X:4. ISOTOPIC AGES FROM THE SØR-RONDANE MOUNTAINS, DRONNING MAUD LAND

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Introduction

The geological investigation of the Sør-Rondane mountains (Prinsesse Ragnhild Kyst; lat. 72° S., long. 20° to 30° E.) was included in the programme of the three Expéditions Antarctiques Belges, 1958–60.

Numerous rock specimens have been collected, and their geochemical and petrographical study is being undertaken by various institutions.

We present here the results of age measurements carried out on 19 samples, representing the main rock types in this region.

Most of the samples were collected from the eastern part of the Sør-Rondane mountains by E. Picciotto and J. Giot on a 1 000 km dog-hauled sledge journey during the 1958 Expédition Antarctique Belge (led by G. de Gerlache).

The granite specimen GB was provided by F. Bastin and the syenite 21c by T. Van Autenboer.

Due to technical difficulties in the collection and transportation of the rocks, the sampling and measurement programmes, are far from being as complete as they could be. This is particularly true for zircon and total rock determinations, where the required amount of source rock is of the order of several tens of kilograms. Such determinations could only be carried out in a few cases.

Some of the results given in this paper have been published previously (DEUTSCH and others [1961]; PASTEELS and DEUTSCH [1963]). A more detailed account of this work will appear in the reports of the Expédition Antarctique Belge, 1957–58.

Geology

The geological and petrological description of the Sør-Rondane mountains is dealt with in another paper (VAN AUTENBOER, MICHOT and PICCIOTTO [1964]) and other accounts have been published elsewhere (PICCIOTTO and others [1960]; MICHOT [1962, 1963]).

The main features required for a further discussion of our results are repeated here.

The Sør-Rondane mountain range is composed exclusively of crystalline rocks, in which two complexes – a gneissic and an intrusive complex – can be distinguished.

1. *The gneissic complex* is composed of gneisses of various structures and compositions. Intercalations of basic rocks and calcareous layers are present. Quartzite beds and graphite-bearing schists are also present. The gneissic complex was subjected to strong migmatization, resulting in various facies. It may be considered as a sedimentary sequence which has undergone regional metamorphism in the upper catazone, followed by mesozonal retromorphism.
2. *The intrusive complex* is composed of igneous rocks (granite, diorite, syenite) forming homogeneous masses with typically intrusive character. These intrusive massifs are occasionally cross-cut by veins and dykes of various types: aplites, granites and pegmatites, and basic rocks. According to the field evidence, this second complex is clearly younger than the gneissic one.

The succession of geological events is as follows:

1. Deposition of a vast sedimentary complex under geosynclinal conditions.
2. Folding and metamorphism in the upper catazone, accompanied by strong migmatization.
3. Intrusions of masses of granite, diorite and syenite.
4. Intrusion of veins and dykes cutting across the intrusive bodies.

This order is a relative one and the intervals of time separating these different phases may vary considerably.

As this region is composed exclusively of crystalline rocks, only radio-active dating methods are likely to give information on the geological age.

Experimental Procedure

Geochronological studies of crystalline basement complexes have shown the necessity of comparing the results obtained by different dating methods applied to various minerals of each rock (see TILTON [1961]).

We have applied, where possible, the Sr/Rb method on separated minerals and on the total rock, and the Pb/U method on separated zircons. Furthermore, we also report here results of A/K total rock measurements carried out in Leningrad and kindly communicated to us by Professor Ravich.

The minerals were separated by the usual

TABLE 1

Ages of minerals and rocks from the Sør-Rondane mountains (Dronning Maud Land). (A/K ages from KRYLOV and RAVICH [unpublished])

