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ABSTRACT

Rocks in the polymetamorphic terrains of southwestern Sweden are often characterized by disturbed isotopic systems. Ten samples of these rocks have been investigated by U-Pb datings and microscopy of zircons. The results demonstrate how evolutionary constraints and development models can be established even in severely reworked terrains by combining zircon datings and Rb-Sr whole-rock and mineral ages with scanning electron microscopy (SEM) and optical microscopy studies of zircon structure and morphology. The new zircon datings yielded ages between 1 535 and 1 675 Ma and indicate metamorphic reworking, cooling episodes and the presence of relic zircon cores in granites intruded at 1.2 Ga. No Early Proterozoic or Archaean zircons were found, which suggests that the continental crust in southwestern Scandinavia was mainly formed between c. 1.5 and 1.75 Ga.

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INTRODUCTION

Southwestern Sweden belongs to a polymetamorphic crustal segment where magmatism and metamorphism occurred repeatedly during a semicontinuous development spanning at least 900 Ma between c. 850 Ma and 1 800 Ma (Gorbatschev 1980, Gorbatschev and Welin 1980).

Previous work employing Rb-Sr datings (Welin and Gorbatschev 1976b, 1976c, 1978c, 1978d) demonstrated the formation of large amounts of tonalitic and granodioritic plutonic rocks at about 1 700 Ma (the provisional Åmål-I plutonic group of Gorbatschev 1975). These rocks are characterized by low $^{87}Sr/^{86}Sr$ initial ratios and therefore indicate extensive formation of new continental crust in an orogenic process also comprising regional metamorphism that affected all of southwestern Sweden and the adjoining parts of Norway.

The 1 700 Ma old plutonic rocks, which possibly belong to several closely associated sub-groupings, penetrate sedimentary and volcanic rocks of the Stora Le-Marstrand Group, the Åmål supracrustal sequence (Gorbatschev 1977) and farther east, in the vicinity of the Svecokarelian orogenic belt of the central Baltic Shield, also plutonic rocks yielding 50—100 Ma older zircon ages (Welin and Kähr 1980).

The grand orogenic process terminated before 1 550 Ma, when the part of southwestern Sweden that is closest to the Svecokarelian province was cut by numerous sills and dikes of 'hyperite' dolerite. Large, E—W trending dolerite dikes in central Sweden (Patchett 1978) also indicate major brittle deformation of the Baltic Shield at this time.

The subsequent evolution involved several events of metamorphism and magmatic intrusion. As discussed by Gorbatschev and Welin (1980), some of these may be manifestations of distant orogenic processes in an environment which by then was wholly ensialic. Rb-Sr whole-rock datings tend to concentrate around 1 400 Ma (Daly et al. 1979, Skiöld 1976, Welin and Gorbatschev 1978a, 1978b), 1 200 Ma (Gorbatschev and Welin 1975, Welin and Gorbatschev 1976a, Zeck and Wallin 1980, Welin et al. 1981a, and several unpublished datings), and 850—900 Ma (Skiöld 1976). Ages between 1 200 and 900 Ma are broadly equivalent to the Grenvillian of North America. However, in Scandinavia, this development features two distinctly separate culminations of thermal and tectonic activity covered by the term Sveconorwegian as used by Gorbatschev (1980). This term includes the Dalslandian of Lundegårdh (1980).

The multistage geological evolution of southwestern Sweden caused disturbance of the isotopic systems, discordance between Rb-Sr whole-rock and mineral ages, and a general rejuvenation of the K-Ar ages during the Sveconorwegian orogeny.

A straightforward calculation of ages corresponding to definable geological events is therefore often difficult. Available knowledge on metamorphic influences on the isotopic systems may be summarized as follows. In southwestern Sweden, the metamorphic event 900—1 100 Ma ago resulted in nearly complete expulsion of radiogenic argon. All rocks and minerals of whatever age exceeding these figures therefore yield K-Ar ages around 1 000 Ma (Magnusson 1960). As an example of disturbance of the Rb-Sr system, the dating of the Uddevalla tonalite-granodiorite resulted in a Rb-Sr whole-rock reference age of 1 655 Ma and a mineral-whole rock isochron age of 955 ±30 Ma (1σ, ^{87}Rb $\lambda = 1.42 \cdot 10^{-11}a^{-1}$, Welin and Gorbatschev 1976b). Similar results were obtained from the tonalite at Rönnäng (Welin and Gorbatschev 1978c). A zircon dating of a coarse-grained pegmatoid variety of a hyperite yielded an upper intercept with the concordia curve at 1 550 Ma and a lower intercept at 880 Ma (Welin et al. 1980a). The Rb-Sr whole rock-mineral isochron gave an age of 950 Ma. It was concluded that the hyperite magma crystallized 1 550 Ma ago and that subsequent metamorphism opened the Rb-Sr systems of the minerals 900—1 000 Ma ago (Welin et al. 1980a). During the latter event the zircons also suffered episodical loss of lead.

Radiometric datings of rocks and minerals in southwestern Sweden thus show that the metamorphic episode 900—1 000 Ma ago not only opened the K-Ar system but also partly or completely opened the Rb-Sr systems of rocks and minerals and had been able to cause episodic loss of lead from zircons.

The present work is essentially a study of the U-Pb systems of zircons. The results are interpreted by comparisons with Rb-Sr datings and are based on careful SEM and optical microscopy of zircon structures and morphologies.

SAMPLING

Sampling was carried out at ten different localities partly covered by previous Rb-Sr datings. The zircons were separated from samples of fresh rock weighing approximately 50 kg. Five of the samples belong to rocks of the Åmål-I group, one stems from the Åmål volcanic rocks, three are rocks that have yielded Rb-Sr ages around 1 400 Ma or are believed to belong to this group, while one represents the 1 200-Ma Hästefjorden granites. Fig. 1 provides a general map of sampling sites. Their coordinates are given in Table 1.

Åmål supracustals. — The sample 77017 Åmål (metavolcanic rock) is a fine-grained rock featuring small quartz and feldspar phenocrysts in a reddish, leucocratic matrix. The sampled locality is at Tössebäcken, south of Åmål. It belongs to the area where the Åmål supracrustals are best preserved. Foliation is absent or very faint. Off the sampling locality, the metavolcanic rocks are cut by plutonic rocks of the Åmål-I group.

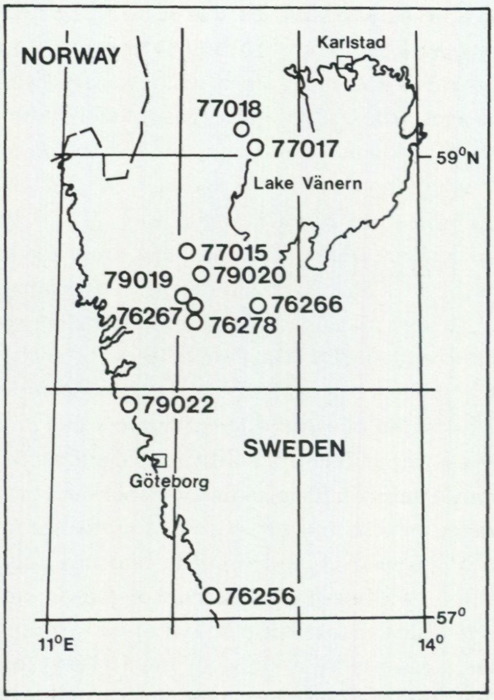

Fig. 1. Map of southwestern Sweden showing location of samples.

Åmål-I plutonic rocks. — All the samples are medium-grained, gray, tonalitic to granodioritic rocks. Samples 76266 Grästorp, 76267 Uddevalla, 77018 Åmål (plutonic), and 79022 Rönnäng belong to occurrences previously dated by the Rb-Sr method (Welin and Gorbatschev 1976c, 1976b, 1978d, and 1978c, respectively). All rocks are gneissic, but only the rock at locality 76266 Grästorp carries sparse, short, thick veins of stromatic leucosome. Here, the sampling was restricted to the paleosome.

Rock 76278 Åkerskog forms the substratum of a locality where the Åmål supracrustal rocks carry fragments of plutonic rocks (Gorbatschev 1979). However, subsequent field work has shown that the contact is the sole of a late Sveconorwegian (late Dalslandian) thrust. Therefore there remain no geological objections against regarding this rock as a normal member of the Åmål-I plutonics.

Table 1. Location of samples.

79020	Hästefjorden	12°10'30"E	58°31'20"N
76256	Varberg	12°14'54"E	57°05'49"N
76266	Grästorp	12°42'38"E	58°19'44"N
77018	Åmål	12°37' E	59°02'15"N
77017	Åmål	12°39' E	58°57'47"N
79019	Lane	12°03'06"E	58°23'47"N
77015	Ödeborg	12°01'10"E	58°32'20"N
76267	Uddevalla	12°06'26"E	58°20'31"N
76278	Åkerskog	12°09'30"E	58°19'30"N
79022	Rönnäng	11°35' E	57°56'21"N

Varberg charnockite. — Sample 76256 Varberg is a massive, medium-grained rock from the Apelviken-Getterön Charnockite Member of Hubbard (1975) in the southern part of Varberg town. The charnockites have been dated previously by the Rb-Sr method (Welin and Gorbatschev 1978b). The regional contexts have been discussed by, a.o., Hubbard and Constable (1980), and Gorbatschev and Welin (1980).

Lane granites. — The Lane granites form cross-cutting, elongate intrusions in the Åmål-I plutonics. Locality 79019 Lane is in the northern part of the eastern granite belt studied by Welin and Gorbatschev (1978a).

Locality 77015 Ödeborg on the western shore of Lake Brötegårdssjön belongs to the complex Ellenö region (Gorbatschev 1971, 1977, Skiöld 1976, 1980), where some granites underlie whereas others cut the Kappebo (Ellenö) supracrustal rocks (Gorbatschev 1977). Approximately 150 m from the sampling locality, the granite is covered by sedimentary breccias of the Kappebo Group, which carry pebbles of the granitic substratum. Petrographically and geochemically, the sampled granite is similar to the massifs of Lane granites dated by the Rb-Sr method.

