A possible basement to the Mesoproterozoic quartzites on Hardangervidda, South-central Norway: zircon U–Pb geochronology of a migmatitic gneiss

ELLEN M. O. SIGMOND, ANNE BIRKELAND & BERNARD BINGEN

Sigmond, E. M. O., Birkeland, A. & Bingen, B. 2000: A possible basement to the Mesoproterozoic quartzites on Hardangervidda, South-central Norway: zircon U–Pb geochronology of a migmatitic gneiss. *Norges geologiske undersøkelse Bulletin 437*, 25-32.

On Hardangervidda, west of the Mandal-Ustaoset fault zone in South Norway, some 80-90 % of the crust consists of orthogneisses and foliated and massive granites. In this plutonic environment the Mesoproterozoic quartzites of the Hettefjorden Group are found as rafts all over Hardangervidda. At Viuvatnet, a migmatitic gneiss is interlayered with and possibly underlies the quartzites. This migmatitic gneiss has no intrusive contact with the quartzites and could possibly represent their basement. Backscattered electron images and U-Pb ion probe data were acquired on zircon from this gneiss. The main population of zircons gives a weighted average age of 1468 ± 12 Ma. This is interpreted to probably reflect a migmatisation event (evidence for which is observed in the field and in the sample) and points to a high-grade metamorphism occurring after deposition of the Hettefjorden Group. A minor zircon population is represented by a zoned zircon at 1667 ± 22 Ma. This date could correspond to the age of crystallisation of the magmatic protolith of the gneiss; and it is similar to the age of a foliated granite in the region, the Mårsbrotet granite. A featureless zircon overgrowth at 1167 ± 104 Ma is believed to provide evidence for Sveconorwegian metamorphic overprinting in the region. Alternative interpretations of the data set are possible; and more geochronological data are necessary in order to understand the regional significance of the 1.67 and 1.47 Ga events.

Ellen M. O. Sigmond, Anne Birkeland & Bernard Bingen, Geological Survey of Norway, 7491 Trondheim, Norway.

Introduction

The Hardangervidda plateau, South Norway, is situated in the Sveconorwegian orogen, to the west of the Mandal-Ustaoset fault zone (Fig. 1; Sigmond 1985). Most of the rocks in the region are of plutonic origin and of granitic composition. Different generations of intrusions range from strongly foliated orthogneisses to massive plutonic rocks. Within these dominantly plutonic rocks, there are rafts of amphibolite-facies gneisses and migmatites of uncertain origin and a few rocks of certain supracrustal origin.

Among the metasupracrustal rocks, the quartzites of the Hettefjorden Group are of special interest because they occur throughout the Hardangervidda region (Fig. 2), and also because they unambiguously represent epicontinental sediments once deposited on a (crystalline?) basement. To find and define this basement is of great importance for our understanding of the geological history of the Hardangervidda area. This has turned out to be particularly difficult, because in most places a close examination has shown that the quartzites were intruded by the surrounding orthogneisses and foliated granites. However, near Viuvatnet, a migmatitic gneiss interlayered with, and possibly underlying the quartzites, shows non-intrusive relationships to the quartzites, and thus could represent the basement to these sedimentary rocks. In this paper new U-Pb ion probe data are reported from zircons extracted from this migmatitic gneiss.

Pre-Sveconorwegian regional geochronology of Hardangervidda

The Precambrian crust west of the Mandal–Ustaoset fault zone displays mainly high-grade orthogneisses and foliated granites of different ages with larger and smaller inclusions of migmatites, gneisses and metamorphic supracrustal rocks. All rocks are intruded by massive Sveconorwegian granite plutons forming a N-S trending belt extending from Mandal to the central part of Hardangervidda (Falkum 1982, Sigmond et al. 1984, Sigmond 1985) (Figs. 1 and 2).

In the area under consideration in this paper (Figs. 2 and 3), west of the Mandal-Ustaoset fault zone and east of the granite belt, regional mapping clearly reveals that the rocks have gone through a long and complicated history of melting and remelting, and different stages of deformation and metamorphism, prior to the intrusion of the Sveconorwegian massive granite plutons (Sigmond 1998). The orthogneisses, the migmatites and the deformation resulting in the dominant E-W folding and foliation (Sigmond 1988 and Fig. 3) are thus pre-Sveconorwegian in age (pre-1100 Ma). These observations have been confirmed by a few absolute age determinations of orthogneisses which yielded intrusive ages in the range 1.65–1.50 Ga. These data have further shown that an Archaean to Palaeoproterozoic crustal component has been recycled in the crust west of the Mandal–Ustaoset fault zone; yet the data have still failed to prove the existence of exposures of magmatic rocks crystallised before ca. 1.7 Ga (Ragn-

