

# CONTACT METAMORPHISM AROUND THE INNSET MASSIF\*

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Different primary chemical compositions of the metasediments on either side of the Innset massif possibly explains the development of different mineral assemblages in the contact zones south-east and north-west of the intrusion. Near the south-eastern contact, a zone of spotted (cordierite-andalusite) argillites has developed outside the inner contact zone of equigranular hornfels. The temperature distribution around the intrusion is discussed in order to explain textural differences between the inner zone of equigranular hornfels and the outer zone of spotted argillites. The extents of the contact zones and the minerals present are in agreement with the calculated temperature distribution around the intrusion. The age of the Innset massif and the surrounding contact aureoles is discussed in relation to the major deformation episodes and the regional metamorphism of the area.

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During an investigation of the Støren group in the western Trondheim Region in summer 1970, my attention was drawn to certain spotted green schists immediately east of Innset. Some samples were collected to check whether the spots represented accretionary lapilli as described by Moore & Peck (1962) among others. Microscopic investigations, however, revealed that such an origin for the spots was improbable.

Elliston's (1963, 1968) hypothesis on 'clay cloth rocks' from the Warramunga geosyncline, Australia, seemed a far more likely explanation for the spotted rocks at Innset.

During the summer of 1971, I therefore combined my investigations of the lavas east of Innset with a more detailed mapping and sampling of the spotted rocks.

The Innset massif is situated some 100 km south of Trondheim, between Innset and Oppdal, in the western part of the Trondheim Region. The eastern part of the massif is cut by the Oslo–Trondheim railway line and by two main roads (E-6 and E-3), so it is readily accessible.

In 1824 C. F. Naumann gave the first known description of the Innset massif. As early as 1850, B. M. Keilhau was aware of a zone of 'hornsteinen' around the intrusion. Goldschmidt (1915) mentions the contact zone (p. 37), and it is shown on his map of metamorphism (Tafel II), but he gives no description of the contact metamorphism.

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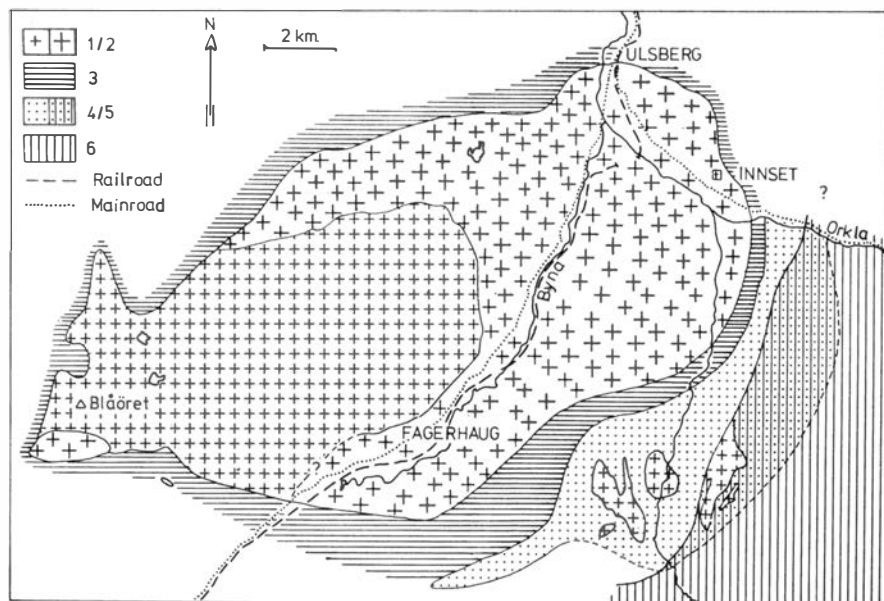


Fig. 1. Map of the Innset massif and the surrounding contact aureoles. Divisions inside the massif are mainly after Goldschmidt (1916). 1. Trondhjemite and trondhjemitic part of the Innset massif. 2. Intermediate to mafic parts of the Innset massif. 3. Inner zone of equigranular hornfelses. 4. Zone of spotted argillites. 5. Zone of spotted argillites overprinted by the regional metamorphic garnet zone. 6. Regional metamorphism only, Barrovian-type almandine-amphibolite facies.

