages of 492–493 Ma for Stekenjokk, 469–476 Ma for Björkvattnet, and 438–442 Ma for Viken. The ages within each group are remarkably similar in 82011 and 83048, but in 83047 the ages are divided into two subgroups. The possibility that this sub-division is partially an artifact of the measuring technique cannot, however, be excluded. The two coarsest grain size fractions from 83047, which constitute the younger subgroup, were those measured for Pb isotopic composition using an electron multiplier as detector, and any non-linearity in this instrument would cause a minor bias in the measured ratios.

The concordia curve, from the age of the present samples and down to the origin, is not very curved. Thus, minor Pb-loss from zircon cannot always be readily detected since samples which have lost some Pb will still plot very close to the concordia. However, due to variations in size and other parameters, different zircon fractions are variably susceptible to Pb-loss. Thus, when analyses of several fractions from the same sample are available, Pb-loss may be indicated by slightly different U-Pb ages for the different fractions. In the present case, the data for sample 82011 from Stekenjokk strongly suggest that the zircons in this rock have been closed systems for U and Pb since the rock crystallized. The U–Pb and Pb isotope ratios for the three analysed size fractions from this sample are indistinguishable from each other and the average $^{206}Pb/^{238}U$ ages and $^{207}Pb/^{235}U$ ages are identical at 492 ± 1 Ma and 493 ± 4 Ma, respectively.

For sample 83047 from Björkvattnet, the possible division of U–Pb and Pb isotope ratios for the five analysed zircon fractions into two subgroups suggests that these zircons may have lost some Pb. If the two coarsest grain size fractions, which may be analytically less reliable, are excluded, the three remaining fractions give indistinguishable U–Pb and Pb isotope ratios with average $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages of 476 ± 1 and 482 ± 4 Ma, respectively. The results for sample 83048 from Viken cannot be treated with the same confidence as the others, since only two fractions were analysed, and they both have a large analytical uncertainty.

General support for the interpretation that the zircons in this study are concordant or practically concordant is found in the results from a metamorphosed trondhjemite at Brattåsruet in the Lower Köli Nappes (Claesson et al. 1983). Three zircon fractions from this rock gave almost concordant U–Pb ages, while the coarsest size fraction was strongly discordant. Thus, our preferred interpretation is that the present zircons have been closed or practically closed systems for U and Pb following their crystallization. If this model is accepted, the most precise age estimate for each sample is its average $^{206}Pb/^{238}U$ age. For 83047, the finer grain size fractions are considered the most reliable. The average $^{206}Pb/^{238}U$ ages are 492 ± 1 Ma for Stekenjokk (sample 82011), 476 ± 1 Ma for Björkvattnet (sample 83047), and 440 ± 2 Ma for Viken (sample 83048). We consider the precisions in these average ages to be unrealistically high, but they are nevertheless likely to reflect or lie close to the three intrusion ages. As discussed above, the age for Stekenjokk is the most reliable, while the possibility that those for Björkvattnet and Viken are slightly young due to post-crystallization Pb-loss cannot be completely ruled out.

Discussion

Structural and stratigraphic model

The rocks analysed in this paper are interpreted to be intrusions, and thus provide minimum ages for the particular rocks they intrude. However, as indicated above, the high-level intrusions at Stekenjokk and Björkvattnet display a similar chemistry to the felsic volcanites in the host formation, the Stekenjokk Quartz-Keratophyre. Bearing in mind the reliability of the intrusion age from Stekenjokk, it is inferred that the age of 492 ± 1 Ma lies close to the age of this volcanic activity. The slightly different intrusion at Viken, on the other hand, is a thinner, dyke-like body displaying a chilled margin relationship to the surrounding metasedimentary rocks; volcanic rocks are not present in this part of the sequence. Thus, the Viken intrusion may be significantly younger than its immediate host rock and the two other bodies. This relationship gains support from the distinctly younger $^{206}Pb/^{238}U$ age of 440 ± 2 Ma for this body.