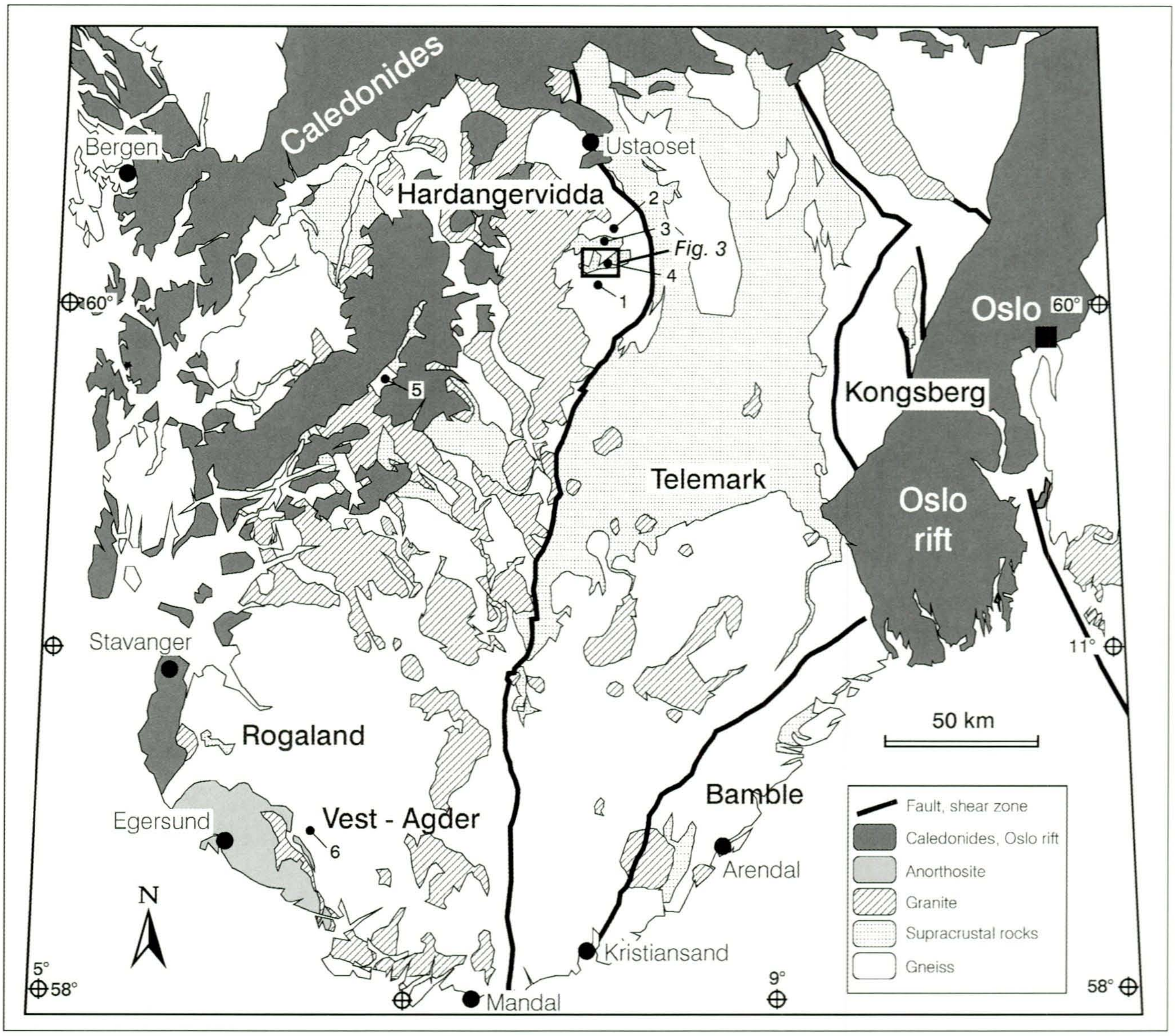

Fig. 1. Geological sketch map of South Norway simplified from Sigmond et al. (1984). Numbers refer to localities quoted in the text.

hildstveit et al. 1994, Birkeland et al. 1997).

One of the light-coloured foliated granites, the *Mårsbrotet granite* (location 1 in Fig. 1), gave a U–Pb upper intercept zircon age of 1649 +33/-19 Ma (Ragnhildstveit et al. 1994). This granite displays cross-cutting relationships relative to the surrounding orthogneisses, these gneisses should thus be older than 1.65 Ga. The *Skrykkjevieren orthogneiss* (location 2 in Fig. 1) is nowhere in direct contact with the Mårsbrotet foliated granite, and igneous looking zircons from this orthogneiss showed a bimodal age distribution with frequency maxima at 1591 ± 7 and 1500 ± 7 Ma (Birkeland et al. 1997). The first date is probably recording the age of intrusion of the protolith, whereas the second is thought to be related to a remelting with the formation of felsic veins. A minor 2.84 – 2.73 Ga zircon population in this gneiss may possibly be providing evidence for inherited Archaean material in the source region of the magma or of contamination by Archaean material during intrusion.

High-grade supracrustals are divisible into the *Festningsnutan* and *Hettefjorden Groups* (Sigmond 1998). The Festningsnutan Group consists of light coloured fine- to medium-grained gneisses, interpreted as metamorphic supracrustal rocks. It includes some highly deformed gneissic conglomerate layers. The Hettefjorden Group consists of medium- to coarse-grained grey quartzite with some layers of mica gneiss. The quartzite covers a large area around Hettefjorden, but occurs elsewhere on Hardangervidda only as smaller rafts less than 1 km^2 in surface area (Fig. 2).

The Festningsnutan and Hettefjorden Groups are closely associated in the field and have experienced the same phases of folding and metamorphism. The relative timing of deposition of the two groups is difficult to establish in the field, but they are most probably more or less coeval. Detrital zircons were separated and analysed from a sample of metaconglomerate taken from the Festningsnutan Group (location 3 in Fig. 1; Bingen et al. submitted manuscript). Twelve Proterozoic grains range from 1.99 to 1.57 Ga and three grains give ages in the range 2.76–2.24 Ga. These data imply that the deposition of the sediment is not older than 1572 ± 10 Ma. Detrital zircons were also analysed from a sample of quartzite of the Hettefjorden Group (location 4 in Fig. 1; Bingen et al. submitted manuscript). Nine of the 32 analysed zircons are Archaean and range from 3.25 to 2.77 Ga. Proterozoic zircons range from 2.42 to 1.52 Ga with a frequency maximum at 1.90-1.85 Ga. The age of deposition of this quartzite is not well constrained as the data on the youngest analysed zircon scatter between 1539 ± 21 Ma and 1480 ± 17 Ma. A conservative estimate of the age of this zircon is given by the most concordant analyses at 1536 ± 24 Ma, indicating that the deposition of the sediment is not older than 1536 ± 24 Ma.