The most thorough description of the Innset massif has been given by Goldschmidt (1916). According to him it represents a complicated differentiated intrusion, ranging from norite to quartz biotite diorite (the opdalite-trondhjemite type rock series). He reports that the intermediate and basic members of the rock series are concentrated in the eastern parts of the massif, while the western parts are trondhjemitic, except for the extreme south-western tip, which again is more basic. This rough division fits well with my brief observations.

### Geological setting

Geological investigations (Rohr-Torp 1972) in the Oppdal-Innset area indicate that the Innset massif is situated within the Krokstad sediments of Lower to Middle Ordovician age, except for the extreme western side, which partly borders on the older volcanic Støren group. In the main, the Krokstad sediments formed as a result of an erosion of the basic volcanics of the Støren group. They consist of alternating green metagreywackes, conglomerates, sandstones and siltstones.

Intrusive breccias and apophyses of the opdalite-trondhjemite rocks along the contacts show clearly the true intrusive character of the Innset massif into the Krokstad sediments.

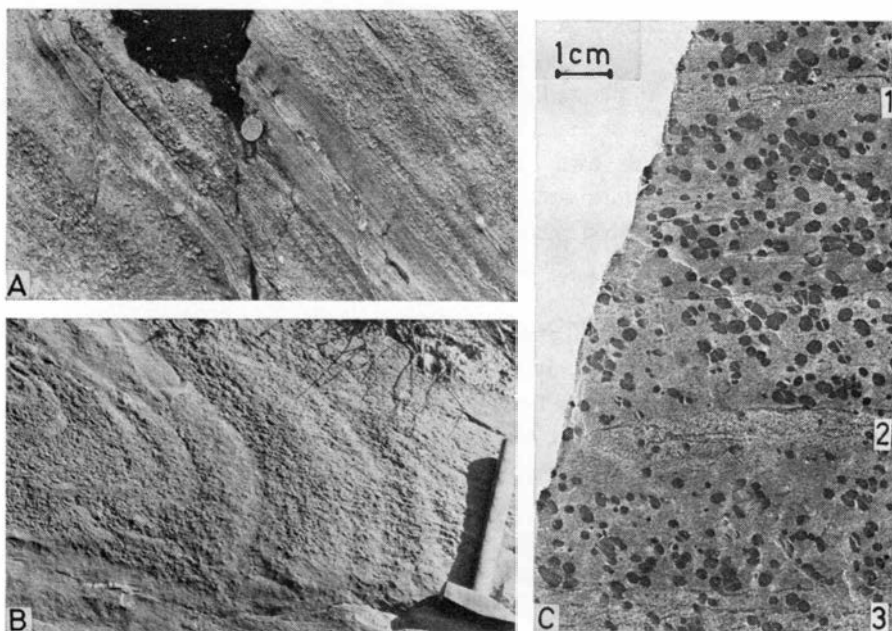


Fig. 2. A, B. Spotted argillites alternating with more sandy, unspotted beds. Road cuts east of Innset. C. Polished hand specimen from the same area; note small amount of spots within the graded sandy horizons 1, 2 and 3.

### THE CONTACT AUREOLES

The contact aureoles which surround the Innset massif are shown in Fig. 1. The inner zone (3 in Fig. 1) has the same general appearance all around the massif. It is composed of equigranular, fine to medium-grained hornfelses, and its width varies from 200 m to 2000 m. The appearance of the hornfelses of this zone is much the same as that of the metasediments elsewhere in the area, except that they are often grey instead of green, and foliation is usually weak or even absent altogether. This is the only contact aureole developed around most of the massif, but near the south-eastern contact it is succeeded by an outer zone of spotted argillites (Fig. 1 (4/5)).