The chronostratigraphic significance of the new ages is subject to some uncertainty due to the present controversy concerning the early Palaeozoic time-scale (Snelling 1985). However, this controversy concerns mainly the latest Ordovician to Devonian. All suggested time-scales place the Stekenjokk and Björkvattnet ages of 492 ± 1 Ma and 476 ± 1 Ma in the early Ordovician (Tremadoc to Arenig), while the age for Viken, 440 ± 2 Ma, is Caradoc or Ashgill. The volcanites in the Stekenjokk Quartz-Keratophyre are probably also Tremadoc in age and the stratigraphically younger Blåsjö Phyllite is, at least partly, Ashgill or older. Thus, the pre-Silurian age of these intrusions and their host rocks, previously suggested by Stephens (1982), is now established. Furthermore, the data accord very well with the early Ordovician (Tremadoc) age forwarded by Sundblad & Gee (1984) for the black phyllite horizon near the stratigraphic top of the Stekenjokk Quartz-Keratophyre. These new data, taken together with the age constraints in the Lower Köli and the stratigraphic contrasts between the Lower and Middle Köli, necessitate the existence of a major tectonic break between these units in northern Jämtland and southern Västerbotten, as proposed by Stephens (1982). The data are further in accordance with, but no proof of, the inversion of the stratigraphy in the Stikke Nappe of the Middle Köli.

Tectonic model

A two-stage tectonic model, which relies in part on the trace-element chemistry of mafic volcanic and high-level intrusive rocks, has been suggested for the sequence in the Stekenjokk Quartz-Keratophyre, Lasterfjället Greenschist and Blåsjö Phyllite with its characteristic bimodal igneous activity (Stephens 1980b, 1982). Mafic rocks in the Stekenjokk Quartz-Keratophyre show affinities to both subduction- and rift-related basalts while those at higher stratigraphic levels in the Lasterfjället Greenschist and Blåsjö Phyllite are entirely rift-related. This change in the character of the mafic rocks has been inferred to be related to rifting of an island arc complex. Although the waning stages of the igneous activity related to subduction are preserved in the Stekenjokk Quartz-Keratophyre, much of the mafic igneous activity in all three formations is related to rifting. The rifting was accompanied by subsidence and deposition of clastic rocks belonging to the Blåsjö Phyllite in a marginal basin environment.

The significance of the felsic rocks in this rifted arc setting has been enigmatic. It has been suggested that the felsic rocks in the bimodal Stekenjokk Quartz-Keratophyre formed by partial melting of a basaltic parent during construction of the island arc (Stephens 1982). However, field relationships indicate that felsic igneous activity continued during or after deposition of the clastic rocks in the Blåsjö Phyllite when the mafic rocks were solely rift-related. Furthermore, the data presented here probably indicate a relatively long period during the Ordovician when felsic igneous activity occurred. These considerations suggest that the felsic rocks in the Blåsjö Phyllite and possibly even in the Stekenjokk Quartz-Keratophyre were related to the rifting stage. In such a model, evidence for subduction is restricted to some of the mafic rocks in the Stekenjokk Quartz-Keratophyre and is probably Tremadoc in age.

Conclusions

1. The U–Pb ages for the investigated zircon fractions are concordant or practically concordant, and the most precise age estimates are given by the $^{206}Pb/^{238}U$ ratios. The ages are 492 ± 1 Ma and 476 ± 1 Ma for two metamorphosed trondhjemites from Stekenjokk and Björkvattnet in the Stekenjokk Quartz-Keratophyre, and 440 ± 2 Ma for a metamorphosed trondhjemite from Viken in the Blåsjö Phyllite. The age for the Stekenjokk sample and less confidently even the other two ages reflect the times of emplacement of these bodies.

