Geochronological investigation of the Ingdal Granite Gneiss and discordant pegmatites from the Western Gneiss Region, Norway

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Tucker, R. D. & Krogh, T. E.: Geochronological investigation of the Ingdal Granite Gneiss and discordant pegmatites from the Western Gneiss Region, Norway. *Norsk Geologisk Tidsskrift*, Vol. 68, pp. 201–210. Oslo 1988. ISSN 0029-196X.

A seven-point (three zircon and four titanite) U–Pb discordia-line from the Ingdal granite gneiss defines upper- and lower-intercept ages of 1653 ± 2 Ma and 396 ± 5 Ma interpreted as the time of Ingdal granite emplacement, and the time of gneiss formation and partial Pb-loss from zircon and titanite during a regional metamorphic event, respectively. These isotopic data suggest that this part of the Western Gneiss Region was heated and cooled very quickly at both the upper- and lower-intercept ages, and that it did not experience significant Sveconorwegian (ca. 1250–900 Ma) or Finnmarkian (ca. 530–480 Ma) isotopic disturbance. A six-point Rb–Sr whole-rock errorchron (MSWD = 11) from the same body of the Ingdal granite gneiss defines a date of 1665 ± 49 Ma interpreted as a less precise age of granite emplacement. Rb–Sr mineral dates from three strongly discordant, non-foliated granite pegmatites fall in the age range of 415–379 Ma. A Rb–Sr biotite date of 372 ± 4 Ma from the Ingdal granite gneiss establishes a minimum age of isotopic disturbance in the region.

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Introduction and geologic setting

The Western Gneiss Region (WGR) of south-central Norway is the souternmost and largest basement culmination in the Scandinavian Caledonides. In its deep, southern portion, basement gneisses of the WGR consist largely of Proterozoic (ca. 1750–1450 Ma) para- and orthogneiss, migmatite gneiss, anorthosite and gabbro (Brueckner 1972, 1979; Lappin et al. 1979, Mearns 1984, Gorbatschev 1985) and, to a lesser extent, Sveconorwegian (ca. 1250–900 Ma) mangerite gneiss, granodiorite, augen gneiss and pegmatite (Brueckner et al. 1968; Brueckner 1972; Krill 1983; Mearns 1984); all these rocks have been strongly deformed and metamorphosed (some to eclogite-facies conditions; Griffin et al. 1985) during the Caledonian (ca. 450–380 Ma) orogeny. Near its northern end, however, granitoid gneisses of the WGR are intercalated and folded together with schistose and stratified rocks of the Caledonian nappe stratigraphy (Tucker 1986) and here, roughly north of a transect from Oppdal to Molde, mineral dates from Early Proterozoic basement gneisses show no evidence of Sveconorwegian isotopic disturbance (Pidgeon & Råheim 1972; Tucker et al. 1987) and Sveconorwegian rocks are as yet unreported (Kullerud et al. 1986). A major task confronting geologists working in the WGR, therefore, is to decipher the Precambrian history of a terrane whose younger, Caledonian history is regionally pervasive and, in places, very intense. This goal is best achieved by applying a variety of isotopic dating techniques, particularly the U–Pb method of zircon and titanite dating, to rocks whose geologic setting is well-established.

In the region west of Trondheim (Fig. 1), the WGR exhibits a progressive (north)east to (south)west increase in Caledonian metamorphic grade (Tucker 1985) and a contrast in deformational style: in the east, overturned and highly modified basement gneiss domes are present, whereas in the west, greatly attenuated sheath-like, map-scale folds are dominant. Bedrock units in the area consist of migmatite- and granite gneiss and, to a lesser extent, stratiform and schistose supracrustal rocks. Supracrustal rocks (both parautochthonous metasedimentary and allochthonous nappe units) have been mapped according to paleotectonic facies and, in general, the