Location	Lat. Long.	Sample number	Source rock	Mineral	Method	Age (m.yr.)
Romnaesfjellet	71°27′ S. 23°57′ E.	R1	Porphyroblastic granite of intrusive type	B	Sr/Rb	476±15
		R1a	Porphyroblastic granite of intrusive type	B	Sr/Rb	485±15
				Z	^{207}Pb/^{206}Pb	540±10
					^{207}Pb/^{235}U	518±20
					^{206}Pb/^{238}U	514±20
				WR	A/K	350
		91R	Pegmatite vein in granite	B	Sr/Rb	465±15
Småhausane 1180	71° S. 25° E.	S12	Quartz-diorite	B	Sr/Rb	460±15
				WR	A/K	475
		S18	Diorite	B	Sr/Rb	460±15
		S17	Fine-grained granite vein in diorite	B	Sr/Rb	501±15
					Sr/Rb	488±15
Nordtoppen 1100	71°27′ S. 25°17′ E.	S9a	Gneiss xenolith in diorite	B	Sr/Rb	476±15
		S9b		B	Sr/Rb	481±15
				Z	^{207}Pb/^{206}Pb	550±150
					^{207}Pb/^{235}U	555±55
					^{206}Pb/^{238}U	555±20
		S96	Gneiss xenolith in diorite	B	Sr/Rb	495±15
Nordtoppen 950	71°26′ S. 25°20′ E.	S20a	Granitic vein in diorite	B	Sr/Rb	463±15
				Z	^{207}Pb/^{206}Pb	500±30
					^{207}Pb/^{235}U	508±20
					^{206}Pb/^{238}U	510±20
				WR	A/K	380
Gunnestadbreen	72° S. 24° E.	GB	Granite of intrusive type	B	Sr/Rb	474±15
				B+H	Sr/Rb	472±15
				F	Sr/Rb	480±160
				Z	^{207}Pb/^{206}Pb	575±10
					^{207}Pb/^{235}U	524±20
					^{206}Pb/^{238}U	512±20
				WR	A/K	350

TABLE 1 (continued)

Location	Lat. Long.	Sample number	Source rock	Mineral	Method	Age(m.yr.)
Austkampane	72° S. 25° E.	K16	Muscovite-biotite-corundum-gneiss	B	Sr/Rb	492±15
				M	Sr/Rb	499±15
					Sr/Rb	519±15
Strandrudfjellet	72° S. 25° E.	T7	Migmatitic gneiss	B	Sr/Rb	457±15
		T4	Fine-grained microcline-granite (anatectic ?)	B	Sr/Rb	483±15
				F	Sr/Rb	460±90
				WR	Sr/Rb	488, 548, 464, 503 } 500±50
Bautaen	72° S. 26° E.	A3	Fine-grained microcline-granite (anatectic ?)	B	Sr/Rb	497±15
					Sr/Rb	506±15
				F	Sr/Rb	475±60
					Sr/Rb	478±60
				WR	Sr/Rb	553, 650, 585 } 593±60
Gunnar Isachsenfjellet	72° S. 26° E.	G13	Coarse pegmatite	B	Sr/Rb	493±15
		G6	Migmatitic gneiss	B	Sr/Rb	517±15
				WR	A/K	440
Trillingane	71°50′ S. 27°49′ E.	Tr7	Amphibole- and biotite-gneiss	B	Sr/Rb	473±15
		Tr12	Leucocratic pegmatite	B	Sr/Rb	476±15
Lunckeryggen	72°00′ S. 24°40′ E.	21c	Syenite	B	Sr/Rb	488±15

Location: The geographical names refer to the map of the Sør-Rondane published by the Norsk Polarinstitutt (1957). The coordinates are given in detail when known; in the other cases, they are rounded to the nearest degree.
Mineral: B = biotite; M = muscovite; F = feldspar; WR = whole rock; Z = zircon; H = hornblende.
Method: $\lambda\ ^{87}Rb = 1.39 \times 10^{-11}$ yr.$^{-1}$;
$\lambda\ ^{238}U = 1.54 \times 10^{-10}$ yr.$^{-1}$; $\lambda^{235}U = 9.72 \times 10^{-10}$ yr.$^{-1}$.
$\lambda_e\ ^{40}K = 5.85 \times 10^{-11}$ yr.$^{-1}$; $\lambda_\beta{}^{40}K = 4.80 \times 10^{-10}$ yr.$^{-1}$.

methods: shaking table, heavy liquids and magnetic separator. The rock samples appeared fresh and weighed roughly 1 kg. Zircons were obtained from specimens weighing 20 to 50 kg (except in the case of S9).

Isotopic dilution methods were used for the determination of rubidium, strontium, lead and uranium, as described by ALDRICH and others [1956] and TILTON and others [1957].

The isotopic ratios were measured with a 33 cm radius Nier-type mass spectrometer equipped with an electron multiplier and a single-filament solid sample source.