Rocks within the spotted aureole are usually slightly deformed, and primary structures are often preserved. The bedding runs nearly parallel to the intrusive contact; the dip is some  $60^\circ$  south-east.

The spots occur in well-defined argillitic layers, interbedded with unspotted sand and greywacke layers 0.5–20 m thick. Within the spotted layers, the same alternation of unspotted sandy horizons and spotted argillitic horizons is seen on a smaller (dm) scale. This is shown in Figs. 2A and 2B, which illustrate spotted beds as seen in road cuts east of Innset (riksveg 3). In Fig. 2B, the distribution of spots accentuates a primary slump structure.

On an even smaller scale (cm), alternation of sandy unspotted and ar-

gillitic spotted material is seen in hand specimen, also within the spotted horizons (Fig. 2C).

When first seen in the sediments some few hundred metres away from the contact, the spots are small, 1–2 mm along the long axis, but rapidly become bigger further away from the intrusion, and soon reach their average size of 3–4 mm (occasionally more than 1 cm along the long axis). For several hundred metres the spots are now frequently seen in the metasediments before they gradually decrease the further they are away from the intrusion.

The spots are shaped like a triaxial ellipsoid; minor axes are approximately equidimensional, while the long axis is some 1.5 times the small axes. On weathered surfaces the spots protrude; on fresh surfaces they are very often covered by a thin, sleek, dark surface composed of biotite. The interior of the spots, however, is pale grey, paler than the matrix of the rock.

The sequence from the intrusive breccia contact of the Innset massif, through the equigranular hornfels and the zone of spotted argillites, is well exposed along riksveg 3, east of Innset.

Further away from the intrusion the road passes into an area of strong rock deformation, regionally metamorphosed in the almandine–amphibolite facies, corresponding to the garnet zone of Goldschmidt (1915). South of the road this zone partly coincides with the eastern part of the aureole of spotted argillites (not clearly seen along the road), thus giving rise to rocks which show characteristic features of both zones (Fig. 1 (5)). The grey argillites of this area are often almandine bearing and strongly deformed; the spots, however, may be well preserved.

## ROCKS OUTSIDE THE CONTACT AUREOLES

Outside the contact zones, the same argillites and metagreywackes are found along with basic lavas and tuffs. If they have ever been affected by contact metamorphism, it is no longer traceable because the mineral assemblages of the albite–epidote–hornfels facies are the same as those of the middle part of the Barrovian type greenschist facies, which is the regional metamorphic facies of most of the rocks outside the contact aureoles. Only the south-eastern part of the area has been exposed to regional metamorphism in the almandine–amphibolite facies, and the strongly deformed rocks of this area show no relics of any contact aureole outside the zone of spotted argillites.

## Microscopic description of the contact rocks

The contact mineral assemblages near the north-western contact of the Innset massif are different from those near the south-eastern contact. The two areas are therefore treated separately.

Table 1. Approximate mineral composition of the different contact metamorphosed rocks around the Innset massif.

	Quartz + Biotite plag.	Amphi- bole	Ortho- amphi- bole	Chlorite Epidote	Cordie- rite	Cordie- rite + anda- lusite	Musco- vite	Garnet	Kyanite	Opaque min.
N.W. CONTACT										
Greywackes										
Argillites										
Greywackes										
Argillites (a)										
Argillites (b)										
Greywackes										
Argillites (a)										
Argillites (b)										
Argillites										
S.E. CONTACT										
Greywackes										
Argillites										
Greywackes										
Argillites (a)										
Argillites (b)										
Argillites										

Present in all samples

Present in some samples

Present (mainly) as pseudomorphs

Inner zone of even-grained hornfels

Inner zone of even-grained hornfels

Zone of spotted argillites

Zone of spotted argillites overprinted by the garnet zone

The dominant rock types within the entire contact area are alternating argillites (originally siltstones) and lithic greywackes. Within each aureole (Fig. 1), the contact metamorphic mineral assemblages of the argillites and those of the lithic greywackes are described.