Hästefjorden granite. — As described by Gorbatschev and Welin (1975), the twin Hästefjorden and Ursand granite massifs exhibit textural variation from massive, fine-grained granites in the west to coarser, gneissic granites and eventually coarse augen gneisses in the east. The sampled rock 79020 is a finely medium-grained granite from the westerly, submassive-massive part of the Hästefjorden massif. The Hästefjorden granite forms the substratum of the Dal Group. Welin and Gorbatschev (1976a) report a previously determined Rb-Sr age.

Fig. 2. Zircon crystal with rounded core of older zircon. Sample 79020 Hästefjorden. Total length of the zircon crystal is 390 μm. Polarized light, 10 μm thin section.

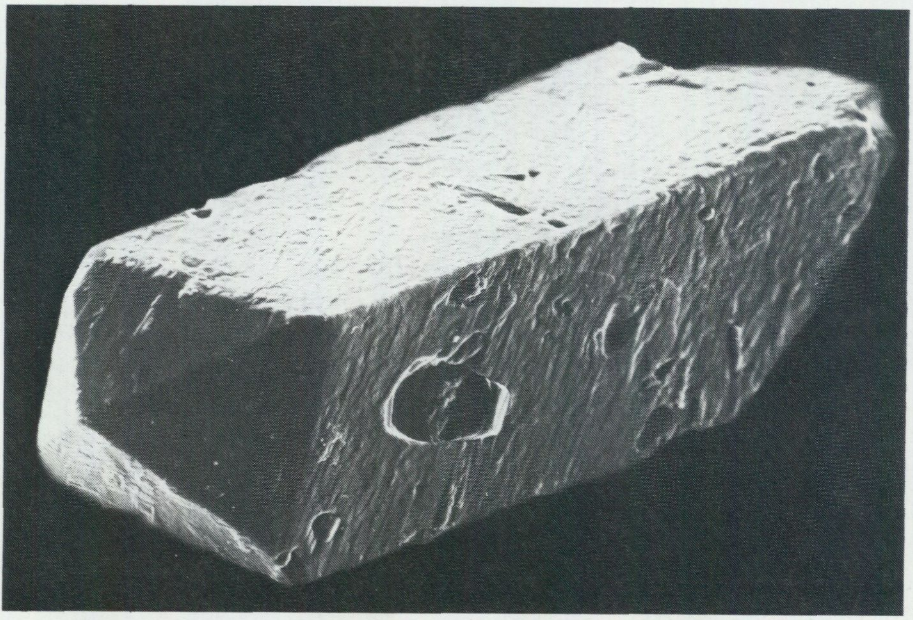

Fig. 3. SEM photomicrograph of zircon crystal. Sample 79020 Hästefjorden. Total length of crystal is 100 μm.

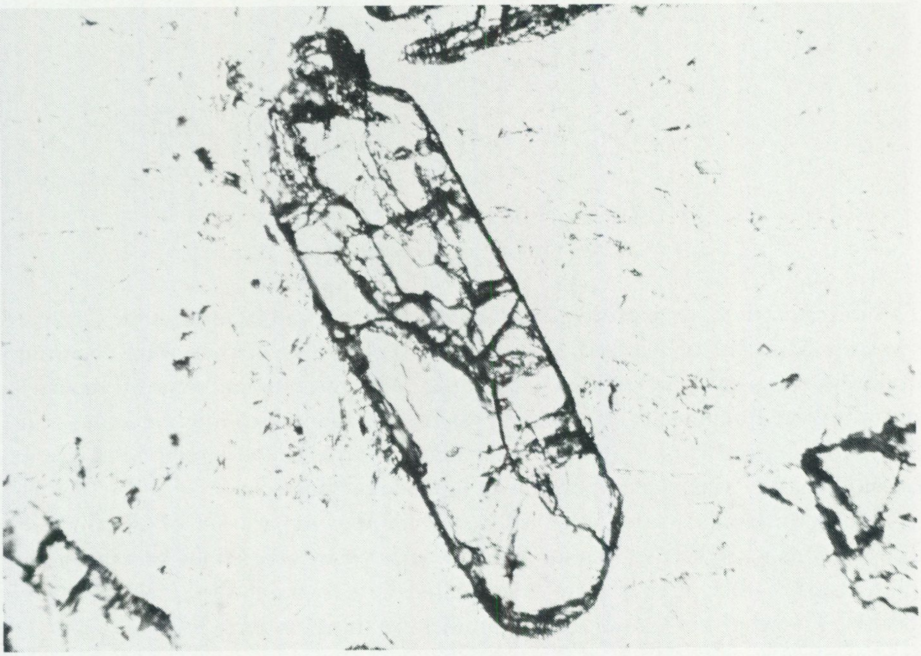

Fig. 4. Zircon crystal. Sample 79019 Lane. Total length of the zircon crystal is 210 μm. Polarized light, 10 μm thin section.

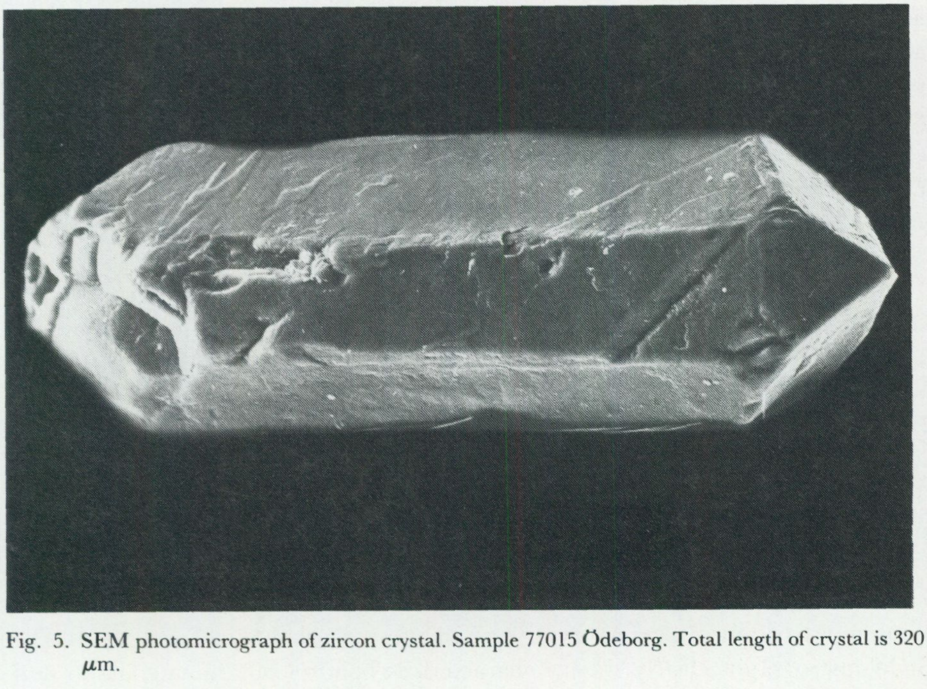

Fig. 5. SEM photomicrograph of zircon crystal. Sample 77015 Ödeborg. Total length of crystal is 320 μm.

MICROSCOPIC OBSERVATIONS AND ANALYTICAL METHODS

The radiometric datings were carried out at the Laboratory for Isotope Geology, Swedish Museum of Natural History, Stockholm. The zircons were separated from the rocks by conventional techniques. The pure zircon concentrates were split into size fractions, each of which was further subdivided into a magnetic and a non-magnetic portion. The final selection of the amount of zircon necessary for isotopic analysis was made by handpicking under a microscope.

The zircon concentrates were also used for the preparation of 10 μm thick thin-sections with parallel, planar surfaces, which were studied under a polarizing microscope. Other zircons were investigated in a scanning electron microscope (SEM). The results of the microscope studies are shown in Figs. 2—11.

According to the SEM studies, the zircons consist of two morphologically different classes. The *first class* consists of zircons from samples 79020 Hästefjorden, 79019 Lane, 76256 Varberg, and 77015 Ödeborg. The habits of these zircons are shown by the photomicrographs, Figs. 2—5. The zircon crystals of this class are characterized by well developed prismatic habits and are terminated by pyramids of a few, low-order indices. The crystal edges are sharp. The sizes of the crystals usually range between 74 and 150 μm. The zircons separated from the charnockite at Varberg (sample 76256) are an exception. They consist almost entirely of fragments of crystals, which must in general have been larger than 200 μm. A few preserved smaller crystals, however, show that the Varberg zircons belong to the described morphological class.

Under the polarizing microscope, the zircons exhibit varying characteristics: the transparency varies from dull to clear, zoning is often present, and there are sometimes small, opaque, black inclusions. Fissures are common, which is clearly seen in Figs. 2 and 4. The zircons from the Hästefjorden granite contain rounded cores (Fig. 2). All observations indicate that these cores consist of older zircons, which have acted as crystallization nuclei for younger, external shells of zircon. These outer shells are thick and entirely cover the older cores. The ultimate products are new, well-formed crystals shown in the SEM micrograph of Fig. 3.

The *second morphologic class* comprises zircons from samples 76266 Grästorp, 77018 Åmål, 77017 Åmål, 76267 Uddevalla, 76278 Åkerskog, and 79022 Rönnäng. Photomicrographs of zircons from these samples are shown in Figs. 6—11. The SEM micrographs clearly show a characteristic habit of subordinate prisms and dominant pyramids of high-order indices. Semi-ellipsoidal crystals are the net result of the combination of the various forms. Under the polarizing microscope, the colour and the transparency vary. In all crystals there are frequent microfissures, which are not seen at the crystal surfaces as shown in the SEM micrographs (Figs. 7, 9 and 11). Zoning is observed only in some zircons from Åkerskog and more frequently in zircons from Rönnäng. The best developed prismatic zircon crystals of this morphologic class occur also in the Åkerskog and Rönnäng granitoids. Inclusions of quartz and biotite are common. All the rocks with semi-ellipsoidal zircons are foliated, polymetamorphic igneous rocks where the observed morphologic features are believed to indicate recrystallization of presumably primary, magmatic zircons, originally probably similar to those described as the first class (cf. p. 10).