2. The age for the Stekenjokk sample lies close to the age of the volcanic rocks in the Stekenjokk Quartz-Keratophyre. This is inferred to be probably Tremadoc. The stratigraphically younger Blåsjö Phyllite is, at least partly, Ashgill or older.

3. The age data confirm earlier suggestions that there exists a major tectonic break in the lower part of the Köli succession in northern Jämtland and southern Västerbotten, separating the Lower and Middle Köli Nappes.

4. The age data support earlier interpretations that the stratigraphy in the lower thrust unit of the Middle Köli (Stikke Nappe) is inverted.

5. The felsic igneous activity is considered to belong to a prolonged rifting stage which overlapped in time with and succeeded the waning stages of an island arc development. This arc was active probably during the Tremadoc.

Acknowledgements. – We thank Ebbe Zachrisson, SGU, Uppsala, and Krister Sundblad, University of Stockholm for help with sample collection and numerous lively discussions. David Gee, Allan Krill, Eric Welin and Ebbe Zachrisson read a preliminary version of the manuscript and all provided constructive remarks which improved the manuscript. The work by the first author was financed with grants 4901–107 and 4901–109 from the Swedish Natural Science Research Council.

Manuscript received May 1987

References

Bassett, M. G. 1985: Silurian stratigraphy and facies development in Scandinavia. *In* Gee, D. G. & Sturt, B. A. (eds.), *The Caledonide Orogen – Scandinavia and Related Areas.* John Wiley & Sons, 283–292.

Bruton, D. L. & Bockelie, J. F. 1980: Geology and palaeontology of the Hølunda area, western Norway – a fragment of North America? *In* Wones, D. R. (ed.), The Caledonides in the USA. *Virginia Polytechnic Institute and State University, Department of Geological Sciences Memoir 2*, 41–47.

Bruton, D. L. & Harper, D. A. T. 1985: Early Ordovician (Arenig–Llanvirn) faunas from oceanic islands in the Appalachian–Caledonide orogen. *In* Gee, D. G. & Sturt, B. A. (eds.), *The Caledonide Orogen – Scandinavia and Related Areas.* John Wiley & Sons, 359–368.

Bruton, D. L., Lindström, M. & Owen, A. W. 1985: The Ordovician of Scandinavia. *In* Gee, D. G. & Sturt, B. A. (eds.), *The Caledonide Orogen – Scandinavia and Related Areas.* John Wiley & Sons, 273–282.

Claesson, S., Klingspor, I. & Stephens, M. B. 1983: U–Pb and Rb–Sr isotopic data on an Ordovician volcanic-subvolcanic complex from the Tjopasi Group, Köli Nappes, Swedish Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar 105*, 9–15.

Gee, D. G. 1975: A tectonic model for the central part of the Scandinavian Caledonides. *American Journal of Science 275-A*, 468–515.

Juve, G. 1977: Metal distribution at Stekenjokk: primary and metamorphic patterns. *Geologiska Föreningens i Stockholm Förhandlingar 99*, 149–158.

Krogh, T. E. 1973: A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotope age determinations. *Geochimica et Cosmochimica Acta 37*, 485–494.

Kulling, O. 1933: Bergbyggnaden inom Bjökvattnet-Virisenområdet i Västerbottenfjällens centrala del. *Geologiska Föreningens i Stockholm Förhandlingar 55*, 167–422.

Ludwig, K. R. 1980: Calculation of uncertainties of U–Pb isotope data. *Earth and Planetary Science Letters 46*, 212–220.

Roberts, D., Grenne, T. & Ryan, P. D. 1984: Ordovician marginal basin development in the central Norwegian Caledonides. *In* Kokelaar, B. P. & Howells, M. F. (eds.), Marginal basin geology: volcanic and associated sedimentary and tectonic processes in modern and ancient marginal basins. *Geologicial Society of London Special Publication 16*, 233–244.