The dominant accessory minerals of the investigated samples are apatite, tourmaline, sphene and zircon.

## NORTH-WESTERN SIDE

### *The zone of even-grained hornfelses (Fig. 1 (3))*

The hornfelses adjacent to the contact are hypidioblastic equigranular (0.08–0.4 mm, usually 0.15 mm). Foliation, if present, is seen as preferred orientation of flaky minerals, while primary bedding is usually obliterated.

*Lithic greywackes.* – Four samples were investigated (Table 1); sericite, not listed in the table, is present as an alteration product in plagioclase.

U-stage determinations showed that two different amphiboles are present in all samples. (1). Common hornblende: X: Yellow, Y: Olive green, Z: Bluish green.  $Z:c = 21\text{--}24^\circ$ ,  $2V_X = 56\text{--}61^\circ$ . (2). Actinolite: X = Y: Pale yellow, Z: Pale green,  $Z:c = 16\text{--}18^\circ$ ,  $2V_X = 72\text{--}81^\circ$ .

*Argillites.* – Five samples were investigated (Table 1); sericite, which is present as an alteration product in plagioclase, is not listed in the table.

## SOUTH-EASTERN SIDE

### *The zone of even-grained hornfelses (Fig. 1' (3))*

The grain size and texture are the same as for the hornfelses north-west of the intrusion.

*Lithic greywackes.* – Six samples were investigated (Table 1).

U-stage determinations showed that two different amphiboles are present in all but one sample. (1). Common hornblende (all samples): X: Yellow, greenish yellow, Y: Green, olive green, Z: Bluish green, dark green,  $Z:c = 22\text{--}26^\circ$ ,  $2V_X = 56\text{--}68^\circ$ . (2). Cummingtonite (all but one sample): X = Y: Colourless, Z: Pale greenish yellow, pale greyish yellow,  $Z:c = 12\text{--}14^\circ$ ,  $2V_Z = 77\text{--}81^\circ$ .

*Argillites.* – Three samples were investigated. They can be separated into two groups.

(a) Two samples contain orthoamphibole and cordierite. One of the samples has unaltered cordierite and orthoamphibole, the other shows only pseudomorphs after these minerals. The cordierite pseudomorphs are composed of some 70 % sericite along with minor amounts of quartz, plagioclase, chlorite, epidote and opaque minerals. The grain size and habit of

cordierite (and the pseudomorphs) within this zone, are the same as for plagioclase and quartz. The mineral composition is given in Table 1. The orthoamphibole pseudomorphs are mainly composed of talc and chlorite. U-stage determinations of unaltered orthoamphibole gave: X: Yellow-grey, Y: Brown, Z: Greyish brown,  $Z:c = 0^\circ$ ,  $2V_Z = 76^\circ$ . The orthoamphibole thus seems to be an iron-rich anthophyllite (Deer, Howie & Zussman 1966).

(b) The last sample is strongly altered. Cordierite is not present; pinite pseudomorphs occur in the same way as described above. Pseudomorphs of much the same appearance, but usually somewhat bigger and with a metapoikilitic appearance are also present. They possibly represent pseudomorphs after andalusite (see below). The biotite also suffers from alteration to chlorite. The mineral composition is given in Table 1.

*The zone of spotted argillites (Fig. 1 (4))*

*Lithic greywackes.* – As mentioned, the spotted argillites alternate with unspotted greywackes. These are inequigranular with large clastic grains (0.5–3 mm), mainly of quartzite, keratophyre, quartz and feldspar set in a fine-grained matrix (approx. 0.04 mm). The greywackes show a well-defined foliation of elongated minerals, and sometimes the primary bedding is seen as alternating bands rich and poor in coloured minerals.