A further indication of metamorphic recrystallization is shown by the zircons of the metavolcanic rock (sample 77017 Åmål). These zircons are smaller (average length 40—60μm) than the zircons in the investigated metaplutonic rocks, which is in accordance with the authors' observations of zircon sizes in other metavolcanic and plutonic rocks in the Baltic Shield. The zircon habit of the Åmål metavolcanic rock is quite similar to that of the semi-ellipsoidal type described above (Figs. 8, 9A and 9B). These crystals do not exhibit the well-developed prismatic habit of zircons commonly observed in unmetamorphosed volcanic rocks. The Åmål metavolcanic rock was formed from a silicic, quartz-porphyritic lava. A detrital character of the zircons is consequently ruled out. It is therefore assumed that the zircons of both the volcanic and the plutonic rocks have acquired similar, semi-ellipsoidal crystal habits as a result of recrystallization.

The chemical preparation of the zircon samples was carried out essentially according to the method described by Krogh (1973). The purification of lead was made by electrolytic deposition on a Pt electrode. The isotope ratios measured with an AVCO 901 mass spectrometer have not been corrected for mass fractionation. The measured ^{207}Pb/^{206}Pb value for the U.S. National Bureau of Standards reference lead 981 is 0.91480 as compared to the recommended value of 0.91464. The error (lσ) in the ^{207}Pb/^{235}U ratio has been estimated to 0.03 and in the ^{206}Pb/^{238}U ratio as 0.001. For the common lead correction, the following ratios have been used:

Samples	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
79020	17.0	15.6	36.5
76256 79019	16.0	15.5	36.3
76266 76267			
76278 77015	16.0	15.4	35.8
77017 77018			
79022			

The contamination during the chemical preparation of a zircon sample for mass spectrometric analysis was 3 ng Pb. The calculation of ages according to the episodic loss model was made according to Pankhurst and Pidgeon (1976). The decay constants recommended by Steiger and Jäger (1977) were used.

The results of the isotopic analyses and the calculations of apparent ages are given in Table 2. The analytical results have also been plotted in Concordia diagrams, Figs. 12—21.

Fig. 6. Zircon crystals of semi-ellipsoidal habit. Sample 76266 Grästorp. Total length of longest crystal is 200 μm. Polarized light, 10 μm thin section.

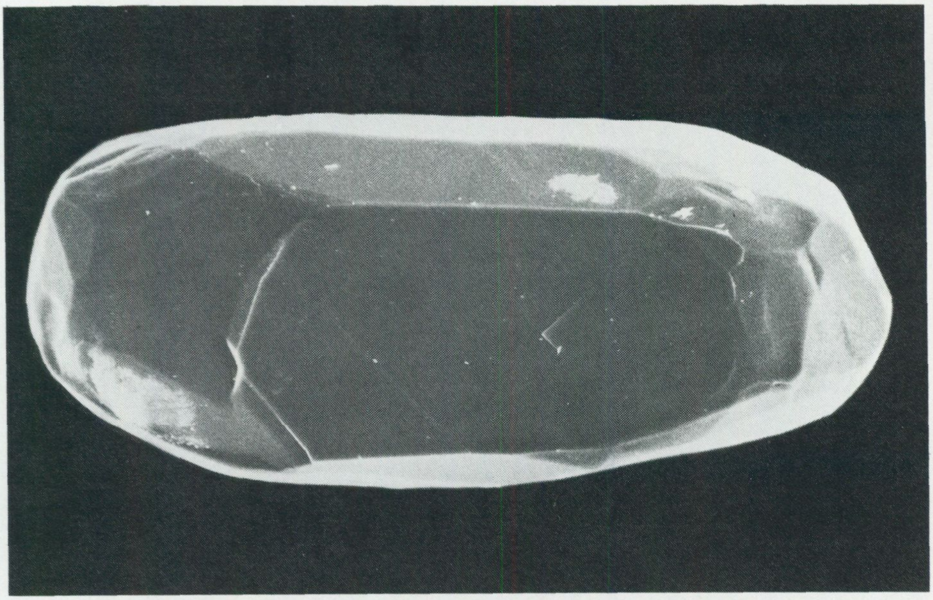

Fig. 7. SEM photomicrograph of zircon crystal. Sample 76266 Grästorp. Total length of crystal is 400 μm.

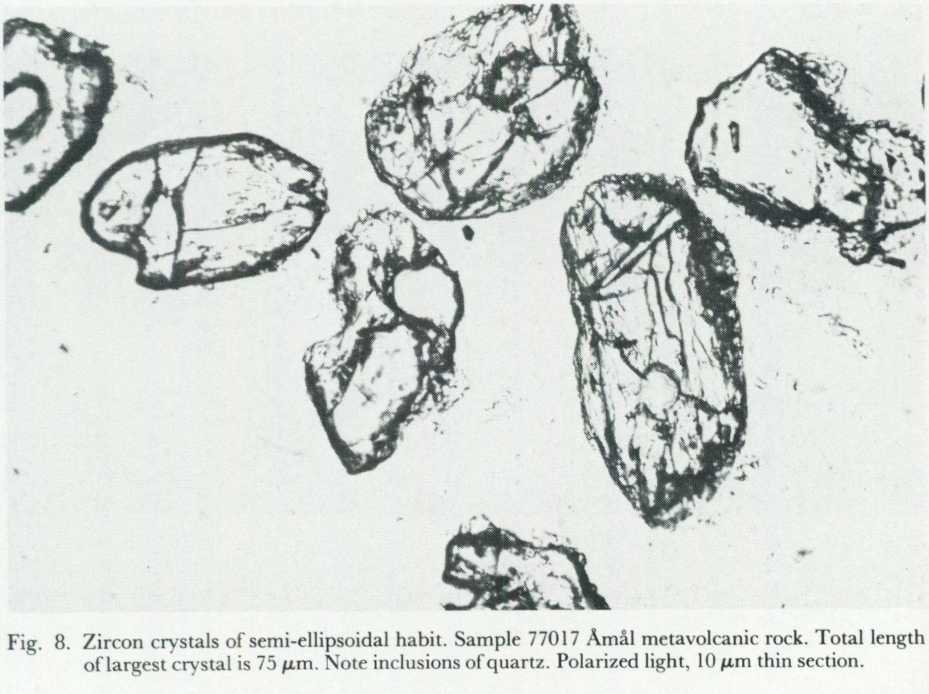

Fig. 8. Zircon crystals of semi-ellipsoidal habit. Sample 77017 Åmål metavolcanic rock. Total length of largest crystal is 75 μm. Note inclusions of quartz. Polarized light, 10 μm thin section.

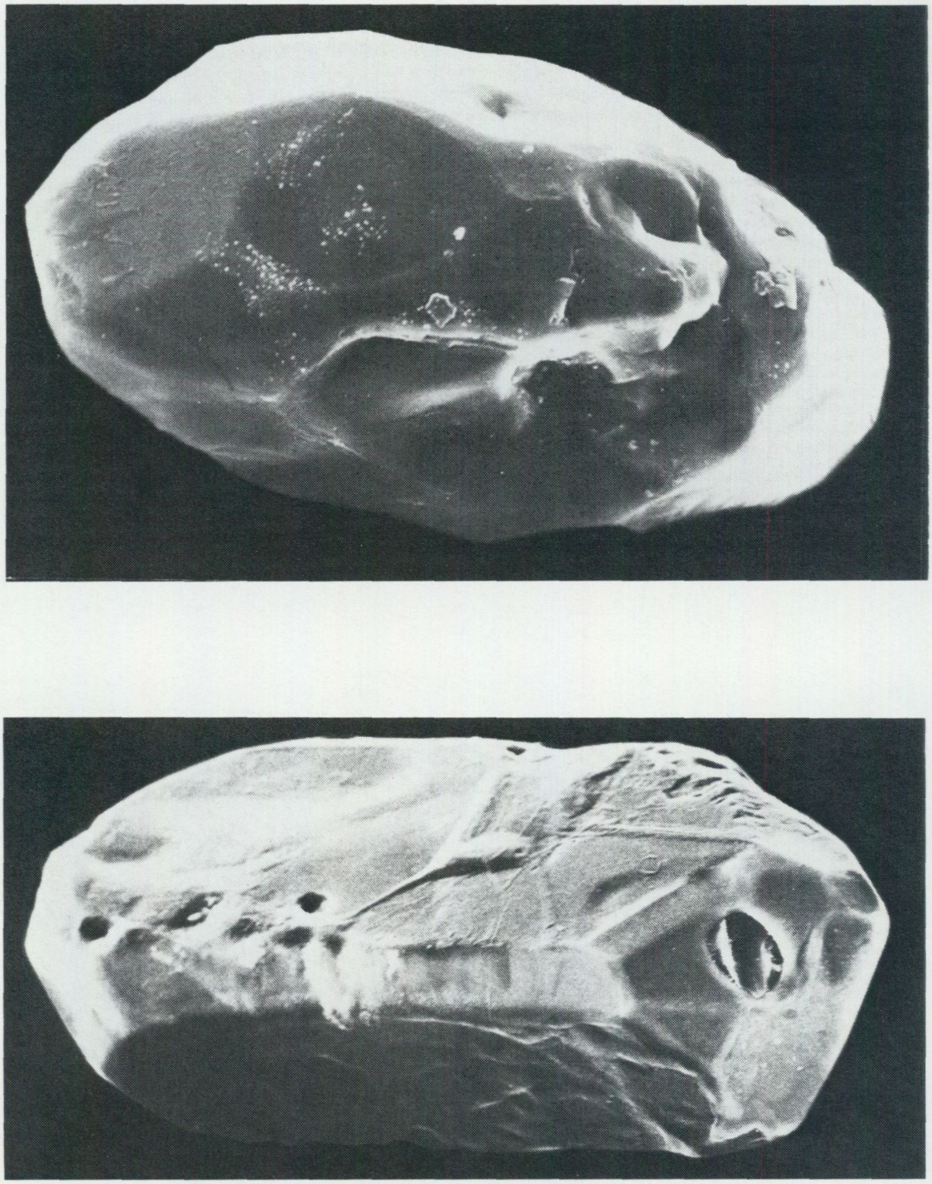

Fig. 9A and 9B. SEM photomicrographs of zircon crystals. Sample 77017 Åmål metavolcanic rock. 9A (above) shows a semi-ellipsoidal crystal with pyramid faces developed at the terminations. 9B (below) shows partly recrystallized primary magmatic zircon. Total length of crystals about 160 μm.