Roberts, D., Sturt, B. A. & Furnes, H. 1985: Volcanite assemblages and environments in the Scandinavian Caledonides and the sequential development history of the mountain belt. *In* Gee, D. G. & Sturt, B. A. (eds.), *The Caledonide Orogen – Scandinavia and Related Areas.* John Wiley & Sons, 919–930.

Sjöstrand, T. 1978: Caledonian geology of the Kvarnbergsvattnet area, northern Jämtland, central Sweden. *Sveriges geologiska undersökning C 735*, 107 pp.

Snelling, N. J. 1985: An interim time-scale. *In* Snelling, N. J. (ed.), The chronology of the geological record. *Geological Society of London Memoir 10*, 261–265.

Steiger, R. H. & Jäger, E. 1977: Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters 36*, 356–362.

Stephens, M. B. 1977: Stratigraphy and relationship between folding, metamorphism and thrusting in the Tärna–Björkvattnet area, northern Swedish Caledonides. *Sveriges geologiska undersökning C 726*, 146 pp.

Stephens, M. B. 1980a: Spilitization, element release and formation of massive sulphides in the Stekenjokk volcanites, central Swedish Caledonides. *Norges geologiske undersøkelse 360*, 159–193.

Stephens, M. B. 1980b: Occurrence, nature and tectonic significance of volcanic and high-level intrusive rocks within the Swedish Caledonides. *In* Wones, D. R. (ed.), The Caledonides in the USA. *Virginia Polytechnic Institute and State University, Department of Geological Sciences Memoir 2*, 289–298.

Stephens, M. B. 1982: Field relationships, petrochemistry and petrogenesis of the Stekenjokk volcanites, central Swedish Caledonides. *Sveriges geologiska undersökning C 786*, 111 pp.

Stephens, M. B. & Gee, D. G. 1985: A tectonic model for the evolution of the eugeoclinal terranes in the central Scandinavian Caledonides. *In* Gee, D. G. & Sturt, B. A. (eds.), *The Caledonide Orogen – Scandinavia and Related Areas.* John Wiley & Sons, 953–978.

Stephens, M. B. & Gee, D. G., in press: Terranes and polyphase accretionary history in the Scandinavian Caledonides. Geological Society of America Special Paper.

Stephens, M. B., Furnes, H., Robins, B. & Sturt, B. A. 1985: Igneous activity in the Scandinavian Caledonides. *In* Gee, D. G. & Sturt, B. A. (eds), *The Caledonide Orogen – Scandinavia and Related Areas.* John Wiley & Sons, 623–656.

Sundblad, K. 1980: A tentative 'volcanogenic' formation model for the sediment-hosted Ankarvattnet Zn–Cu–Pb massive sulphide deposit, central Swedish Caledonides. *Norges geologiske undersøkelse 360*, 211–227.

Sundblad, K. & Stephens, M. B. 1983: Lead isotope systematics of strata-bound sulfide deposits in the higher nappe complexes of the Swedish Caledonides. *Economic Geology 78*, 1090–1107.

Sundblad, K. & Gee, D. G. 1984: Occurrence of a uraniferous-vanadiniferous graphitic phyllite in the Köli Nappes of the Stekenjokk area, central Swedish Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar 106*, 269–274.

Zachrisson, E. 1964: The Remdalen syncline. *Sveriges geologiska undersökning C 596*, 53 pp.

Zachrisson, E. 1969: Caledonian geology of northern Jämtland – southern Västerbotten. *Sveriges geologiska undersökning C 644*, 33 pp.

Zachrisson, E. 1982: Spilitization, mineralization and vertical metal zonation at the Stekenjokk strata-bound sulphide deposit, central Scandinavian Caledonides. *Transactions of the Institution of Mining and Metallurgy (Section B: Applied earth science) 91*, B192–B199.

Zachrisson, E. 1984: Lateral metal zonation and stringer zone development, reflecting fissure-controlled exhalations at the Stekenjokk-Levi stratabound sulfide deposit, central Scandinavian Caledonides. *Economic Geology 79*, 1643–1659.