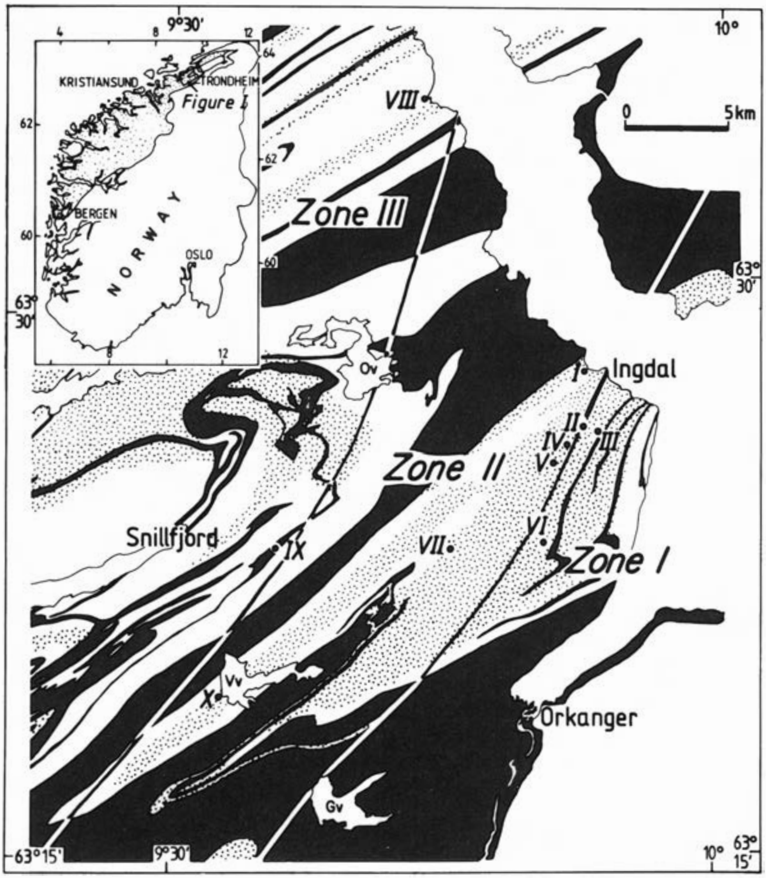

Fig. 1. Simplified geologic map of the northern portion of the Western Gneiss Region (stippled in inset map) showing the distribution of supracrustal rocks (black), migmatite tonalite gneiss (white), and microcline-rich granite gneiss (stipple); the stock of Ingdal granite gneiss in the Austvatn dome is represented as the mass of microcline-rich gneiss between Ingdal and Våvatn (Vv). Roman numerals indicate sample locations and heavy lines delineate the approximate boundaries of Caledonian metamorphic Zones I (garnet–staurolite), II (kyanite–garnet–staurolite), and III (kyanite–garnet). Abbreviated lake names are: Gv – Gagnåsvatnet, Ov – Øyangsvatnet, and Vv – Våvatnet.

lowest tectonostratigraphic units contain rocks representative of the pre-Caledonian continental margin, whereas highest units contain translated elements of island-arc and oceanic-crust terranes. All supracrustal rock units can be correlated with nearby members of the Caledonian nappe stratigraphy (Tucker 1986).

In contrast, parautochthonous(?) granitoid gneisses representing the former Baltoscandian shield are broadly subdivided into tonalite and granite migmatite gneiss (Åstfjord and Våvatn migmatite gneiss) and a distinctive suite of non-migmatitic, microcline-rich gneisses (Tucker 1985, 1986). One such microcline-rich gneiss, the Ingdal granite gneiss (Ramberg 1943), forms the bulk of the Austvatn dome (Fig. 1) and consists of three principal textural varieties thought to represent facies of a single intrusive stock (Tucker 1985). The purpose of this paper is to compare the U–Pb zircon age of the Ingdal granite gneiss with the Rb–Sr whole-rock age from the same gneiss, and to present evidence for Caledonian isotopic disturbance in this part of the WGR. In addition, Rb–Sr mineral dates from three, structurally discordant granite pegmatite dikes in the area are presented, and the constraints that these data place on models of both the Early Proterozoic and early Paleozoic history of the WGR are discussed.

Samples

Ramberg (1943, 1973) first described and mapped the body of microcline-rich granite gneiss that crops out in and around the village of Ingdal (Fig. 1) and on the north side of Trondheimsfjord at Raudbergsneset. Tucker (1985) later identified the Ingdal granite gneiss as the major gneiss type of the Austvatn dome and broadly grouped the gneiss into three facies-types based on easily rec-

Table 1. Major- and trace-element chemistry and CIPW norms of the Ingdal granite gneiss.

	I[1]	II[3]	III[2]	IV[3]	V[2]	VI[2]
SiO_2	74.69	68.30	72.15	76.93	70.21	73.91
TiO_2	0.27	0.43	0.30	0.10	0.50	0.19
Al_2O_3	13.37	14.80	14.11	12.10	14.25	13.48
FeO	0.68	1.97	1.41	0.53	1.81	0.97
MgO	0.28	0.97	0.53	0.02	0.57	0.16
MnO	0.08	0.07	0.06	0.06	0.10	0.06
CaO	0.67	2.25	1.14	0.44	1.46	0.76
K_2O	5.08	4.22	4.32	4.83	5.49	4.88
Na_2O	3.80	4.10	4.40	3.70	3.60	4.20
Fe_2O_3	0.57	1.36	0.74	0.83	0.86	0.48
H_2O^+	0.36	0.52	0.53	0.41	0.44	0.39
CO_2	0.15	0.10	0.07	0.07	0.12	0.09
P_2O_5	0.04	0.14	0.06	0.01	0.12	0.03
L.O.I.	0.08	0.08	0.05	0.01	0.08	0.05
	100.12	99.31	99.87	100.04	99.61	99.65
q	28.6	20.5	24.0	33.9	21.6	26.7
or	30.6	25.4	26.0	28.9	33.3	29.2
ab	34.8	37.5	40.2	33.7	33.2	38.2
an	3.1	9.6	5.4	2.2	6.7	3.6
di	—	0.6	—	—	—	—
hy	1.2	4.1	2.9	0.3	3.3	1.4
il	0.4	0.6	0.4	0.1	0.7	0.3
mt	0.6	1.4	0.7	0.9	0.9	0.5
co	0.6	—	0.3	—	—	—
ap	0.1	0.3	0.1	—	0.3	0.1
Nb	25	21	21	33	20	21
Zr	216	214	221	249	260	200
Y	50	43	46	96	48	40
Sr	71	225	130	20	192	47
Rb	254	176	159	315	208	152
Zn	30	63	49	97	67	42
V	9	43	20	n.d.	25	n.d.
Ba	682	762	531	42	994	271