Fig. 10. Zircon crystal of semi-ellipsoidal habit. Sample 76267 Uddevalla. Total length of crystal is 150 μm. Polarized light, 10 μm thin section.

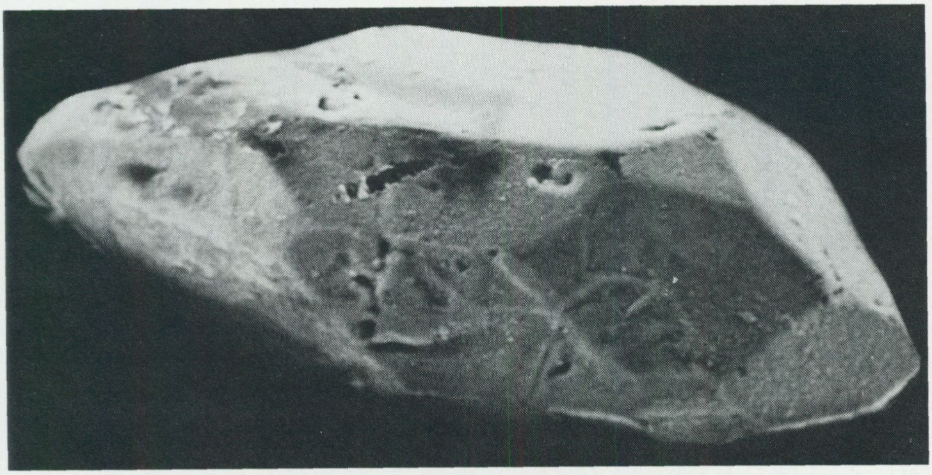

Fig. 11. SEM photomicrograph of zircon crystal of semi-ellipsoidal habit. Sample 76267 Uddevalla. Pyramids and prisms are clearly visible. Total length of crystal is 300 μm.

Table 2. U-Pb isotopic analyses of zircon.

No.	Fraction	Concentration in ppm		Lead atomic ratio			Atomic ratios corrected for c.l.			Apparent ages		
		U	Pb_{rad}	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{208}Pb}$	$\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$
Granite 79020 Hästefjorden												
1	>150μm m 1.5A	1206	144.4	1136	0.10265	0.17728	0.11245	1.40031	0.09031	687	889	1432
2	>150μm m 1.6A	732	95.8	690	0.10121	0.17061	0.12670	1.40828	0.08061	769	892	1212
3	106-150μm nm 1.6A	792	119.2	1111	0.10471	0.17738	0.14131	1.79334	0.09204	852	1043	1468
4	>150μm nm 1.6A	671	99.4	1250	0.09569	0.14280	0.14360	1.67091	0.08439	865	998	1302
5	106-150μm nm 1.6 A	737	129.5	633	0.10376	0.16949	0.17081	1.91588	0.08135	1017	1087	1229
6	45-74μm nm 1.6A	466	85.1	637	0.10644	0.18131	0.17514	2.03374	0.08421	1040	1127	1298
7	>150μm nm 1.6A	505	93.0	1031	0.09752	0.15409	0.17792	2.05563	0.08379	1056	1134	1288
8	106-150μm nm 1.6A	396	74.9	1408	0.09831	0.16110	0.17938	2.18572	0.08837	1064	1177	1391
9	106-150μm nm 1.6A	492	93.8	2083	0.09277	0.14367	0.18280	2.16633	0.08595	1082	1170	1337
10	>150μm nm 1.6A	318	64.1	685	0.10558	0.17661	0.19357	2.26624	0.08491	1141	1202	1314
11	106-150μm nm 1.6A	262	59.0	787	0.10613	0.17861	0.21444	2.60756	0.08819	1252	1302	1387
Charnockite 76256 Varberg												
1	106-150μm m 1.6A	113	22.1	1087	0.09411	0.23253	0.17602	1.96787	0.08108	1045	1105	1223
2	74-106μm m 1.6A	109	22.5	1563	0.08784	0.22766	0.18695	2.02865	0.07870	1105	1125	1165
3	106-15μm 1.6A	105	21.7	3571	0.08568	0.20786	0.18835	2.12205	0.08171	1112	1156	1239
4	150-210μm m 1.6A 1.5°	99	21.0	1136	0.09328	0.25669	0.18837	2.09672	0.08073	1112	1148	1215

Charnockite 76256 Varberg (continued)												
5	106-150µm nm 1.6A	105	22.8	2326	0.08566	0.23526	0.19343	2.12324	0.07961	1140	1156	1187
6	106-150µm nm 1.6A	99	21.6	1449	0.09030	0.24921	0.19404	2.15307	0.08048	1143	1166	1209
7	150-210µm nm 1.6A	99	21.4	521	0.10889	0.29763	0.19209	2.16331	0.08168	1133	1169	1238
8	44-74µm nm 1.6A 1.5°	103	22.2	4545	0.08519	0.22437	0.19358	2.18887	0.08201	1141	1178	1246
9	44-74µm nm 1.6A	103	22.7	372	0.12112	0.31273	0.19734	2.25502	0.08288	1161	1198	1266
10	44-74µm nm 1.6A	104	23.3	2778	0.08711	0.23313	0.19967	2.25631	0.08196	1174	1199	1245
11	150-210µm nm 1.6A 1.5°	48	11.4	971	0.09638	0.25949	0.20929	2.35731	0.08169	1225	1230	1238
Granite 76266 Grästorp												
1	>150 µm nm 1.5A	55	14.2	1163	0.10968	0.16302	0.24282	3.27372	0.09778	1401	1475	1582
2	106-150 µm nm 1.5A	72	20.5	465	0.12809	0.24430	0.25877	3.50749	0.09831	1484	1529	1592
3	44-74 µm nm 1.5A	119	34.0	3125	0.10145	0.17767	0.26242	3.51111	0.09704	1502	1530	1568
4	74-106 µm nm 1.5A	129	36.6	1220	0.11197	0.19524	0.25994	3.60777	0.10066	1490	1551	1636
Granite 77018 Åmål												
1	210µm nm 1.2A brown	63	24.5	222	0.16134	0.79923	0.25175	3.43576	0.09898	1448	1513	1605
2	150-210µm nm 1.2A	132	39.4	311	0.14287	0.34558	0.25836	3.50232	0.09832	1481	1528	1592
3	45-74µm nm 1.2A	144	45.4	441	0.13034	0.32729	0.27004	3.68432	0.09895	1541	1568	1604
4	106-150µm nm 1.6A	126	39.6	758	0.11769	0.29079	0.27102	3.71623	0.09945	1546	1575	1614
5	74-106µm nm 1.6A	139	44.5	493	0.12701	0.31500	0.27504	3.75180	0.09893	1566	1583	1604
6	45-74µm nm 1.6A	144	45.9	625	0.12180	0.30340	0.27447	3.77376	0.09972	1563	1587	1619

Metavolcanic rock 77017 Åmål

1	74-106µm m 1.6A 1.5°	536	105.3	1298	0.11096	0.13416	0.18899	2.61457	0.10034	1116	1305	1630
2	45-74µm m 1.6A	446	99.0	3571	0.10153	0.07674	0.22143	2.98368	0.09773	1289	1404	1581
3	45-74µm m 1.6A 1.5°	492	111.8	2381	0.10267	0.07827	0.22745	3.03678	0.09683	1321	1417	1564
4	74-106µm nm 1.6A 1.5°	362	86.4	4546	0.10261	0.10193	0.23263	3.19178	0.09951	1348	1455	1615
5	106-150µm nm+m 1.6A	417	168.7	5055	0.10080	0.18089	0.23803	3.22742	0.09834	1376	1464	1593
6	45-74µm nm 1.6A	406	96.7	2632	0.10320	0.08060	0.23768	3.21140	0.09799	1375	1460	1586
7	45-74µm nm 1.6A	379	92.2	6250	0.10101	0.07375	0.24241	3.30149	0.09877	1399	1481	1601

Granite 79019 Lane

1	>150µm nm 1.5A	606	80.6	943	0.10854	0.15014	0.12811	1.65543	0.09372	777	991	1502
2	>150µm m 1.5A weathered	992	140.5	1852	0.09905	0.13483	0.13640	1.72104	0.09151	824	1016	1457
3	106-150µm nm 1.6A	653	122.9	2778	0.09872	0.12464	0.18134	2.34131	0.09364	1074	1225	1501
4	74-106µm nm 1.6A	387	79.1	3704	0.09861	0.12368	0.19640	2.56648	0.09477	1156	1291	1523

Granite 77015 Ödeborg

1	44-74µm nm 0.9-1.2A	1004	135.1	199	0.15847	0.45473	0.11267	1.37166	0.08829	688	876	1389
2	74-106µm nm 0.9-1.2A	841	123.4	260	0.14190	0.41463	0.12322	1.49871	0.08821	749	930	1387
3	44-74µm nm 1.0A white	783	124.9	270	0.14265	0.38923	0.13600	0.17041	0.09088	822	1010	1444
4	74-106µm nm 1.0A clear	713	120.6	324	0.13412	0.35087	0.14615	1.83474	0.09105	879	1058	1448