In the Røldal region, to the southwest of the Hardangervidda plateau, various gneisses, mainly augen gneisses, have given a Rb-Sr whole rock errorchron age of 1488 ± 30 Ma, (location 5 in Fig. 1; Berg 1977). This age was interpreted as probably reflecting the age of crystallisation of the granite protolith (Berg 1977).

U-Pb ion probe dating

The sample

Sample S.95-157 was collected east of Viuvatnet on Hardangervidda (Fig. 3) in a ca. 200 m-thick unit of stromatic migmatitic gneiss (Fig 4) structurally interlayered with, and possibly underlying the quartzite of the Hettefjorden Group. These units are affected by a common deformation and metamorphism, and the original field relationships are not preserved. As cross-cutting or intrusive relationships with the overlying quartzite have not been observed, the migmatitic gneiss could therefore represent part of an original basement to the quartzites.

The sample is a medium- to coarse-grained *migmatitic* banded gneiss with 1 to 5 cm-thick, alternating, dark-

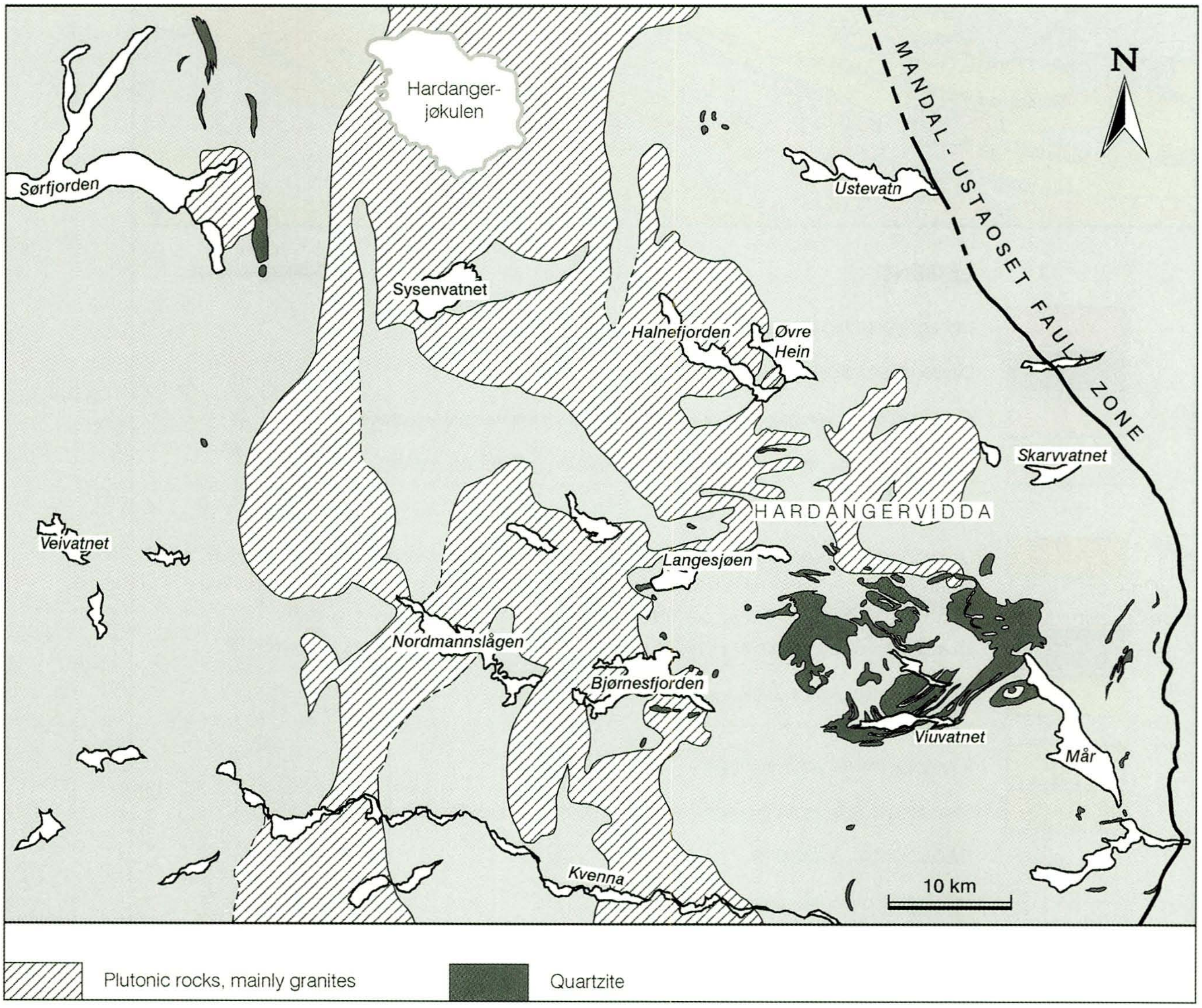

Fig. 2. Occurrences of quartzite on Hardangervidda. The allochthonous Precambrian rocks in Caledonian nappes and the autochthonous and allochthonous Cambro-Silurian rocks are not shown.