The precision of the Sr/Rb ages depends essentially on the ratio of the common strontium content to the radiogenic strontium in the sample. The reproducibility of the age was of the order of ±3 per cent for all analysed biotites and from 10 to 20 per cent for the feldspars and total rocks.

The analysed zircons were pre-washed with hot concentrated nitric acid for 1 hr., then rinsed carefully with triple distilled water.

The validity of the Pb/U procedure has been verified many times by duplicating the analyses and by adding the stable isotope tracer either before or after the borax fusion of the zircons. A check on the standard zircon of Pacoima (SILVER and others [1963]) was carried out.

The precision of the $^{207}Pb/^{206}Pb$ age depends mainly on the correction for common lead. The contamination level measured in our laboratory was of the order of 0.5 γ of lead in a 0.3 to 0.5 g sample of zircon. The isotopic composition of this contaminating lead appears to be similar to a "normal modern" lead of composition: 1/18.6/15.8/38.9 (CHOW and PATTERSON [1959]).

For sample S20a the common lead amount is significantly higher than the contamination level; it most probably originates from the sample itself. In this case, an assumption must be made on the composition of the common lead; the following $^{207}Pb/^{206}Pb$ ages are obtained when using alternatively for correction:

a "normal modern" lead, 485 m.yr.;

a 500 m.yr. "model age" lead with the composition 1/18.1/15.6/38.0, 511 m.yr.

The average of these two values is reported in table 1. The uncertainties of the 207/206 ages given in this table represent twice the standard deviation of the measured isotopic ratios. In the case of sample S20a, an additional uncertainty of 10 m.yr. is taken into account, due to the composition of the common lead.

For the 206/238 and 207/235 ages, the uncertainty reported takes into account the experimental error in the measurement of the 207/206 ratio (almost negligible), as well as the analytical errors in the determination of the Pb/U ratio (of the order of 4 per cent).

Results

The results are given in table 1 and fig. 1 and a short description of the samples is given in the appendix. The ages obtained by the various methods will be discussed first.

A/K AGES ON TOTAL ROCK

These ages range from 350 to 475 m.yr., with the exception of S12, and they are lower than those obtained by other methods. The discrepancies, ranging from 0 to 30 per cent, are probably due to argon losses by diffusion and would not correspond to any definite geological event. The mineral most sensitive to these losses is known to be potassium feldspar; biotite has a higher retention of argon. The observed discrepancies are consistent with this pattern. Indeed, the only rock displaying an A/K age not lower than the Sr/Rb biotite age is the diorite S12, which contains (modal composition) 5.5 per cent potassium feldspar and 16 per cent biotite, whereas the granite R1, showing a marked discrepancy between these two ages, contains 60 per cent feldspar and 3.6 per cent biotite.

Sr/Rb AGES

It is well established that, under metamorphic

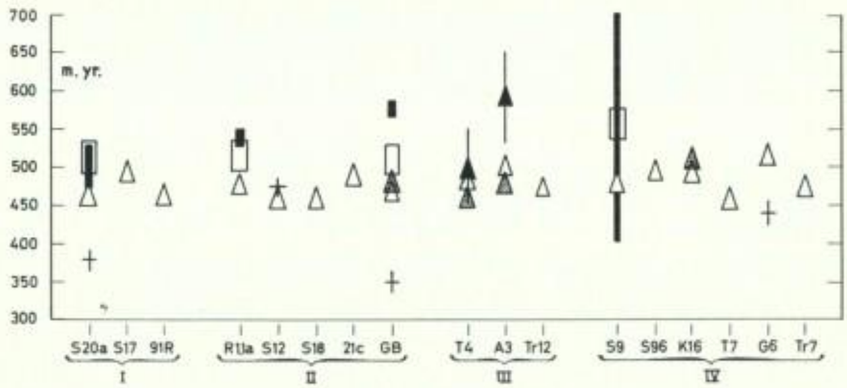

Fig. 1. Isotopic ages on minerals and rocks from the Sør-Rondane mountains.

+ A/K on total rock (RAVICH, KRYLOV).
△ Sr/Rb on biotite.
▲ Sr/Rb on muscovite or feldspar.
▲ Sr/Rb on total rock.
□ 206/238 on zircon.
■ 207/206 on zircon.