1, 2, and 3 Facies types after Tucker (1985).
n.d. Not determined.

ognizable textural criteria and mineralogical modes. Major- and trace-element compositions and CIPW norms of these textural varieties are given in Table 1.

Six, 12 kg samples of the Ingdal granite gneiss were collected for Rb–Sr whole-rock analysis (Fig. 1). One sample was collected from the fine-grained, Type-1 facies, three samples from the medium- to coarse-grained Type-2 facies, and two samples from the porphyritic Type-3 facies (Table 2). In addition to these samples, 25 kg of sample III was collected for U–Pb zircon and titanite analyses, and additional 5 kg hand-specimens of samples II, VI, and VII were collected for U–Pb sphene analyses (Table 3).

A less extensive collection of strongly discordant, non-foliated, granite pegmatite was also made. Three, 20 kg samples of biotite–muscovite–garnet granite pegmatite were collected at Grønningen (VIII), Snilldalen (IX), and Våvatnet (X) (Fig. 1). At Grønningen and Våvatnet, the pegmatite dikes are discordant across a gneissosity in the Våvatn migmatite gneiss, and at Snilldalen the pegmatite is discordant across the contact of the lowermost supracrustal schist and the underlying Våvatn migmatite gneiss. Many more discordant pegmatite dikes are present in the area of Fig. 1, however, and they are commonly found in the (south)western (and structurally deeper) parts of metamorphic Zone II, and throughout Zone III. In all cases, the structurally discordant pegmatites are non-foliated, post-deformational igneous bodies and, in some cases, they are compositionally zoned with a quartz-rich central seam and a feldspar-rich margin. Moreover, they are mineralogically simple (consisting largely of microcline, oligoclase, and quartz), and commonly have xenolithic fragments closely matching their host-rock.

Analytical techniques

All samples for Rb–Sr analyses were crushed in a steel-jaw crusher and powdered in a steel-mill ring at Norges geologiske undersøkelse (Trondheim). Mineral separates of biotite from sample III of the Ingdal granite gneiss, and biotite, microcline, and plagioclase from samples VIII, IX, and X of the discordant pegmatites were obtained by conventional mineral-separation techniques. In all cases, final purity to >99% was achieved by hand-picking.

Rubidium and strontium concentrations were determined by isotope dilution using a mixed ^{87}Rb–^{84}Sr spike. Strontium ratios were measured on a thermal-ionization Micromass MS–30 mass spectrometer at the Mineralogisk-Geologisk Museum (Oslo) (Table 2) and normalized to a $^{86}Sr/^{88}Sr$ value of 0.1194 (Steiger & Jager 1977). Age calculations were made using a ^{87}Rb decay constant of $1.42 \times 10^{-11}y^{-1}$, and data were regressed by the method of York (1969) using uncorrelated errors. Measurement error of the $^{87}Sr/^{86}Sr$ value for each sample is given in Table 2 and errors for the $^{87}Rb/^{86}Sr$ ratio are taken to be 0.5%. All age and intercept errors are quoted at the 2-sigma confidence level.

Zircon and titanite were separated from pul-

Table 2. Rb–Sr analytical results, Sr evolutionary parameters, and model ages.