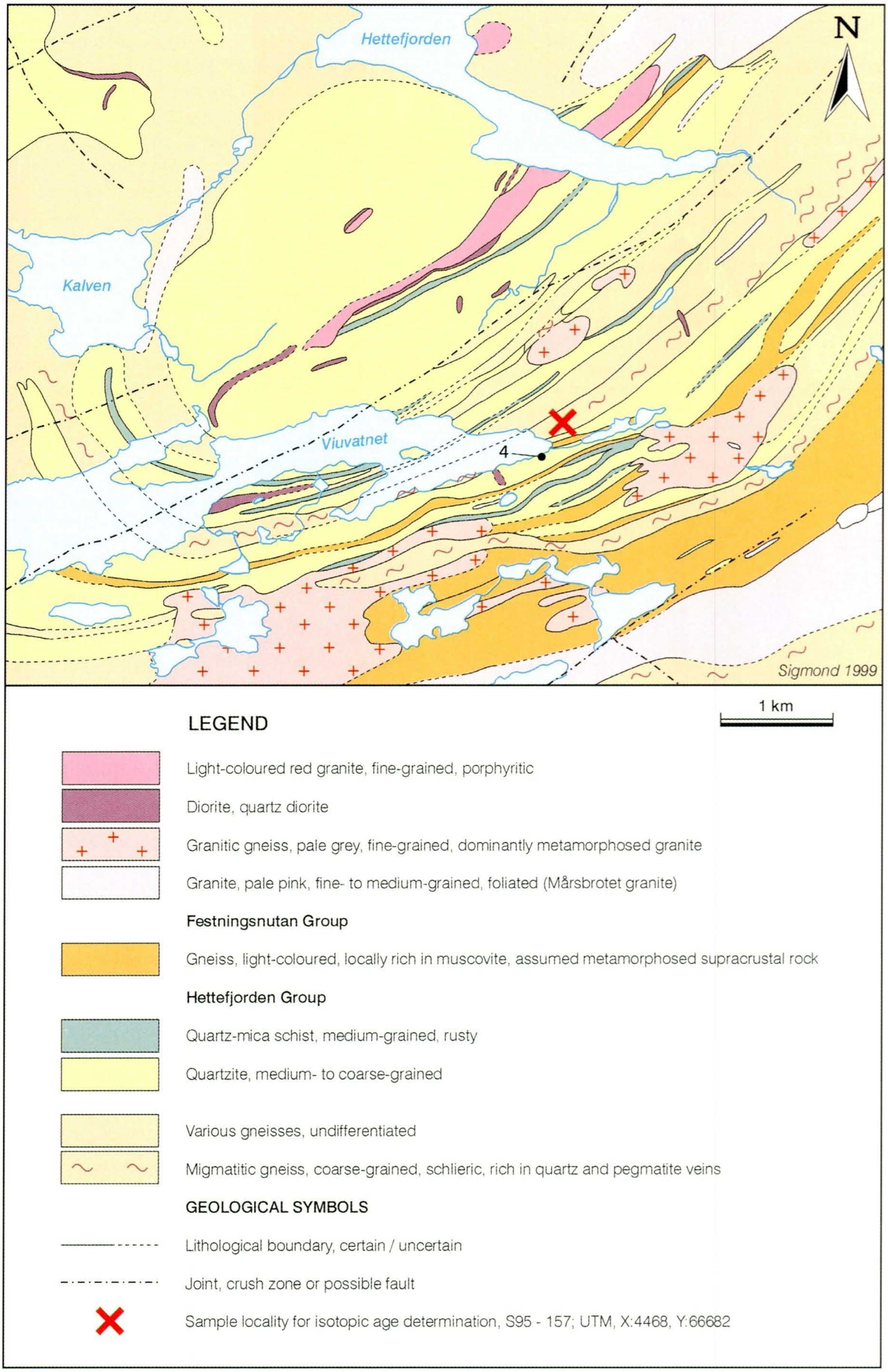

Fig. 3. Geological map from the Viuvatnet area, Hardangervidda, showing the sampling site.

Fig. 4. Stromatic, migmatitic gneiss east of Viuvatnet. A granodioritic paleosome alternates with granitic neosome. The neosome pods and bands generally have concordant, but also in places transecting contacts (Photo, J. Ragnhildstveit).

coloured and light-coloured layers. The dark-coloured granodioritic paleosome contains saussuritised plagioclase, amphibole, greenish-brown biotite, some quartz and microcline, with accessory epidote, allanite, titanite, apatite and zircon. In some darker layers amphibole is prominent. The granitic neosome forms bands, veins, schlieren and pods, which generally are concordant with the foliation but may also transect it (Fig. 4). This indicates a syn- to posttectonic partial melting of the protolith. The neosome consists mainly of microcline, quartz, plagioclase, greenish-brown biotite and opaque minerals (magnetite) with accessory epidote, allanite, chlorite, apatite and zircon. Plagioclase grains commonly contain quartz inclusions and show a myrmekitic texture. Perthite and antiperthite textures are common in the feldspar. It is worth noting that myrmekite, perthite and antiperthite are not observed in the feldspars in the paleosome; these structures are probably a result of the partial melting process.

Method

Zircon was purified from the whole rock sample using a Wilfley water table, heavy liquids and a magnetic separator. About 60 crystals were mounted in epoxy and polished to approximately half thickness. Backscattered electron images of these grains were taken, to characterise the internal structure and guide spot analysis (Fig. 5). Nineteen grains were analysed for Th, U and Pb by SIMS using a Cameca IMS 1270 instrument at the Nordsim laboratory, Swedish Museum of Natural History, Stockholm. Analyses were carried out following the method outlined in Whitehouse et al. (1997, 1999). They were performed with a ca. 4 nA O_2^- beam and a spot size of ca. 40 µm, using the Geostandard 91500 reference zircon with an age of 1065 Ma (Wiedenbeck et al. 1995). A common Pb correction was applied with modern isotopic composition (Stacey & Kramers 1975) on the basis of the ^{204}Pb signal. The analyses are listed in Table 1. They were plotted in a Tera-Wasserburg concordia diagram (Fig. 6), and the weighted average age was calculated at the 95 % confidence level using the ISOPLOT program (Ludwig 1995).