Granodiorite 76267 Uddevalla

1	106-150μm nm 1.7A mixt	198	51.4	3333	0.10037	0.20621	0.23388	3.10169	0.09618	1355	1433	1551
2	74-106μm nm 1.7A mixt	183	48.0	1887	0.10303	0.21086	0.23669	3.12262	0.09568	1370	1438	1562
3	44-74μm nm 1.7A mixt	267	71.3	260	0.14967	0.32677	0.23921	3.17931	0.09639	1383	1452	1555
4	106-150μm nm 1.7A white	195	52.3	2941	0.10125	0.20568	0.24137	3.21503	0.09660	1394	1461	1560
5	>150μm nm 1.0A white	176	48.4	4348	0.09921	0.20371	0.24702	3.27083	0.09603	1423	1474	1548
6	>150μm nm 1.0A mixt	160	44.3	2778	0.10184	0.22159	0.24611	3.28856	0.09691	1418	1478	1566
7	106-150μm nm 1.7A clear	132	39.5	909	0.11279	0.25326	0.26450	3.55619	0.09751	1513	1540	1577

Granite 76278 Åkerskog

1	44-74μm nm 1.3A	453	109.1	452	0.12830	0.22770	0.22359	3.01299	0.09773	1301	1411	1581
2	74-106μm nm 1.3A	387	97.9	435	0.13062	0.23132	0.23456	3.19481	0.09878	1358	1456	1601
3	106-150μm nm 1.3A	378	103.2	521	0.12741	0.22621	0.25083	3.48954	0.10090	1443	1525	1641
4	>150μm nm 1.3A	351	97.0	295	0.14633	0.26773	0.25575	3.51585	0.00997	1468	1531	1619

Tonalite 79022 Rönnäng

1	>150μm nm 1.0A	531	108.7	2632	0.10117	0.10553	0.20026	2.64967	0.09596	1177	1315	1547
2	106-150μm nm 1.0A	447	96.8	4762	0.09911	0.09811	0.21219	2.81268	0.09614	1241	1359	1550
3	74-106μm nm 1.0A	449	104.7	5264	0.09956	0.10579	0.22677	3.02904	0.09688	1318	1415	1565
4	45-74μm nm 1.0A	315	79.4	3704	0.10298	0.16203	0.23411	3.20269	0.09922	1356	1458	1610

nm = nonmagnetic fraction

m = magnetic fraction

INTERPRETATION OF THE ISOTOPIC ANALYSES

Preliminary calculations of ages according to the episodic loss model indicate that in several cases this simple, one-stage model cannot be applied. This conclusion is strengthened by comparisons with the previously published Rb-Sr whole-rock ages of these rocks. The analysed zircons have suffered the complex polygenetic evolution of southwestern Sweden and the interpretation of their isotopic data is therefore not straightforward. The zircon samples have been attributed to three subdivisions, each representing a particular model for the interpretation of the isotopic data.

Model I. — The results of the isotopic analyses of zircon fractions separated from the Hästefjorden granite were plotted in the concordia diagram of Fig. 12. The Rb-Sr whole rock age of the Hästefjorden granite is 1 215 ±15 Ma (lσ), (Welin and Gorbatschev 1976a). This age is also marked on the concordia curve. However, the distribution of the zircon fractions in the concordia diagram does not allow the calculation of a primary crystallization age common to all the fractions.

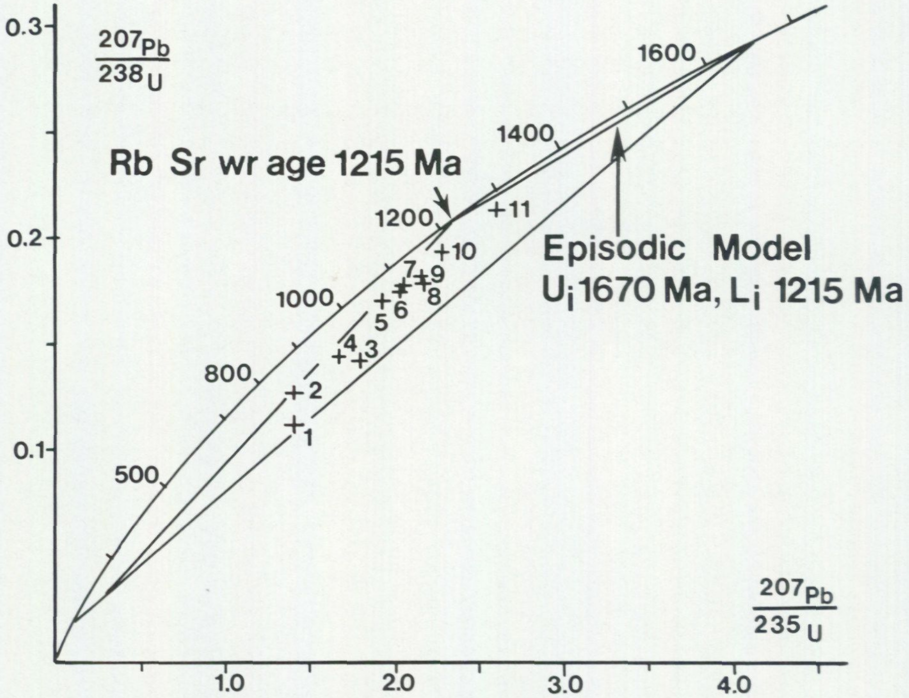

Fig. 12. Concordia plot of zircons from the Hästefjorden granite.

There exist no relationships between magnetic properties, grain sizes or uranium contents which could make an interpretation possible. The microscopic investigations (p. 10) show that a large number, possibly most of the zircons have cores of older zircon (Fig. 2).

To explain the distribution of the isotopic analyses in the concordia diagram (Fig. 12), a line was drawn to illustrate an episodic loss of lead at 1 215 Ma from 1 670 Ma old zircons. Another line was drawn from 1 215 Ma to an arbitrarily selected intercept at 200 Ma, which is a common lower intercept in Precambrian zircon dating.

The zircons from the Hästefjorden granite are assumed to consist of a mixture of ≥1 670 Ma old zircons derived from the older bedrock in southwestern Sweden (cf. Table 4) and new shells formed 1 215 Ma ago. The zircon cores have probably suffered lead loss both during the incorporation into the granite magma at about 1 215 Ma and later, together with their new shells, in more recent time. The result of this complex development is that all zircon fractions are distributed within a triangle delimited by the two episodic lead loss lines and a third line indicating a hypothetical lead loss from 1 670 Ma old zircons. This interpretation of the isotopic analyses is fully supported by the geology of the Hästefjorden granite (Welin and Gorbatschev 1976a) and the associated Ursand granite (Gorbatschev and Welin 1975) massifs.

Model II. — A feature common to all zircons of this category is that their isotopic data points do not plot along regression lines within the analytical errors. Zircons from samples 76256 Varberg, 76266 Grästorp and 77017 Åmål (metavolcanic) have been referred to model II.

The largest scatter of the analytical points in the concordia diagrams is shown by the zircons of the Varberg charnockite (Fig. 13). As described above (p. 10), the zircons of this rock mostly consist of fragments of large crystals which belong to the prismatic, primary magmatic type. No microscopic observations of features (e.g. cores) indicating a prehistory could be detected.

A two-stage model has been applied to explain the development of the discordancy of the Varberg zircons. Such a model does not allow the calculation of an original age, and it is therefore tentatively assumed that the Rb-Sr whole rock age of 1 420 Ma represents the crystallization of the magma as well as that of the zircons (Welin and Gorbatschev 1978b). The charnockite had subsequently been affected by the 900—1 000 Ma old metamorphic event, which is assumed to have caused an episodic loss of lead from the zircons. In more recent time, new lead losses may have occurred. The two-stage loss of lead must have affected the zircons to various degrees, depending e.g. on grain size and physical and chemical properties. A linear array of the analytical points in the concordia diagram cannot

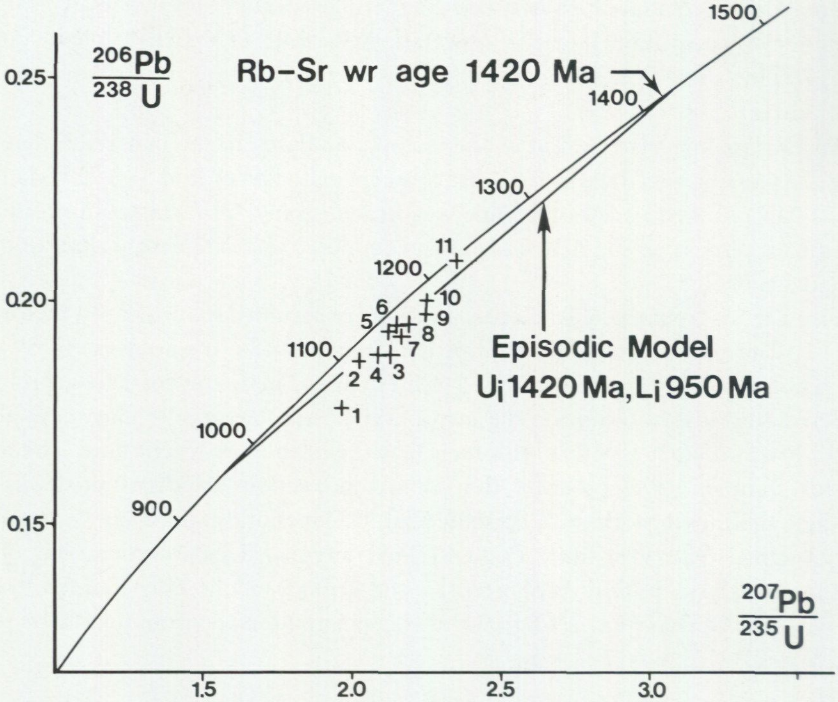

Fig. 13. Concordia plot of zircons from the Varberg charnockite.

therefore be expected. Three zircon fractions, all of them nonmagnetic and representing the largest grain sizes, fall on an episodic lead-loss line intersecting the concordia at 1 420 and 950 Ma. The most magnetic and smallest fractions appear to have been particularly affected by the late episodes of lead loss. They have the most discordant ages. It must be noted that the Rb-Sr whole rock system has not been affected by the metamorphic event 900—1 000 Ma ago. Possibly, episodic loss of lead from zircons can occur under metamophic conditions which have not disturbed the Rb-Sr whole rock system.