Sample description	Rb [ppm]	Sr [ppm]	$^{87}Rb/^{86}Sr$	$f^{e}_{Rb/Sr}$	$^{87}Sr/^{86}Sr_m$	$^{87}Sr^{a}/^{86}Sr_T$	$\varepsilon^{e}_{Sr}(T)$	$T^{Sr\,e}_{DM}$ Ga
Ingdal Granite Gneiss			5.163[b]	60.5[b]	0.82514 ± 10[b]	0.70200[b]	−7.12	1.653
I Whole-rock 1[c] (379/449)[d]	264.838	73.572	10.657	126	0.94600 ± 7	0.69312	−133	1.593
II Whole-rock 3[c] (349/444)[d]	169.035	221.905	2.213	25.3	0.75340 ± 8	0.70082	−23.9	1.615
III Whole-rock 2[c] (348/459)[d]	162.035	133.971	3.527	41.0	0.78875 ± 8	0.70498	+35.3	1.702
Biotite	815.817	19.127	132.633	1580	1.47239 ± 34	0.76993	+937	0.406
IV Whole-rock 3[c] (341/442)[d]	163.478	223.670	2.124	24.3	0.75269 ± 14	0.70225	−3.56	1.644
V Whole-rock 2[c] (332/432)[d]	206.061	187.960	3.194	37.1	0.78010 ± 7	0.70424	+24.8	1.691
VI Whole-rock 2[c] (292/432)[d]	144.217	51.361	8.279	97.6	0.90322 ± 18	0.70659	+58.2	1.687
Discordant Pegmatites								
VIII *Grønningsbukta* (506/383)[d]								
Whole-rock	96.190	255.755	1.091	12.0	0.73085 ± 6	0.72496	+298	1.819
Biotite	747.616	43.394	51.275	610	1.00083 ± 11	0.72413	+288	0.406
Microline	360.119	342.596	3.051	35.4	0.74190 ± 50	0.72543	+304	0.882
IX *Snilldalen* (289/296)[d]								
Whole-rock	47.813	280.564	0.494	4.89	0.72717 ± 8	0.72437	+289	3.789
Biotite	807.176	26.672	92.208	1100	1.25078 ± 72	0.72777	+338	0.416
Microline	344.235	365.615	2.732	31.6	0.73922 ± 13	0.72382	+280	0.917
Plagioclase	11.673	398.095	0.085	0.013	0.72415 ± 14	0.72367	+279	207
X *Våvatnet* (215/269)[d]								
Whole-rock	208.159	312.708	1.929	22.0	0.72601 ± 9	0.71461	+150	0.816
Microline	372.714	328.172	3.294	38.3	0.73360 ± 42	0.71413	+144	0.636
Plagioclase	34.928	324.563	0.312	2.72	0.71636 ± 10	0.71452	+149	3.570

[a] For Ingdal granite gneiss whole-rock values, T = 1653 Ma; for all other samples, T = quoted Rb–Sr age.
[b] Average of the six whole-rock values; $I^{Sr}_{DM}(T) = 0.7025$.
[c] Ingdal granite facies types as described in Tucker (1985).
[d] Universal Transverse Mercator (UTM) grid coordinates on 1:50,000 topographic map-sheets: 1521 I Orkanger, 1522 II Rissa, and 1521 IV Snillfjord.
[e] Calculated after DePaolo & Wasserburg (1976) and DePaolo (1981).

verized samples of Ingdal granite gneiss by conventional mineral separation techniques at the Royal Ontario Museum, Toronto. Clear, crack-free zircon was hand-picked for analysis, and all fractions were strongly abraded to reduce discordance and test for possible, inherited core-components (Krogh 1982, Table 3). Titanite was hand-picked from moderately magnetic factions with care taken to avoid selecting pale, inhomogeneous titanite and contaminant phases.

Zircon was dissolved in Teflon capsules and processed after the method of Krogh (1973) using a mixed ^{205}Pb-^{235}U spike (Krogh & Davis 1975). Titanite was dissolved in sealed Savilex Teflon beakers on a hotplate and uranium and lead were extracted in ion-exchange columns using a modification of the procedure described by Corfu & Stott (1986). Mass spectrometry was performed with VG–354 and Micromass MS–30 mass spectrometers in Toronto using the silica-gel–phosphoric acid loading technique (Cameron et al. 1969). Total lead and uranium blanks throughout the measurement period averaged between 5 and 20 and 2 and 10 pg, respectively. Further details of the analytical techniques and dating methods used in this study can be found in Krogh & Turek (1982) and Davis et al. (1982). Errors on the calculated ages (Davis 1982) are reported at the 2-sigma confidence level and isotopic ratios and decay constants conform to the recommended values of Steiger & Jager (1977). All U–Pb results are reported in Table 3.

Rb–Sr Results

Ingdal granite gneiss. Rb–Sr isotopic for six whole-rock samples from the Ingdal granite gneiss are presented in Table 2 and Fig. 2. The samples have a range in their measured $^{87}Rb/^{86}Sr$ of 8.5 and the slope of the best-fit line through these data corresponds to an age of 1665 ± 49 Ma. The scatter of data points about this line is unacceptably large (MSWD = 11), however, and the date must