Results

Zircons were abundant in the sample and the extracted zircons represent both paleo- and neosome. Zircons in the sample are long and short prisms with rounded tips. Almost round grains are also present. Twenty analyses were performed in 18 grains. The analyses are concordant to slightly reversly discordant except for a few notably discordant points. The ^{207}Pb/^{206}Pb age of 16 analyses range from 1484 ± 24 to 1399 ± 44 Ma (Fig. 6) with a weighted average value of 1459 ± 13 Ma (MSWD = 2.8). If the concordant analyses in crack-free zircon are selected, a better average of 1468 ± 12 Ma (n = 11; MSWD = 1.8) is obtained. These analyses have a well-grouped Th/U ratio of 0.43 ± 0.07, typical for zircon crystallised in a magmatic environment (Fig. 6). The main zircon po-

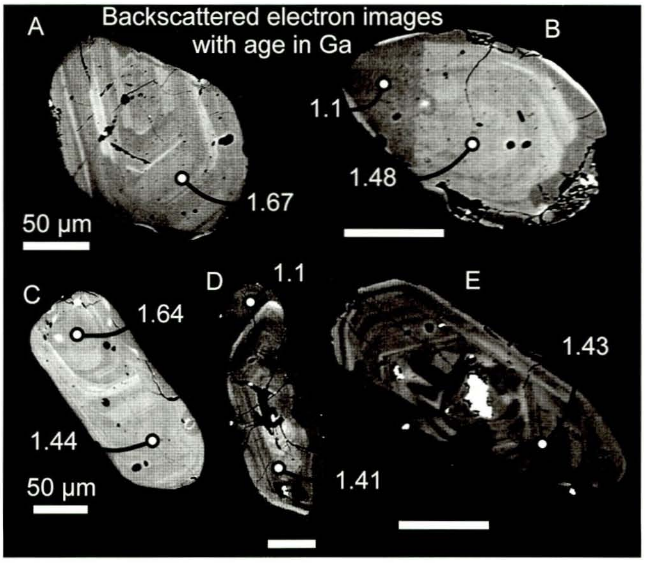

Fig. 5. Backscattered electron images of zircons from the migmatitic gneiss east of Viuvatnet. The locations of the centre of the SIMS analytical spots are indicated.

(A) The crystal has a somewhat diffuse prismatic zonation. At the upper end of the crystal the zonation is clearly truncated, indicating a break in the original crystal. There is also a transgressive overgrowth into the core at the upper end of the crystal, indicating a late new growth or recrystallisation during a high-grade event.

(B) The crystal has a prismatic zoning pattern. The zonation is truncated at the pointed tip and overgrown by a featureless new zircon. At the opposite end there is a transgressive overgrowth of the same generation of new zircon.

(C) The crystal has a small, unzoned rounded core. The zircon overgrowth has a regular, oscillating, zoning pattern consistent with a prismatic, euhedral grain which determines the outer shape of the crystal. The crystal is broken, and there is some transgressive, featureless zircon along the upper long edge.

(D) The crystal has a core with a diffuse prismatic zoning pattern. Along the side to the right, a new featureless zircon transgresses into the core and transects the zonation. The new generation of zircon forms tips at both ends of the crystal.

(E) The core of the crystal has an irregular zoning which is not controlled by the crystallographic structure. The rim has a prismatic zoning indicating an original euhedral, prismatic external shape.