A similar two-stage model has been applied in the interpretation of the isotope analyses of zircons separated from another sample of this category (76266 Grästorp). From the lower intercept with the concordia curve, which represents assumed lead losses during the 950 Ma old metamorphic episode, a line has been drawn through the data point representing the least discordant zircon (Fig. 14). The upper intercepts then represent the maximum age of the zircons according to this particular episodic lead loss model. The assumed maximum age of the zircons from sample 76266 Grästorp is 1 670 Ma, which is slightly lower than the Rb-Sr age of the rock (Welin and Gorbatschev 1976c).

To evaluate the geological significance of the maximum age, it is necessary to

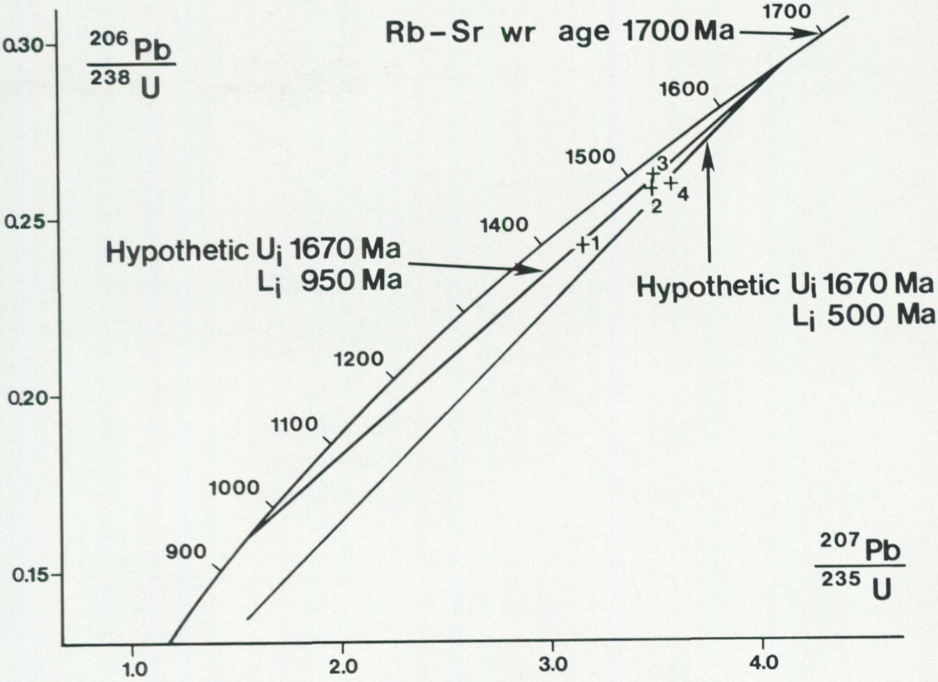

Fig. 14. Concordia plot of zircons from the Grästorp granodiorite.

consider the recrystallization of the zircons in terms of the metamorphic and structural development of the Grästorp granitoid. The zircons from this rock belong to the morphologically complex, semi-ellipsoidal type (Figs. 6 and 7). However, it is unlikely that the suggested recrystallization was connected with the 950 Ma metamorphic event. The reason is that the Grästorp granitoid is foliated and in a stage of migmatization resulting in the formation of leucosome veins. Approximately 1 200 Ma ago, the rock had been intruded by younger granites (Gorbatschev and Welin 1975). These later granites contain prismatic, well developed zircon crystals of a primary, magmatic type. The recrystallization of the zircons of the Grästorp granitoid must therefore have occurred earlier than 1 200 Ma ago. In fact, our understanding of the tectonic development of southwestern Sweden indicates an intense metamorphic and deformational event before the intrusion of the Lane and Ödeborg granites approximately 1 540 Ma ago (cf p. 4). A lead loss from the zircons caused by metamorphic recrystallization at this early stage, which is close in time to the age as dated by the Rb-Sr method, would naturally require an explanation more elaborate than the two-stage model applied here.

The interpretation of the age of the remaining sample of this category, the

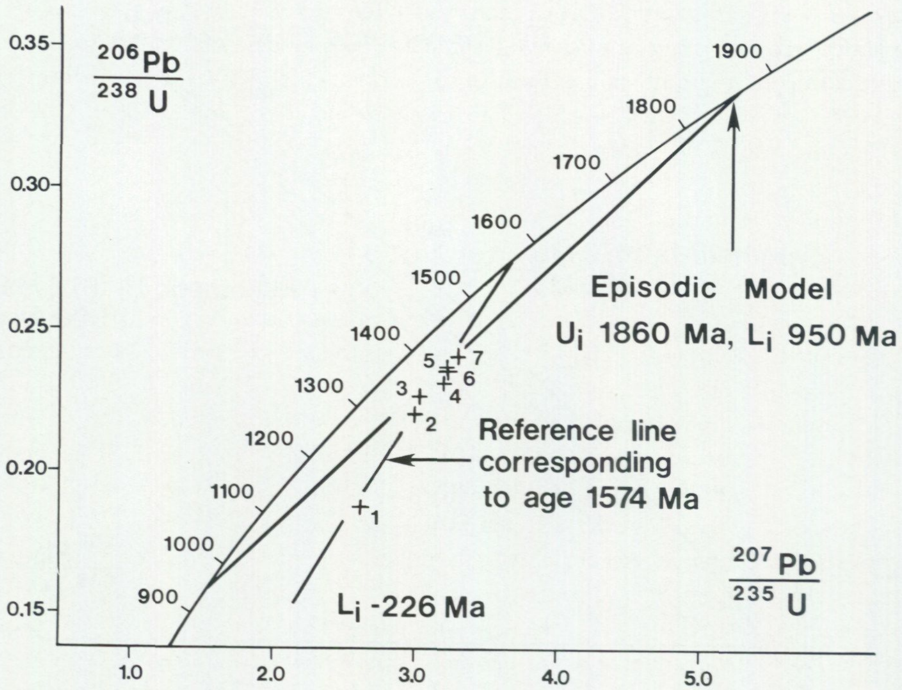

Fig. 15. Concordia plot of zircons from the Åmål metavolcanic rock.

zircons from the Åmål metavolcanic rock (77017), is also subject to considerable uncertainty (Fig. 15). If a hypothetical, two-stage model is used, a maximum age of 1 860 Ma can be calculated in a way similar to the interpretation of the Grästorp zircons. Geological evidence on the validity of this maximum age is difficult to produce. It may, however, be noted that the Åmål supracrustal rocks contain fragments of coarse-grained, foliated augen-gneiss (Gorbatschev 1979). The augen-gneiss xenoliths may be hypothetically correlated with gneissic granitoids in the eastern part of southwestern Sweden. At Munkfors, these rocks have a zircon age of 1 777 Ma (Welin and Kähr 1980). If the suggested correlation is valid, 1 777 Ma must be a maximum age of the Åmål metavolcanic rock.

A regression line through the analytical data of the Åmål metalvolcanic zircons has an upper intercept with the concordia curve at 1 574 Ma. Considering the fact that the Rb-Sr whole rock age of the intrusive Åmål granite is 1 684 ±44 Ma (1σ), the intercept at 1 574 Ma cannot represent the primary crystallization of the zircons (Welin and Gorbatschev 1978d). As described above (p. 11), the zircons are strongly recrystallized (Figs. 8, 9A and 9B). It may therefore be tempting to correlate the recrystallization with the age given by the upper intercept age at 1 574 Ma.

Model III. — To this interpretative model we refer zircons with ages that can be calculated according to a one-stage, episodic lead loss model. Within the limits of analytical error, the data points form linear arrays which have lower concordia intercepts between 90 and 500 Ma. This category includes samples 79019 Lane, 77015 Ödeborg, 76267 Uddevalla, 77018 Åmål, 76278 Åkerskog, and 79022 Rönnäng.

The zircons from the Lane and Ödeborg granites form well developed, prismatic crystals of a magmatic type (Figs. 4 and 5). The upper concordia intercepts of the discordia lines are at 1 535 Ma and 1 553 Ma, respectively (Figs. 16 and 17). The Rb-Sr whole rock age of the Lane granite is, however, 1 430 ±27 Ma (Welin and Gorbatschev 1978a). The difference in comparison to the zircon age is larger than the sum of calculated errors. In the Svecokarelian province of the Baltic Shield, the Rb-Sr whole rock ages usually are 40—80 Ma lower than the zircon ages of the corresponding rocks (Welin et al. 1980b, 1981b). It is conceivable that within the framework of the tectonic evolution of southwestern Sweden, the Rb-Sr whole rock system was locally affected in a way similar to that observed in the Svecokarelian province. Accordingly, the zircon ages of the Lane and Ödeborg granites are interpreted to represent the crystallization age of the rock melt. The Rb-Sr whole rock age then represents a subsequent closure of the Rb-Sr isotopic system that cannot be related to any specific geological event.

For the Uddevalla, Åmål, Rönnäng, and Åkerskog zircons the ages calculated according to the episodic loss model are 1 587 ±18 Ma (1σ), 1 616 ±12 Ma (1σ), 1 658 ±34 Ma (1σ), and 1 675 ±28 Ma (1σ), respectively (Figs. 18, 19, 20, and 21).