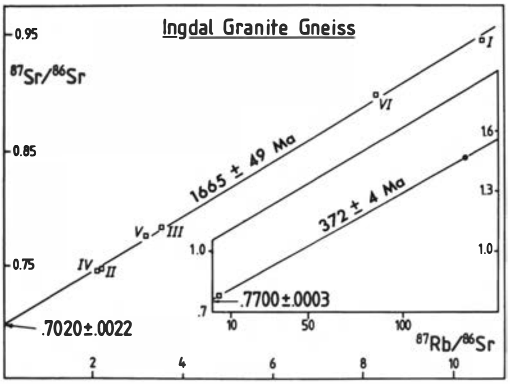

Fig. 2. Rb–Sr isochron plot of whole-rocks I–VI from the Ingdal granite gneiss (MSWD = 11). Inset to Fig. 2 shows the biotite–whole-rock regression line from sample III and its calculated age and initial $^{87}Sr/^{86}Sr$.

be considered as an imprecise determination at best. The initial $^{87}Sr/^{86}Sr$ obtained from the regression calculation is 0.7020 ± 0.0022, suggesting that the source for the granite had a low, 'mantle-like' initial strontium value.

The range in calculated $\varepsilon_{Sr}(T)$ and T_{DM} model-ages for individual whole-rocks is large (Table 2) and probably reflects the extent of post-crystallization disturbance experienced by these samples. Nonetheless, the 'Depleted Mantle' model-age (T_{DM}) for the six whole-rock samples (1.653 Ga, Table 2) agrees remarkably well with the U–Pb zircon upper-intercept age for the Ingdal granite gneiss (1.653 Ga, see sections below), and the calculated 'Depleted Mantle' initial strontium value (0.7025; Table 2) is close to the initial strontium value from the whole-rock regression line (0.7022, Fig. 2).

The Rb and Sr isotopic composition of a biotite separate from sample III is given in Table 2, and the calculated biotite age is 372 ± 4 Ma. Likewise, the Rb and Sr isotopic composition of whole-rock pegmatite samples VIII, IX, and X, and essential minerals from each pegmatite are given in Table 2 and shown in Fig. 3. All pegmatite samples fail to regress to a single whole-rock isochron, but mineral and whole-rock analyses from pegmatites VIII and X define internal, best-fit isochrons with low MSWD values; mineral and whole-rock analyses from pegmatite IX scatter about an 'errorchron' in excess of analytical error. Model dates and initial $^{87}Sr/^{86}Sr$ values for whole-rocks and minerals from pegmatites VIII, IX, and X are given in Fig. 3.

Discordant pegmatites. Minerals and the whole-rock from pegmatite VIII define a 3-point isochron corresponding to an age of 379 ± 4 Ma (MSWD = 1) and an initial $^{87}Sr/^{86}Sr$ of 0.7249 ± 0.0001. Minerals and the whole-rock from pegmatite (IX), however, scatter about a 4-point line (MSWD = 12) with a slope corresponding to an age of 398 ± 12 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7241 ± 0.0003. The isochron of pegmatite X is based on two minerals and whole-rock analyses, and the calculated age is 415 ± 7 Ma (MSWD = 1); its initial $^{87}Sr/^{86}Sr$ is 0.7145 ± 0.0001.

The initial $^{87}Sr/^{86}Sr$ from all pegmatite samples are high (>0.7144) and variable (Δ = 0.0104) suggesting that they have been derived from old

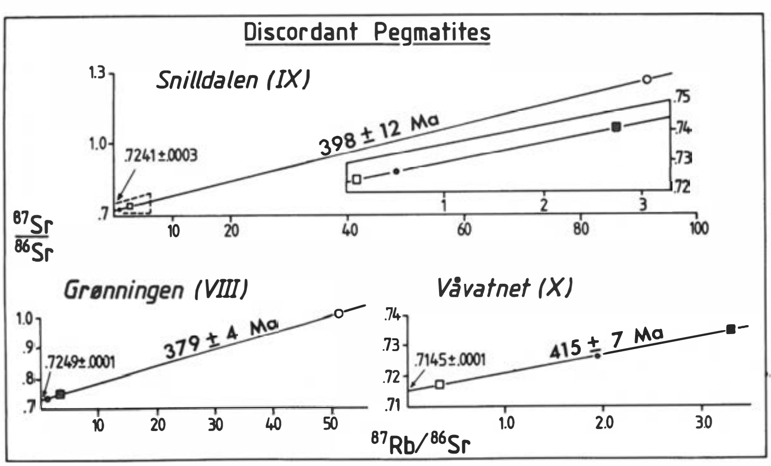

Fig. 3. Rb–Sr isochron plot of strongly discordant pegmatites from Grønningen (VIII), Snilldalen (IX), and Våvatnet (X). Symbols are as follows: whole-rock – filled circles; biotite – open circles: microcline – filled squares; plagioclase – open squares.

Table 3. U–Pb data, Ingdal Granite Gneiss.