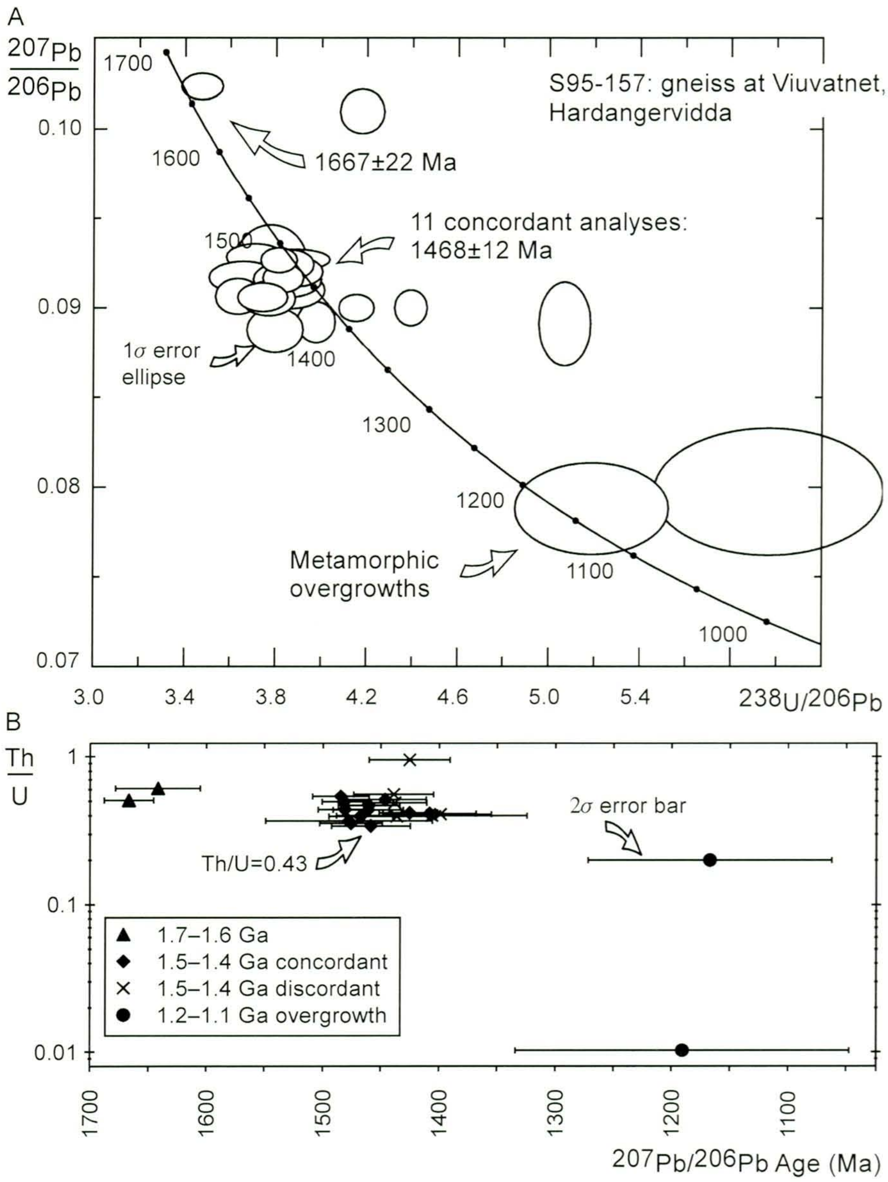

Fig. 6. (A) Tera–Wasserburg concordia diagram with SIMS zircon analyses of sample S95-157. (B) Th/U ratio of the different types of analyses as a function of age.

pulation thus probably has grown in a melt, either in a magma chamber, or in the partial melt (the granitic neosome).

One grain, which cannot be distinguished on the basis of morphology and zoning, gives an age of 1667 ± 22 Ma (Fig. 5A), and the unzoned core of another grain (Fig. 5C) provides a discordant age of 1642 ± 36 Ma. Overgrowths of presumably metamorphic origin are commonly observed at the tips of the grains (Figs. 5B and 5D). They are generally too narrow to permit good analyses with the 40 μm beam. Two overgrowth analyses show low U contents (12 and 52 ppm) and low Th/U ratios (Fig. 6). One of them is concordant at 1167 ± 104 Ma, but this partially covers the overgrowth–core interface.

Backscattered electron images of zircons reveal the distribution of trace elements, mainly Hf, in the crystal lattice. The *main population of zircons* (1468 ± 12 Ma) shows an internal pattern which is not the narrow, regular, oscillatory zonation typical of ideal magmatic crystals. The zonation is more diffuse and shows fading and broadening of the primary pattern (Figs. 5B to 5E), or may be quite irregular as, for example, the core of the zircon in Fig. 5F. According to Pidgeon et al. (1998), such structures may be due to migration of trace elements in a closed system during slow cooling at high temperatures. The crystals may be broken or somewhat resorbed (Figs. 5B and 5D).

One of the *older crystals* (1667 ± 22 Ma) has a somewhat diffuse zonation, which is clearly transected by a younger generation of zircon. This indicates that the crystal has been broken at a later stage (Fig. 5A). Another crystal (Fig. 5C) has a featureless round core (1642 ± 36 Ma) surrounded by an irregularly zoned rim (1436 ± 34 Ma). Such round cores are found in anatectic and partially melted rocks. The core surface may be the paleo-dissolution surface of the original crystal (Vavra 1990).

The *younger zircon ages* (1191 ± 144 and 1167 ± 104 Ma) have been measured only in featureless and locally transgressive rims surrounding the older zircons (Figs. 5B and 5D). This pattern, together with the low Th/U ratio (Fig. 4), indicates that the overgrowths are of metamorphic origin.

Discussion

As noted earlier, the migmatitic gneiss east of Viuvatnet, from which sample S.95-157 was collected, is interlayered with quartzites of the Hettefjorden Group. The new geochronological data on this sample, clustering at 1468 ± 12 Ma (Fig. 6), and on quartzites of the Hettefjorden Group giving a deposition age younger than 1536 ± 24 Ma (Bingen et al. submitted manuscript), are inconclusive and can be interpreted in different ways. Three interpretations (a, b, c) are discussed hereafter, and all are open to revision when more regional data become available in the future.

a) In this interpretation the main zircon population of 1468 ± 12 Ma is related to the conspicuous migmatisation event recorded in the migmatitic gneiss. The zircon date of 1667 ± 22 Ma is attributed to the age of magmatic crystallisation of the protolith. It is well established that a migmatisation event can be associated with zircon crystallisation, the zircons then commonly display a prismatic habit (Vavra et al. 1999). The zircons of the migmatitic-gneiss of this age are prismatic. The distribution of trace-elements is primarily determined by crystal growth and diffusion. Solid-state diffusion at high temperatures in closed systems may have resulted in the shady and even convulted zoning pattern of some crystals (Fig. 5 E). This interpretation would imply that the region was affected by high-grade metamorphism at ca. 1.47 Ga, and that the migmatitic gneiss and the quartzites of the Hettefjorden Group were deformed and metamorphosed together during this event. The idea of a ca. 1.45 Ga regional metamorphic event in the Rogaland-Hardangervidda area was originally proposed by Versteeve (1975) on the basis of a 1453 ± 60 Ma Rb-Sr errorchron in migmatitic gneisses in Rogaland (location 6 in Fig. 1), and is compatible with the structural and geochronological constraints on Hardangervidda. The close correspondence between the age of 1667 ± 22 Ma and the 1649 +33/-19 Ma age for the Mårsbrotet granite is noteworthy. It indicates that these two rock types may belong to the same magmatic event. This first interpretation is in accordance with field observations. However, it is somewhat speculative because of the low abundance of zircon giving the protolith age (one concordant grain at 1667 ± 22 Ma and one discordant core at 1642 ± 36 Ma). In a migmatite, the proportion of newly grown zircon relative to inherited zircon varies from a minority (Oliver et al. 1999; Watt et al. 2000) to a majority (Andersson et al. submitted manuscript, Vavra et al. 1999). The low abundance of zircon at 1.67 Ga in the Viuvatnet-gneiss could be explained by the melting of the zircons in the protolith during migmatisation, or by a an original small grain size. In the last case the magmatic protolith was likely to have been a volcanic or subvolcanic rock. This interpretation (a) leads to the conclusion that the migmatitic gneiss represents a 1.66 Ga year old basement to the quartzite, and that the two rocks have later experienced a common metamorphism at around 1.47 Ga.