The zircons from the Uddevalla and Åmål granodiorites are of the semi-ellipsoidal morphological type (Figs. 10 and 11). Geological evidence refers both the Uddevalla and the Åmål granodiorite to the Åmål-I group (Welin and Gorbatschev 1976b). It is therefore probable that metamorphic recrystallization of the zircons has occurred in close association with the intrusion of the host rock in analogy to the previously suggested recrystallization of the Grästorp zircons.

The zircons from the Rönnäng and Åkerskog localities are sometimes zoned. Prismatic crystals with only slight rounding of the crystal edges are rather frequent. This suggests a lower degree of recrystallization. Consequently, the upper intercept ages of these zircons may closely approach their primary crystallization age. This interpretation is in accordance with the geological observations, which refer both Åkerskog and Rönnäng granitoids to the Åmål-I group (Welin and Gorbatschev 1978c, Gorbatschev 1979). The Rb-Sr whole rock ages of the Uddevalla, Åmål, and Rönnäng granitoids also indicate that these rocks belong to the Åmål-I group.

It is thus likely that the Åmål-I plutonics have all been exposed to an early deformational and metamorphic event, which caused the recrystallization of zircons and a loss of radiogenic lead produced before the recrystallization.

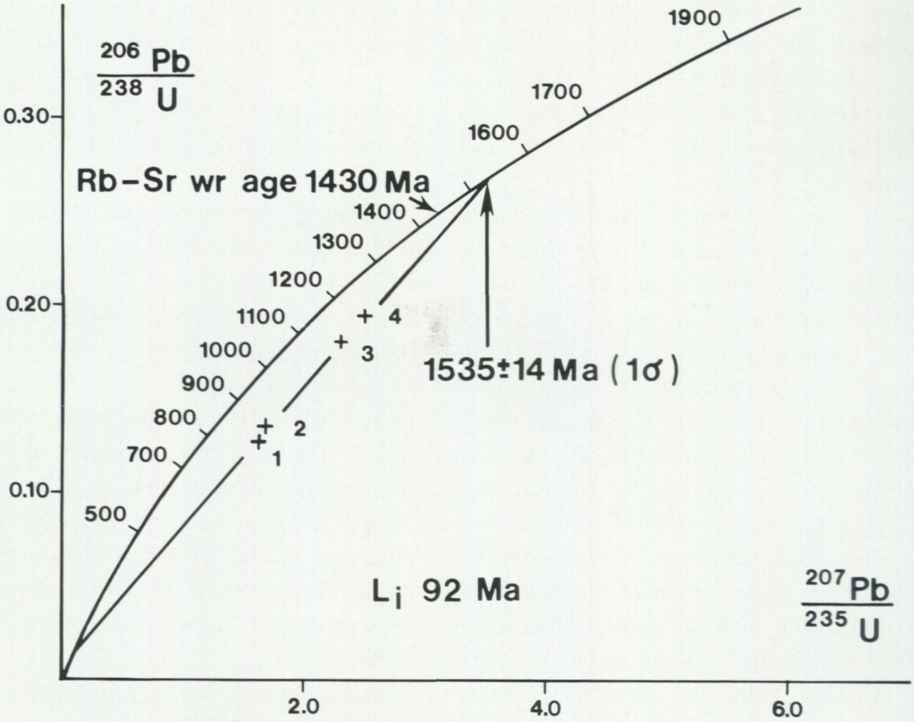

Fig. 16. Concordia plot of zircons from the Lane granite.

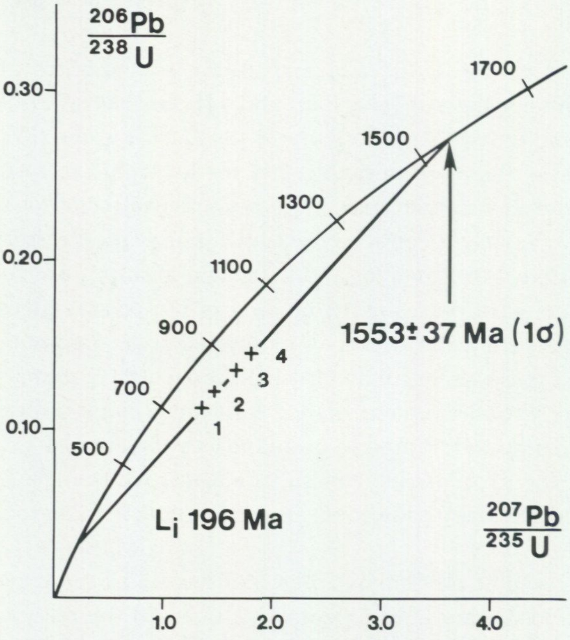

Fig. 17. Concordia plot of zircons from the Ödeborg granite.

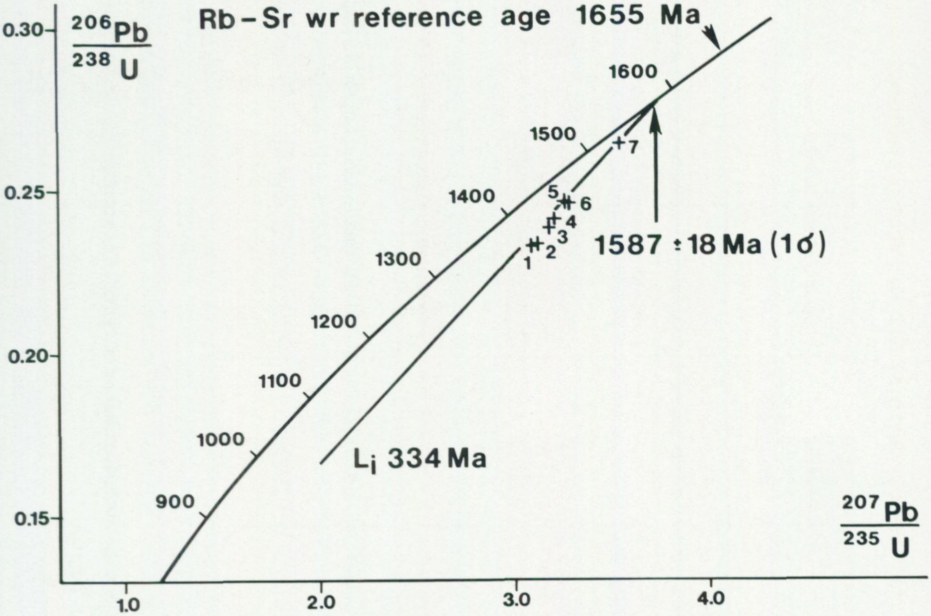

Fig. 18. Concordia plot of zircons from the Uddevalla granodiorite.

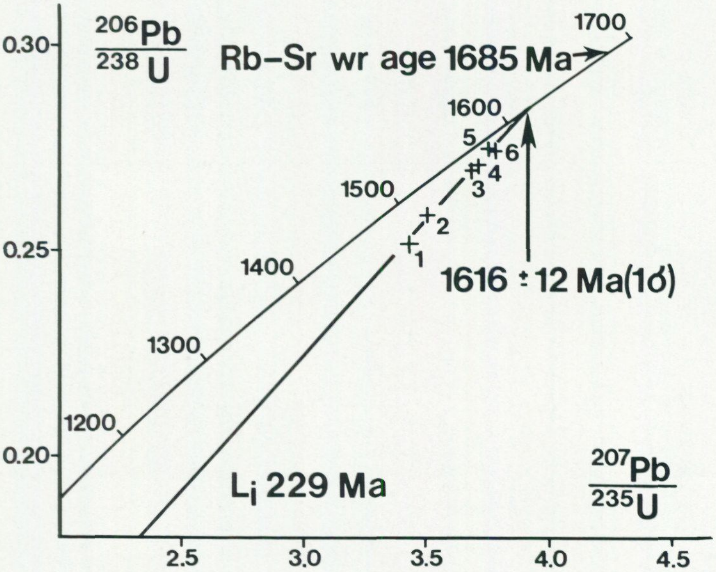

Fig. 19. Concordia plot of zircons from the Åmål granodiorite.

Table 3. Comparison of the present zircon ages with previous radiometric datings. All Rb-Sr ages are based on a ^{87}Rb decay constant $\lambda = 1.42 \times 10^{-11} a^{-1}$.

Interpretation	Sampled rocks	U-Pb zircon age Ma	Rb-Sr whole rock Ma	Rb-Sr whole rock -mineral Ma	Sources of Rb-Sr ages
			Errors given as 1 σ		
Model I	Granite, Hästefjorden	meaningless	1215±15	-	Welin and Gorbatschev 1976a
Model II	Charnockite, Varberg	meaningless	1420±25	-	Welin and Gorbatschev 1978b
	Granodiorite, Grästorp	1670 1)	1700±40	-	Welin and Gorbatschev 1976c
	Metavolcanite, Åmål	1574-1860 2)	-	-	
Model III	Granite, Lane	1535±12	1458±12	-	Welin and Gorbatschev 1978a
	Granite, Ödeborg	1553±37	-	-	
	Granodiorite, Uddevalla	1587±18 3)	1655 ref.line	975±30	Welin and Gorbatschev 1976b
	Granodiorite, Åmål	1616±12 3)	1684±44	-	Welin and Gorbatschev 1978d
	Tonalite, Rönnäng	1658±34 3)	1675±55	1010±50	Welin and Gorbatschev 1978c
	Granodiorite tonalite, Åkerskog	1675±28 3)	-	-	

1) Maximum age based on a two-stage model; possibly indicates an age of metamorphic recrystallization