Fractions		Concentrations		Atomic ratios					Age [Ma]	
No. Properties (1)	Wt. [mg]	U [ppm] (2)	Pb common [pg] (3)	$^{206}Pb/^{204}Pb$ (4)	$^{207}Pb/^{206}Pb$ (5)	$^{208}Pb/^{206}Pb$ (5)	$^{206}Pb/^{238}U$ (6)	$^{207}Pb/^{235}U$ (6)	$^{207}Pb/^{206}Pb$ (6)	% Discordance
Ingdal Granite Gneiss										
II Granite Gneiss [TO-A22B] (445/348) [7]										
1 Tit. 1.35M, −100 + 200, pb, A	0.815	90	1671	743	0.11899	0.973	0.2800	3.9012	1643	6
III Granite Gneiss [TK-84-52] (459/347) [7]										
2 Tit. 1.35M, −100 + 200, b, t, A	0.637	95	1823	520	0.12569	0.604	0.2582	3.5612	1624	15
3 Zircon ONM, −100 + 200, cl, s, A	0.254	113	67	4945	0.10107	0.141	0.2578	3.5478	1620	15
4 Zircon ONM, −200 + 325, cr, f, A	0.068	179	74	2229	0.10317	0.068	0.2404	3.2743	1601	23
5 Zircon ONM, −200 + 325, py, ov, A	0.093	241	24	10315	0.09763	0.119	0.2260	3.0433	1579	31
VI Granite Gneiss [TO-A26] (432/292) [7]										
6 Tit. 1.35M, −100 + 200, pb, A	2.053	70	8183	288	0.14425	0.559	0.2140	2.8600	1566	34
VII Granite Gneiss [TO-Z97] (378/280) [7]										
7 Tit. 1.35M, −100 + 200, pb, A	0.561	49	1408	116	0.18914	0.398	0.0868	0.8302	909	90

Notes:

(1) NM, M = non-magnetic, magnetic at indicated degree of tilt of Frantz isodynamic separator (at 1.6A and 0° slope); 1.35M = magnetic at 10° slope at 1.35A. 100, 200 = size in mesh; py = pale-yellow; cl = clear; ov = oval shaped, resorbed; t = turbid; b = brown; pb = pale brown; cr = cracked; f = faceted; s = subhedral; db = dark brown; A = abraded.

(2) Concentrations are known to ±0.5% for sample weights over 1 mg, ±1–2% for sample weights between 1.0 and 0.2 mg, and ±5% for sample weights of about 0.1 mg.

(3) Corrected for 0.177 mole fraction of common Pb in the ^{205}Pb spike.

(4) Measured ratio relative to total radiogenic Pb.

(5) Corrected for fractionation and blank; U blank = 3 pg; Pb blank = 25 pg; Pb and U fractionation correction = 0.1%/amu.

(6) Corrected for fractionation, spike, blank, and initial common Pb; error for zircon is estimated at 0.25% for Pb/U and 0.1% for $^{207}Pb/^{206}Pb$ at the 2-sigma level (errors are estimated from replicate analyses); error for titanite is estimated at 0.5% for Pb/U and 0.1% for $^{207}Pb/^{206}Pb$.

(7) Universal Transverse Mercator (UTM) grid coordinates on standard 1:50,000 topographic map-sheet; 1521 I Orkanger.

crustal rocks, relatively enriched in ^{87}Sr but of variable strontium isotopic composition. The biotite date of sample III (372 Ma) is younger than any of the pegmatite ages, and indicates that the terrane last cooled through the biotite blocking-temperature by ca. 372 Ma.

U–Pb results

Ingdal granite gneiss. The results of U–Pb isotopic analyses of three zircon and four titanite fractions from the Ingdal granite gneiss are given in Table 3 and shown in Fig. 4. Zircon fractions 3 and 5 were morphologically alike displaying pitted and bulbous forms characteristic of resorbed zircons; fraction 4 consisted largely of poorly faceted and slightly cracked grains showing little sign of crystal resorption. All analyzed fractions were clear to slightly turbid, and all fractions were relatively low in uranium and free of inclusions and contaminant phases. Their degree of discordance increases with decreasing grain-size.

Four titanite fractions (1, 2, 6, and 7) were analyzed to complement the zircon study. One fraction (no. 2) was separated from sample III from which zircon was analyzed, whereas other titanite fractions were separated from rocks selected for Rb–Sr analysis (II, IV, III); titanite no. 7 was separated from sample VII which was not included in the Rb–Sr whole-rock study (Fig. 1).

All titanites are discordant and titanites 1 and 2 are more discordant than zircons 3, 4, and 5. A common regression of titanite and zircon results in a single discordia-line with intercept-ages of 1653 ± 2 Ma and 396 ± 5 Ma, and a 42% probability of fit of all points to the line. Regression lines through various subsets of colinear data (e.g. all zircon or all titanite analyses, or all zircon analyses and the titanite from sample VI) results in discordia upper-intercepts with essentially identical ages, although lower-intercept ages can vary significantly depending on whether titanite no. 7 is included in the regression. Nonetheless, there is no justification for excluding any point from the age regression and the preferred interpretation is that titanite and zircon crystallized together at 1653 Ma ± 2 Ma, but were variously affected by a Scandian metamorphic event at 396 ± 5 Ma.