b) The second possibility is that the migmatitic gneiss is a supracrustal rock originally interlayered with the quartzite, and thus could be included in the Festningsnutan Group. In the field, the originally supracrustal rocks of the Festningsnutan Group and the migmatitic gneiss occur near to each other (Fig. 3), but they are quite different in appearance. In the supracrustrals the original character can be seen in some places (folded pebbles, small phenocrysts, possible layering, etc). The rocks are fine to medium grained and never show a migmatitic character. The migmatitic gneiss is medium to coarse grained and its original character cannot be discerned, either in the

Table1. Ion-probe analyses of zircon in sample S95-157

Grain /spot	W[a] (µm)	W/L[b]	Zoning[c]	U (ppm)	Pb (ppm)	Th (ppm)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	±σ (%)	$^{206}Pb/^{238}U$	±σ (%)	Disc[d] (%)	$^{207}Pb/^{206}Pb$[e] (Ma)	±σ	$^{206}Pb/^{238}U$[e] (Ma)	±σ
01a	130	0,70	opz	200	72	102	8200	0,1023	0,6	0,2878	2,2		1667	11	1630	31
43b	85	0,40	nz	204	63	125	11010	0,1010	1,0	0,2393	1,9	14	1642	18	1383	24
03a	90	0,65	opz	259	81	92	11010	0,0924	0,7	0,2584	2,0		1476	14	1482	27
04a	110	0,60	pz	373	121	354	930	0,0900	0,9	0,2277	1,3	6	1425	17	1322	16
05a	95	0,45	opz	161	52	75	21590	0,0917	0,7	0,2610	1,9		1460	13	1495	25
11a	80	0,40	opz	163	51	55	4010	0,0916	0,9	0,2598	3,2		1459	17	1489	42
20a	90	0,50	opz	401	129	199	36820	0,0927	0,5	0,2575	3,2		1481	10	1477	42
29a	125	0,65	opz	98	31	40	6610	0,0888	1,1	0,2634	2,6	-3	1399	22	1507	36
32a	110	0,40	opz	236	80	127	19130	0,0928	0,6	0,2696	2,8		1484	12	1539	38
33a	126	0,50	pz	174	54	69	7060	0,0920	0,7	0,2570	2,4		1467	14	1474	31
34a	75	0,40	opz	223	66	93	18560	0,0900	0,7	0,2408	1,5		1425	13	1391	19
35a	105	0,45	opz	222	74	97	15480	0,0917	0,8	0,2735	3,4		1461	15	1558	46
36b	90	0,55	opz	208	65	86	1600	0,0892	1,0	0,2515	1,7		1408	20	1446	22
37a	100	0,50	opz	214	69	94	13690	0,0927	0,6	0,2623	1,7		1481	12	1502	23
38a	120	0,55	opz	46	15	17	3730	0,0925	1,9	0,2647	3,4		1477	36	1514	46
40a	100	0,45	opz	159	55	88	9710	0,0906	0,9	0,2752	2,2	-5	1439	17	1567	31
40b			opz	205	68	100	12670	0,0906	0,7	0,2673	2,4	-2	1438	14	1527	32
43a	85	0,40	opz	132	42	52	11340	0,0905	0,9	0,2655	2,6	-1	1436	17	1518	35
44a	85	0,30	opz	472	117	189	1060	0,0891	2,1	0,1973	1,8	16	1406	41	1161	19
45a	105	0,45	opz	222	72	114	4740	0,0910	0,9	0,2587	3,1		1446	18	1483	41
31a	80	0,35	m	52	12	10	1770	0,0788	2,6	0,1927	5,3		1167	52	1136	55
33b	126	0,50	m	12	2	0	6220	0,0797	3,6	0,1676	6,9	6	1191	72	999	64

a) Width of the grain. b) Width / length ratio. c) Zoning pattern: opz: oscillatory prismatic zoning, pz: prismatic zoning, nz: no visible zoning, m: overgrowth. d) Degree of discordance in %, calculated at the closest 2s limit. Blanks indicate concordance within 2σ error. e) Age field or in the microscope. Further, the main zircon population at 1.47 Ga in the migmatitic gneiss does not correspond to any of the zircon ages found in the two lithostratigraphic groups, something that should be expected if the migmatitic gneiss was part of the sequence. This interpretation is therefore considered to be less likely than the first.

(c) A third, alternative interpretation is to attribute the main magmatic zircon population in the migmatitic gneiss to the intrusion of a granodioritic sill into the quartzites at 1468 ± 12 Ma. The zircon grain dated to 1667 ± 22 Ma could reflect either inheritance from the source or contamination during intrusion. In this case the strong metamorphism and syn-to posttectonic migmatisation observed in the rocks is not reflected in the zircon ages. The metamorphism should then be younger than 1.47 Ga (but pre-Sveconorwegian), but no such ages have been reported from any rocks from this part of Hardangervidda. This interpretation therefore seems less likely.

Whatever the interpretation, the age of 1167 ± 104 Ma on a metamorphic overgrowth is considered to provide evidence for a later Sveconorwegian metamorphism in the Hardangervidda region. This age is imprecise and thus does not represent a quantitative estimate for the timing of metamorphism.