I: dykes and veins in intrusive complex.
II: intrusive complex.
III and IV: gneissic complex.

Experimental errors are given by the vertical lengths of the symbols.

action, minerals may lose their radiogenic strontium, whereas a total rock sample may remain a closed system for rubidium and strontium (ALLSOPP [1961]; COMPSTON and JEFFERY [1961]; GAST [1961]; NICOLAYSEN [1961]; SCHREINER [1958]; HURLEY and others [1963]). Among the potassium minerals, biotite loses its strontium most easily, but muscovite and feldspar appear to be more resistant.

Separated minerals

Sr/Rb ages of the biotites range from 460 to 510 m.yr., the mean being 480 m.yr.; all the biotites, whatever the source rock, yield the same age. The significance of this 480 m.yr. Sr/Rb age will be discussed later.

There are only a few measurements on other minerals; muscovites are scarce and potassium feldspars are generally perthitic and too rich in common strontium. The Sr/Rb ages on feldspar are affected by a large experimental error, and they are concordant with the biotite ages within the limits of this error. The muscovite age of K16 is in good agreement with the age of the biotite from the same rock.

Total rock

Measurements could only be carried out on two small samples of granitic migmatite (A3, T4). As their radiogenic strontium 87 content is low, knowing the exact isotopic composition of the common strontium incorporated in the rock at the time of crystallization becomes important.

The common strontium composition was measured on the plagioclase of sample A3. A small correction was made for the rubidium content, assuming an age of 500 m.yr.

The $^{87}Sr/^{86}Sr$ ratio was found to be 0.709 ± 0.004, in agreement with the ratio found in most granitoid rocks from the Basement Complex (HURLEY and others [1963]). Using this value, the two total rock ages are found to be 500 ± 50 m.yr. for T4 and 593 ± 60 m.yr. for A3.

The two rocks belong to the same type and are most probably of the same age. The differentiation of this type of granite would thus have taken place 550 ± 50 m.yr. ago, assuming that these two samples have remained closed systems for rubidium and strontium.

Pb/U AGES ON ZIRCONS

Pb/U ages on zircons could be measured on only 3 granitic rocks (S20a, R1a, GB) from the intrusive complex, and on one gneiss (S9). This, the only sufficiently large sample of the gneissic complex, is unfortunately not very representative as it is a xenolith in the Småhausane diorite body.

The results are as follows:

S20a: the 3 ratios 206/238, 207/235, 207/206 yield concordant ages of 505 ± 25 m.yr.

R1a: the 3 ages are concordant within the limits of error. The zircon age probably lies between 515 and 540 m.yr. It may be slightly older, however, for a small real discordance is not excluded (cf. GB).

S9: the 207/206 age is affected by a large error due to the small size of the sample available. The age of this zircon should lie between roughly 500 and 700 m.yr. In order to be any older, it would have had to have lost more than 75 per cent of its lead 500 m.yr. ago. There is thus no evidence that this zircon is older than the other two.

GB: the 3 ages are slightly discordant, displaying the following pattern: $t\ 206/238 < t\ 207/235 < t\ 207/206$.

The following processes may be involved and may explain the discordance:

(a) Radon loss: in such a case, the true age will be given by the 207/235 ratio, i.e. 520 ± 20 m.yr.
(b) Lead loss continuous or episodic. In this case, the zircon age would be higher than the 207/206 age. If a continuous loss under conditions similar to the cases described by TILTON [1961] is assumed, the real age would be close to 600 m.yr.

An example of important episodic loss would be the loss of 50 per cent of lead, 300 or 400 m.yr. ago. In this case, the true age would then be greater than 700 m.yr. As there is no detectable metamorphic activity younger than 480 m.yr., such a process appears to be improbable here.

(c) Incorporation of older zircons from gneiss (incorporation of radiogenic lead). In such a case, if no lead loss is assumed, the real age would be less than the 206/238 age, i.e. 512 ± 20 m.yr. Such an explanation for the observed discordance does not seem applicable as the zircons of the gneiss sample S9 are not significantly older than 600 m.yr. In conclusion, the zircon age of granite GB most probably lies between 500 and 600 m.yr.