2) Maximum and minimum ages which cannot be related to geological events

3) Due to metamorphic recrystallization of the zircons these ages may be too low

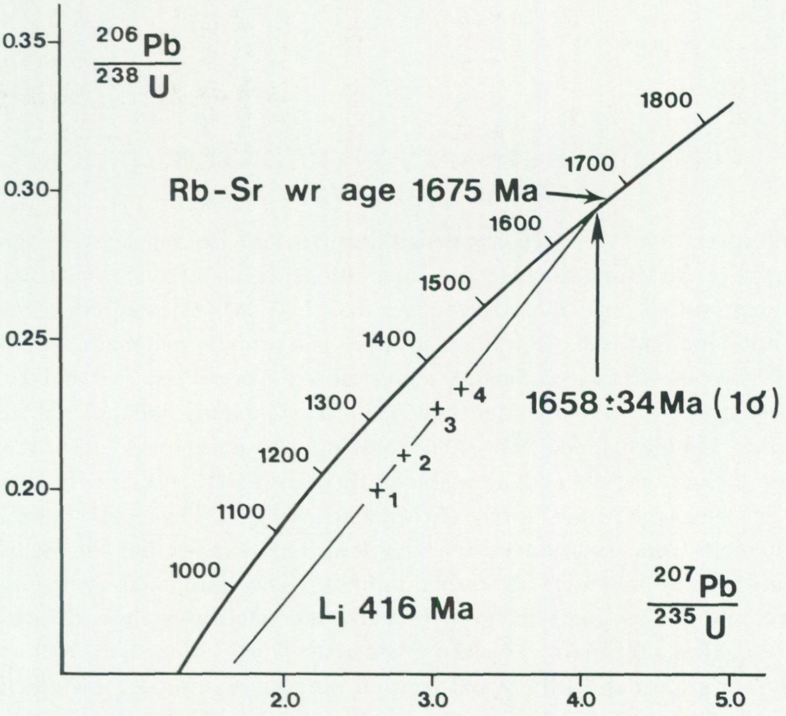

Fig. 20. Concordia plot of zircons from the Rönnäng tonalite.

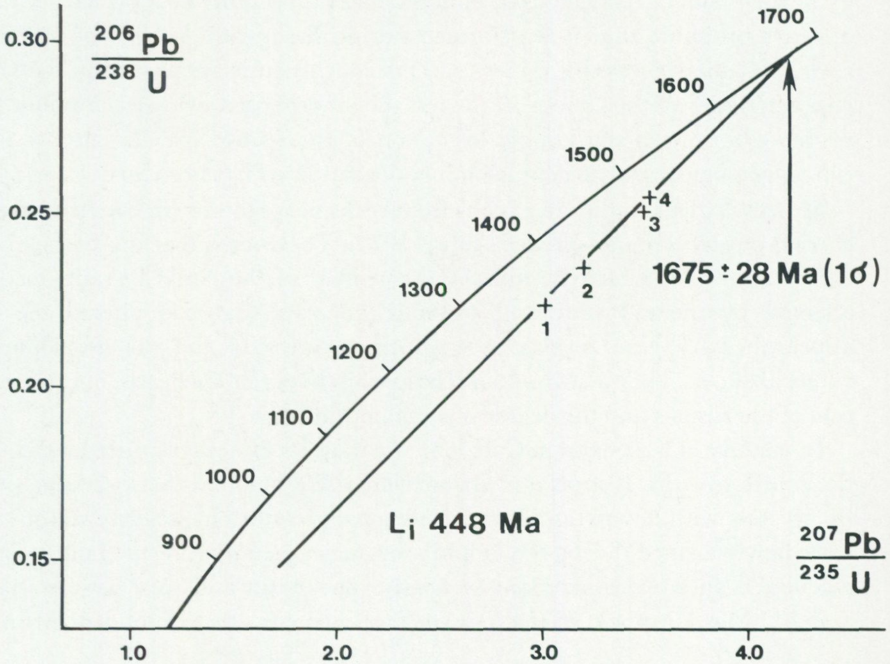

Fig. 21. Concordia plot of zircons from the Åkerskog granodiorite.

CONCLUDING REMARKS ON THE INTERPRETATION OF THE ANALYTICAL DATA

The interpretation of the geological significance of the isotopic analyses has been facilitated by SEM and microscopic observations. It has been shown that zircons from the granitoid rocks that are younger than 1 550 Ma (Hästefjorden, Varberg, Lane, and Ödeborg) have morphologic habits of a primary magmatic type (Figs. 3 and 5). Zircons of semi-ellipsoidal, recrystallized types (Figs. 7, 9 and 11) have only been observed in rocks older than 1 550 Ma (Grästorp, Åmål, Åmål metavolcanic rock, Uddevalla, Åkerskog, and Rönnäng). All these rocks except the Åmål volcanic rock are members of a tonalite-granodiorite-granite suite with low initial $^{87}Sr/^{86}Sr$ ratios (the Åmål-I group of Gorbatschev 1975). The crustal contribution to their melts appears to have been very low. This implies that the inclusion of older zircons in the melts is rather unlikely. The granitoids were originally massive, and in such cases the growth of zircon crystals from the melt preferably forms euhedral, prismatic crystals (Poldervart 1956, Mehnert 1968). Subsequently, all granitoids of the Åmål-I group were more or less strongly deformed and metamorphosed. In this respect they are clearly different from the younger granitoids in southwestern Sweden. Because the semi-ellipsoidal zircon morphology in the foliated, recrystallized plutonic rocks can hardly be a primary feature, it appears probable that it was formed during the metamorphism of the igneous rocks and their accessory minerals. This conclusion is supported by the igneous characteristics of the zircons in the less metamorphosed, younger granitoids. The evidence for the metamorphic formation of the semi-ellipsoidal zircons is thus purely geological and no detailed mineralogical study has been made.

Morphological studies of zircons from rocks in southwestern Sweden have been carried out by Samuelsson and Ahlin (1978). They noted that the zircons in their oldest granitoid, which is probably a member of the Åmål-I group, had been affected by metamorphic and tectonic processes that had altered the initial appearance of these zircons by fracturing, corrosion and the development of external shells. They also found a relationship between the degree of recrystallization of the zircons and the degree of metamorphism.

In a study of zircons from Caledonian paragneisses and granitized sediments in the southern Alps, Köppel and Grünenfelder (1971) found that euhedral, prismatic crystals with few pyramid faces and zonal growths characterize zircons which were newly formed during the amphibolite facies metamorphism of the rocks. The calculated ages are concordant or nearly concordant and vary between 430 Ma and 490 Ma. However, in the paragneisses there also occur rounded zircons with

Table 4. Approximate time-scale of igneous and metamorphic events in southwestern Sweden.

890 Ma	Ensialic processes	Intrusion of youngest granites and associated pegmatites
900-1000 Ma		Regional thermal metamorphism
1220 Ma		Intrusions of alkalic, palingenetic granites (e.g. Hästefjorden)
ca 1300 - 1450 Ma		Little known period of repeated magmatic pulses and migmatization. Folding. Mylonitization
		In the north: amphibolite grade metamorphism intrusions of granites
		In the south: granulite grade metamorphism, intrusion of charnockites (e.g. Varberg)
1540 Ma		Intrusions of granites (e.g. Lane)
1550 Ma		Swarms of dolerite sills and dikes (hyperites)
1600 ? Ma	Crust-generating processes	Folding, metamorphism, migmatization, magmatism
1670 Ma		Intrusion of plutonics of the provisional Åmål-I group
> 1670 Ma		Deposition of oldest supracrustal sequences (e.g. Åmål metavolcanic rocks)

short, subordinate prisms and dominant pyramidal faces. From the mineralogical evidence, Köppel and Grünenfelder concluded that the euhedral crystals had been formed by the recrystallization of older, detrital-type zircons during amphibolite facies metamorphism. The isotopic analyses of both rounded and euhedral crystals plot on the same discordia line. The upper intercept is considered to represent the minimum age of the detrital zircons.

These observations and conclusions definitely support the results of the present investigation. They do not, however, contribute to the discussion of the significance of the upper-intercept ages of the semi-ellipsoidal, recrystallized zircons. The question whether the upper-intercept ages represent the time of primary crystallization of the zircons or a later, metamorphic loss of lead or gain of uranium during the recrystallization of the zircons remains to be definitely settled.

DISCUSSION AND CONCLUSIONS

This study gives an example of the application of SEM and optical microscopic studies of zircon structures and morphologies to the interpretation of multimethod U-Pb, Rb-Sr, and K-Ar datings of rocks in complex, polymetamorphic terrains. The results obtained show that this approach provides a useful test of the validity of various one-stage, two-stage and multistage lead loss models, which can be applied in the interpretation of zircon ages that do not offer straightforward solutions to the problem of crystallization and alteration ages.

A review of the obtained U-Pb zircon ages and previously published Rb-Sr ages of the same rocks is given in Table 3. It is evident that there are large divergencies between the results of the two dating methods. This is a feature common to all rocks of southwestern Sweden.

The most probable estimated ages of each of the dated rock groups are summarized in Table 4, which also shows the results of published radiometric datings in southwestern Sweden and provides a general geochronological framework.

The following are particularly important, specific, regional conclusions of the datings:

1. None of the datings provides evidence of the existence of an Archaean or Early Proterozoic, "Pregothian" core in southwestern Sweden.
2. The previously inferred massive formation of mantle-related tonalitic-granodioritic plutonic rocks at about 1 650 ±50 Ma ago (Gorbatschev and Welin 1980) is wholly confirmed by the present study. These rocks appear to form the backbone of newly generated continental crust in vast areas of southwestern Scandinavia. Their presence argues against a successive, microsegmental growth of this part of the Baltic Shield. A critical survey of all presently available age data offers as yet no basis for the division of these rocks into various chronological subgroups.
3. The crust-generating orogenic process was terminated about 1 550 Ma ago. The subsequent evolution was essentially ensialic.
4. Old zircons suggesting basement remobilization or remelting are present in granites crystallized about 1 200 Ma ago. This confirms the importance of sialic crust in the genesis of these rocks.

The polymetamorphic character of southwestern Sweden is reconfirmed and specified by the reported datings.

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