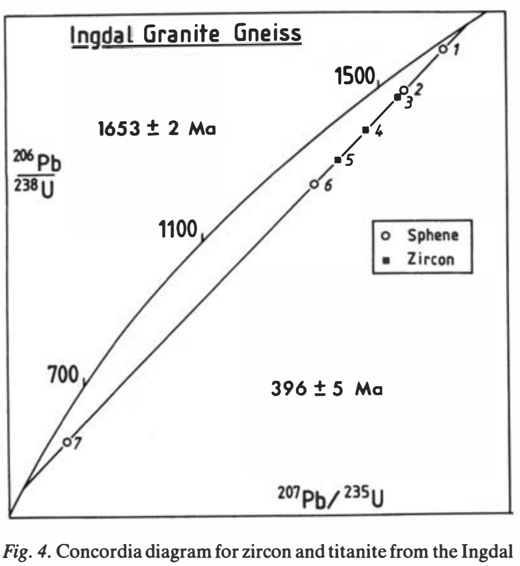

Fig. 4. Concordia diagram for zircon and titanite from the Ingdal granite gneiss. The upper-intercept age is the time of granite emplacement and the lower-intercept age is the time of a regional Scandian metamorphic event. Least discordant titanites (nos. 1 and 2) are from metamorphic Zone I, whereas most discordant titanites (nos. 6 and 7) are from Zone II.

Discussion

Zircon and titanite from the Ingdal granite gneiss define a discordia-line whose upper-intercept age (1653 ± 2 Ma) agrees well with a whole-rock Rb–Sr age estimate at the 2-sigma confidence level. The Rb–Sr date is unreliable, however, because the points do not define an isochron within acceptable error limits (MSWD = 11). The U–Pb zircon age is thus accepted as the age of granite emplacement because zircon is thought to resist total isotopic resetting even during very high grades of metamorphism (Köppel & Grunenfelder 1971; Krogh & Davis 1973; Grauret et al. 1974; Pidgeon & Aftalion 1978; Gebauer & Grunenfelder 1979; Scharer 1980; Schenk 1980; Gebauer et al. 1981). The Early Proterozoic date can only be interpreted as a metamorphic age if all zircon and titanite was totally reset or newly formed during that metamorphism, or if the metamorphism occurred shortly after granite emplacement.

Both titanite and zircon from the Ingdal granite gneiss define the discordia-line and both minerals are interpreted to have first formed during crystallization of the granite. Zircon and titanite have been shown, however, to have markedly different formation and blocking-temperatures (Mattinson 1978), thus implying that granite emplacement and cooling below ca. 500°C (the presumed blocking-temperature of titanite) occurred very quickly. Following its formation at ca. 1653 Ma, titanite remained effectively closed to uranium and lead migration until ca. 396 Ma, when it was variously affected by a short-lived Scandian metamorphic event. During this lower-intercept event, titanite no. 7 in metamorphic Zone II was reset to 90% discordance and titanites 1, 2, and 6 in metamorphic Zone I were reset to 6%, 15%, and 35% discordance, respectively (Fig. 4).

The cause of titanite discordance in this part of the WGR is consistent with either a model of simple mixing of two generations of titanite (i.e. 1653 Ma-old and 396 Ma-old titanite) or episodic and thermally-induced, diffusional Pb-loss of 1653 Ma-old titanite during a metamorphic event 400 Ma ago. In a more complete study of U–Pb titanite and zircon ages from the northern portion of the WGR, Tucker et al. (in prep.) have shown that many gneisses in the region contain two varieties of titanite: a clear to pale-yellow, faceted variety which is always concordant (or nearly so) at ca. 396 Ma, and a dark, turbid variety that is distinctly older. In various gneisses across the region, this 'old' titanite variety exhibits a complete range of age discordance such that it is least discordant where gneisses are at greenschist facies grade (Caledonian) and most discordant (but older than 396 Ma) where at amphibolite facies grade. In a given gneiss, the U–Pb ages of this dark, titanite variety have been duplicated to within 1%, even when sample weights between tests varied by an order of magnitude. Thus, the present data suggest that two generations of titanite are present in nearly every sample, but that the mechanism for generating high degrees of age discordance in the dark, titanite variety is probably diffusional Pb-loss (perhaps recrystallization assisted) during a short-lived thermal event about 396 Ma ago. Moreover, the zircon and titanite discordia-line clearly indicates that the Ingdal granite stock was emplaced and cooled in a short time interval about 1653 Ma ago and that titanite and zircon were not isotopically disturbed by comparable geologic events in the period from 1653 Ma to 396 Ma, or at any time after 396 Ma. Final cooling of the terrane through ca. 300°–350°C (the blocking-temperature of biotite) occurred at approximately 372 ± 4 Ma, the Rb–Sr biotite age from the Ingdal granite gneiss.