Conclusions

Beginning with the younger event, the samples measured may be classified as follows:

TABLE 2

Method	Veins	Intrusive complex	Gneiss and migmatites
Sr/Rb (biotite)	474 ± 10(3)	472 ± 7(5)	486 ± 5 (9)
Sr/Rb (muscovite)			510 ± 15 (1)
Sr/Rb (feldspar)		480 ± 160(1)	470 ± 60 (2)
Sr/Rb (total rock)			550 ± 50 (2)
Pb/U (zircon)	505 ± 25(1)	510 to 540(2) or slightly older	between 520 and 700 (1)

1. Veins cutting the intrusive complex: S17, S20a, 91R.
2. Intrusive complex: R1a, S12, S18, 21c, GB (?).
3. Gneiss and migmatites: T4, A3, Tr12, S9, S96, K16, T7, G6, Tr7.

The distribution of the ages in each group is given in table 2 (the number of samples is shown in brackets).

The following conclusions may be reached:

The *Sr/Rb ages of the biotite* are systematically younger by an amount of 50 to 80 m.yr. than the total rock Sr/Rb ages or the zircon ages. Their close grouping around 480 m.yr. may indicate an event of regional importance, representing a late phase of the same cycle.

This type of discordance has been frequently reported but at the present state of knowledge it is not possible to define its geological meaning.

In the present case, one could consider relating it to the mesozonal retromorphism as observed in thin section.

Some authors (JÄGER [1962]; HURLEY and others [1961]) have related this discordance to the time interval between the crystallization of the rock and its uplift into a superficial zone, where strontium diffusion becomes negligible.

Other mechanisms may also be involved; KULP and ENGELS [1963] have shown that at room temperature biotite may lose strontium by a simple exchange with aqueous solutions.

The emplacement of the *intrusive complex* and its associated veins took place roughly 530 m.yr. ago, and certainly not before 500 m.yr. The granite GB, the origin and localization of which are poorly defined, may be older.

In the *gneissic complex*, there is no evidence for an age higher than 550 to 600 m.yr. even from the zircons from S9 or from the total rock samples A3 and T4. These two rocks are products of the migmatization of the gneissic complex, this process itself being related to the regional metamorphism.

According to these data, the metamorphism of the gneisses and the associated migmatization would be approximately 550 m.yr. old. The two complexes then appear as two more or less contemporaneous aspects of the same geological event.

Their succession as seen in the field would correspond to two episodes of the same tectonic-magmatic cycle. This cycle, according to the geological time-scales, would have taken place during the Middle or Lower Cambrian, and not during the Precambrian era.

As a final statement, it can be said that, although the age of the magmatic activity appears to be well established at around 530 m.yr., attributing a similar age to the regional metamorphism is based on little evidence: one zircon age and two total rock Sr/Rb ages on small samples. It would have to be confirmed by a larger number of measurements on more satisfactory samples than the 3 analysed already.

Comparison with Neighbouring Regions

As the western continuation of the Sør-Rondane mountains, an important range appears between long. 5° and 20° E.; its geology resembles that of the Sør-Rondane (Ravich and others [1962]). The Soviet authors have published A/K ages on rocks from the Wohlthatmassivet and the "Schirmacher Oasis" (Ravich and Krylov [1960]). They have obtained ages ranging from 385 to 465 m.yr. Taking into account argon losses and new unpublished Sr/Rb ages, these rocks may be related to the same geological cycle as that of the Sør-Rondane.

In the eastern region, charnockitic and granitic gneisses are found near the Japanese base Syowa (Nicolaysen and others [1961]). Sr/Rb ages on four biotites range from 500 to 530 m.yr.; an euxenite from a pegmatite associated with these gneisses yields concordant isotopic Pb/U ages of 470±15 m.yr. (Saito and others [1961]).

These gneisses may also be related to the same cycle as that of the Sør-Rondane. However, a systematic difference, outside the limits of error, appears between the biotite ages of these two regions.

A more detailed comparison of the two regions could yield information on the significance of the Sr/Rb ages of biotite.

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Appendix

LOCATION AND SHORT DESCRIPTION OF THE SAMPLES

For a more detailed description see MICHOT [1962, 1963], PICCIOTTO and others [1960], VAN AUTENBOER and others [1964], and the reports of the 1957–58 Expédition Antarctique Belge which are in the press.