Conclusions

On Hardangervidda, the quartzites of the Hettefjorden Group occur generally as rafts in orthogneisses and plutonic rocks. However, a migmatitic gneiss east of Viuvatnet could be part of the basement to the quartzites. The oldest zircon in this gneiss are 1667 ± 22 Ma while the main population of zircons gives an average age of 1468 ± 12 Ma. The first age probably reflects the magmatic crystallisation of the protolith, while the second age most likely relates to the migmatisation event, and points to a high-grade metamorphism at about 1.47 Ga. Unzoned zircon overgrowths formed at 1167 ± 104 Ma point to a Sveconorwegian overprinting in the region.

From this interpretation it follows that the migmatitic gneiss is part of the crystalline basement to the quartzites, and that both rocks have been metamorphosed and deformed together after the deposition of the quartzites.

The present data allow for alternative interpretations of the migmatitic gneiss - quartzite relationship. More data are evidently necessary before we can reach a clearer understanding of the Proterozoic geological evolution in the region.

Acknowledgements

SIMS data were acquired at the NORDSIM laboratory, co-funded by the Norwegian Research Council. T. Sunde, J. Vestin and M. Whitehouse are thanked for supervision during data acquisition and data reduction. Thanks are due to the NGU laboratory for XRF data, mineral separation and technical assistance. We acknowledge P. Padget and D. Roberts for reading the manuscript, and G. -J. de Haas and T. Torske for providing constructive and helpful reviews. This is NORDSIM contribution 41.

References

Berg, Ø. 1977: En geokronologisk analyse av prekambrisk basement i distriktet Røldal-Haukelisæter-Valldalen ved Rb-Sr whole-rock metoden, dets plass i den sørvestnorske Prekambriske Provinsen, og en vurdering av denne provinsen i lys av det generelle geokronologiske mønster i det Nord-Atlantiske Prekambriske området Candid thesis, University of Oslo, 125 pp.

Birkeland, A., Sigmond, E. M. O., Whitehouse, M. J. & Vestin, J. 1997: From Archaean to Proterozoic on Hardangervidda, South Norway. (Extended abstracts) *Norges geologiske undersøkelse Bulletin 433*, 4–5.

Falkum, T. 1982: Geologisk kart over Norge, Berggrunnskart Mandal - 1:250.000. *Norges geologiske undersøkelse.*

Ludwig, K. R. 1995: Isoplot, version 2.82: a plotting and regression program for radiogenic-isotope data. *U.S. Geological Survey, Open-file report 91-445*, 45 pp.

Oliver, N. H. S., Bodorkos, S., Nemchin, A. A., Kinny, P. D. & Watt, G. R. 1999: Relationships between zircon U–Pb SHRIMP ages and leucosome type in migmatites of the Hall Creek Orogen, Western Australia. *Journal of Petrology 40*, 1553–1575.

Pidgeon, R.T., 1991: Recrystallisation of oscillatory zoned zircon: some geochronological and petrological implications. *Contributions to Mineralogy and Petrology 110*, 463-472.

Ragnhildstveit, J., Sigmond, E. M. O. & Tucker, R. D. 1994: Early Proterozoic supracrustal rocks west of the Mandal-Ustaoset fault zone, Hardangervidda, South Norway. *Terra Nova Abstract Supplement 2*, 15–16.

Sigmond, E. M. O. 1985, The Mandal–Ustaoset line, a newly discovered major fault zone in south Norway. In Tobi, A. C. & Touret, J. L., (eds), The deep Proterozoic crust in the north Atlantic provinces. *NATO ASI Series C158*, Reidel, Dordrecht, 323–331.

Sigmond, E. M. O. 1998: Geologisk kart over Norge, berggrunnskart Odda, 1:250.000. *Norges geologiske undersøkelse.*

Sigmond, E. M. O., Gustavson, M. & Roberts, D. 1984: Berggrunnskart over Norge, 1:1 million. *Norges geologiske undersøkelse.*

Stacey, J. S. & Kramers, J. D. 1975: Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters 26*, 207–221.

Vavra, G. 1990: On the kinematics of zircon growth and its petrogenic significance: a cathodoluminiscence study. *Contributions to Mineralogy and Petrology 106*, 90-99.

Vavra, G., Schmid, R. & Gebauer, D. 1999: Internal morphology, habit and U-Th-Pb microanalysis of amphibolite-to-granulite facies zircons: geochronology of the Ivrea Zone (Southern Alps). *Contributions to Mineralogy and Petrology 134*, 380–404.

Versteeve, A. J. 1975: Isotope geochronology in the high-grade metamorphic Precambrian of Southwestern Norway. *Norges geologiske undersøkelse Bulletin 318*, 1–50.

Watt, G. R., Kinny, P. D. & Friderichsen, J. D. 2000: U–Pb geochronology of Neoproterozoic and Caledonian tectonothermal events in the East Greenland Caledonides. *Journal of the Geological Society, London 157*, 1031–1048.

Whitehouse, M. J., Claesson, S., Sunde, T. & Vestin, J. 1997: Ion microprobe U–Pb zircon geochronology and correlation of Archaean gneisses from the Lewisian complex of Gruinard Bay, northwestern Scotland. *Geochimica et Cosmochimica Acta 61*, 4429–4438.

Whitehouse, M. J., Kamber, B. S. & Moorbath, S. 1999: Age significance of U–Th–Pb zircon data from early Archaean rocks of west Greenland – a reassessment based on combined ion-microprobe and imaging studies. *Chemical Geology 160*, 201–224.

Wiedenbeck, M., Allé, P., Corfu, F., Griffin, W. L., Meier, M., Oberli, F., Von Quadt, A., Roddick, J. C. & Spiegel, W. 1995: Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. *Geostandards Newsletter 19*, 1–23.