The close agreement of the Rb–Sr whole-rock date and the U–Pb upper-intercept age indicates that whole-rock systems may remain effectively closed (although disturbed) to large-scale rubidium and strontium migration despite younger deformation and metamorphism at greenschist- and amphibolite-facies conditions. The initial strontium ratio determined from the Rb–Sr errorchron suggests that the Ingdal granite was derived from a source with a low initial strontium value, possibly the mantle or Rb-depleted lower continental crust. Zircons from the Ingdal granite gneiss do not contain a component of older, inherited zircon, but the absence of such inheritance does not preclude the existence of older crust (Scharer et al. 1986). Indeed, the large volumes of granitoid masses in the WGR would seemingly require the presence of pre-existing crust (Barker 1981), at the base of or within which magmas could cool, assimilate and differentiate, and where inherited zircons could be completely dissolved (Harrison & Watson 1983).

The Rb–Sr mineral dates of two strongly discordant pegmatites (VIII and X) suggest that the essential minerals (plagioclase, microcline and, in one case, biotite) achieved and maintained isotopic equilibrium in a closed-system after their time of crystallization; only the minerals in pegmatite IX (MSWD = 12) do not define an isochron within acceptable error limits. The relatively high (>0.7144) and variable ($\Delta = 0.0104$) initial $^{87}Sr/^{86}Sr$ suggests that the pegmatites were derived from old crustal rocks relatively rich in radiogenic strontium, probably the nearby basement gneisses. All pegmatite ages do not, however, overlap to a common time interval (at the 2-sigma confidence interval), suggesting that slight age differences between pegmatites may be real and significant. Geologic mapping indicates that similar pegmatite dikes are geographically restricted to the deep-levels of metamorphic Zone II and throughout Zone III, and that they are only weakly foliated or non-deformed and not associated with large granitoid masses. Rather, the pegmatites appear to have petrologic characteristics in common with mica-bearing pegmatites from deep crustal levels (Jahns & Burnham 1969; Sokolov et al. 1975; Cerny 1982). They are the youngest igneous rocks in the region and their age effectively dates the end of Scandian orogenesis.

Summary

A seven-point (three zircon and four titanite) discordia-line from the Ingdal granite gneiss defines upper- and lower-intercept ages of 1653 ± 2 Ma and 396 ± 5 Ma, respectively. The upper-intercept age is interpreted as the time of zircon and titanite formation and of granite emplacement. The lower-intercept age is interpreted as the time of gneiss formation, regional metamorphism, and cooling of zircon and titanite below their respective blocking-temperatures. Colinearity of widely-separated zircon and titanite samples to single discordia-line is interpreted to indicate that both the upper-intercept granite emplacement event and the lower-intercept metamorphic event resulted in rapid heating and cooling of the terrane. Moreover, the terrane did not experience comparable geologic events in the interval between ca. 1653 Ma and 396 Ma; not at the time of the Sveconorwegian (ca. 1250–900 Ma) or Finnmarkian (ca. 530–480 Ma) orogenies.

During Scandian orogenesis, titanite in the Ingdal granite gneiss experienced variable radiogenic-Pb loss, possibly by thermally-induced diffusion through radiation-damaged sites. The Rb–Sr mineral ages of strongly discordant pegmatite dikes are also evidence for Caledonian metamorphism in the region; the pegmatites crystallized in the interval from ca. 415 to 378 Ma and the relatively high and variable initial $^{87}Sr/^{86}Sr$ values are interpreted to indicate that the pegmatites formed by anatexis of old, radiogenic-Sr rich rocks, possibly the basement gneisses. Similar pegmatites in the WGR are geographically restricted to (south)western and structurally deep levels of metamorphic Zones II and III (Fig. 1). A minimum cooling age (372 ± 4 Ma) of the terrane is indicated by a biotite date from the Ingdal granite gneiss.

Acknowledgements. – The Geological Society of America, the Sigma-Xi Foundation, the American-Scandinavian Foundation, Norges geologiske undersøkelse (NGU, Trondheim), Norges Teknisk-Naturvitenskapelig Forskningsråd (NTNF), and Yale University are gratefully acknowledged for providing financial support of the geologic mapping and structural study of Vestranden's bedrock. Bjorn Sundvoll, Toril Enger (Mineralogisk-Geologisk Museum, Oslo), and Bente Kjøsnes (NGU, Trondheim) provided assistance with Rb–Sr analyses in Norway. Fernando Corfu and Don Davis (Royal Ontario Museum, Toronto) are especially thanked for their help and advice with the U–Pb analyses in Canada. Travel and subsistence expenses during the period of isotopic determinations in Toronto were paid by NSERC grant A–4261 to T. E. Krogh and a NTNF post-doctoral Fellowship to R. D. Tucker.

Manuscript received June 1986

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