S17: *Granite dyke in the Småhausane gabbro-diorite*; from top of nunatak 1180 ("D2"); intrusive dyke 3 to 4 m wide, cutting the gabbro-diorite, and composed of a homogeneous fine-grained pink granite.

S20a: *Granite dyke in the Småhausane gabbro-diorite*; from top of nunatak Nordtoppen 950; intrusive dyke identical with S17.

91R: *Coarse pegmatite in the Romnaesfjellet granite*; from top of Romnaesfjellet nunatak; large flakes of biotite up to 5 cm, taken from a coarse pegmatite vein, cutting the Romnaesfjellet granite.

R1: *Romnaesfjellet granite*; large block from the western wall of Romnaesfjellet nunatak; coarse-grained porphyroblastic red granite; contains phenocrysts of orthoclase up to 7 cm long, set in a matrix composed of quartz, biotite, hornblende and oligoclase.

S12: *Småhausane gabbro-diorite*; from nunatak 1180 ("D2") in the Småhausane group; quartz-biotite-diorite; average grain-size 3 to 5 mm. The rock is composed of plagioclase (30–40 per cent An) set in a matrix of biotite and amphibole. Quartz and potassium feldspar are rare. Accessories are allanite, apatite, zircon and opaque minerals.

S18: *Småhausane gabbro-diorite*; from nunatak "Solveig" in the Småhausane group; same rock as S12, with a more gabbroic facies.

21c: *Syenite*; from Lunckeryggen, between peak 2380 and peak 2750; coarse-grained homogeneous dark syenite (collected by T. Van Autenboer).

GB: *Coarse-grained granite*; large block up to 50 kg, obviously erratic, found near Romnaesfjellet. It is likely to have come from Gunnestadbreen; coarse-grained white granite slightly orientated (collected by F. Bastin).

T4: *Fine-grained pink granite* (*granite des Aiguilles*); from eastern spur of Strandrudfjellet; this sample was taken from a small granitic body (20 to 50 m) displaying intrusive characters into the gneiss series. These granitic masses are frequently found in the Birger Bergersenfjellet area and are considered to be the result of the individualization of granitic material mobilized by the migmatization. The structure is homogeneous on a small scale but shows nebulitic structures when seen in the field. Microscopically, these granites were found by J. Michot to be identical with the granitic lenses or layers in the gneisses. They are composed of quartz, microcline, plagioclase (15 per cent An) and biotite (scarce). The average grain-size of the rock is 2–3 mm.

A3: *Fine-grained pink granite*; from the eastern wall of Birger Bergersenfjellet, in the great cirque south of Bautaen ("Cirque des Aiguilles"); the sample is a fallen block originating most probably from the granitic mass forming the sharp peaks surrounding the cirque; the same rock and same interpretation as for sample T4.

Tr12: *Concordant pegmatite in migmatitic gneiss*; from the western spur of Trillingane 2240; coarse-grained migmatitic gneiss showing an alternation of diorite and pegmatitic layers. The sample is taken in a pegmatitic layer.

S9: *Gneiss xenolith in the Småhausane gabbro-diorite*; from the southern wall of nunatak Nordtoppen 1100; xenolith, 2 to 3 m in size, with well-defined contacts in the gabbro-diorite. Banded gneiss, the sample was taken in a granitic lens.

S96: *Biotitic segregation in S9.*

K16: *Banded gneiss*; from Austkampane, in the cirque south of peak 1760. Banded gneiss containing biotite, muscovite and corundum. This gneiss contains intercalations of coarse-grained marble in lenses or layers 1 to 5 m size.

T7: *Migmatitic gneiss*; from the eastern spur of Strandrudfjellet; fine-grained biotite-gneiss containing elongated lenses composed of quartz and feldspar.

G6: *Migmatitic gneiss*; from the northern wall of Gunnar Isachsenfjellet; fine-grained, granitic migmatite-gneiss with intense micro-folding.

Tr7: *Dioritic gneiss-migmatite*; from the eastern spur of Trillingane 2240; dioritic migmatite-gneiss composed of plagioclase, amphibole, biotite and quartz (rare) surrounding eyes and lenses composed of quartz and feldspar.

G13: *Coarse pegmatite*; from the northern wall of Gunnar Isachsenfjellet; fallen block; coarse pegmatite with biotite flakes up to 5 cm.