Six samples were investigated (Table 1); the plagioclase is completely altered to albite.

U-stage determinations showed that common hornblende (X: Yellow, Y: Green, Z: bluish green,  $Z:c = 19\text{--}23^\circ$ ,  $2V_X = 55\text{--}61^\circ$ ) is the only amphibole present in all but one sample, which also contains actinolite (X = Y: Colourless, Z: Pale greenish yellow,  $Z:c = 17^\circ$ ,  $2V_X = 79^\circ$ ).

*Argillites.* – The spotted argillites have an equigranular matrix (0.02–0.09, usually 0.04 mm) much the same as the matrix of the interbedded, unspotted greywackes. It is composed of roughly equal amounts of anhedral plagioclase and quartz and subhedral biotite (the biotite is variably altered to chlorite, the plagioclase to albite). Epidote and opaque minerals are present in minor amounts. Some of the samples also have pseudomorphs after orthoamphibole. The orientation of platy minerals usually gives a well-defined foliation, not coinciding with the primary bedding, which is sometimes marked by alternating bands rich and poor in coloured minerals.

Some 30 % of the rock volume is occupied by ovoid aggregates (spots). Usually they are some 3.5 mm in cross section, although they can vary from 0.5–13 mm. Depending on the highly variable ratio of sericite to matrix minerals, the spots merge with the matrix in varying degree.

Accurate optical determinations of the minerals within the spots are difficult because of the fine grain size (0.02 mm). An X-ray diffractometer was therefore used as well as a microscope. The spots were found to be composed of some 60 % sericite (varying from 20 to more than 90 %) along with minor amounts of albite, quartz, biotite, chlorite, epidote

and opaque minerals. Tourmaline and apatite may be present in accessory amounts. Vermiculite and illite were also detected.

Usually the spots are smooth and rounded, but occasionally they show six-sided prismatic outlines (Fig. 6F,G), indicating (pp. 20–22) that they represent pseudomorphs after highly poikilitic cordierite porphyroblasts.

Besides the above-described spots, the argillites often also contain spots of a somewhat different type. These are usually less crowded with inclusions of matrix minerals (less poikiloblastic), and their outlines not as vague as is often the case with the former. They have much the same mineral composition as the spots already described, but when showing 'idiomorphic outlines', they form square, often rhombic, prisms (Fig. 6H). In two specimens these square 'spots' are composed of andalusite, which must be the original porphyroblast mineral.

By regarding the spots as originally representing cordierite and andalusite, the spotted argillites can be separated into two groups: (a) Three samples which contain orthoamphibole along with cordierite (Table 1); and (b) 21 samples which contain andalusite along with cordierite (Table 1).

#### SPOTTED ARGILLITES OVERPRINTED BY THE GARNET ZONE (Fig. 1. (5))

*Lithic greywackes from this area are not examined*

*Argillites.* – The argillites from within the garnet zone are so deformed that no primary sedimentary structures can be observed. The spots are usually smeared out, rotated and often broken apart. Five samples were investigated. They contain some 30 % spots; the mineral composition and grain size of spots and matrix are much the same as for the spotted argillites west of the garnet zone, but almandine is often present, and muscovite more often occurs in the matrix (Table 1).

In one sample, the square 'spots' are composed of almost unaltered andalusite. In two others, the pseudomorphs after andalusite, now altered mainly to sericite, contain kyanite. The kyanite forms subhedral grains of different orientation within the pseudomorphs, which themselves have 'idiomorphic, square crystal-outlines'. The kyanite is regarded to have been formed during the younger regional metamorphism (p. 31).

#### Chemical analyses

The minerals present in the spotted argillites, along with the habit of the ovoid spots which sometimes show six-sided prismatic outlines, indicate that these spots represent pseudomorphs after cordierite porphyroblasts as described by Bosma (1964, 1967).

In order to determine the composition, these spots were separated from the matrix by means of a dentist's drill, and analysed by atomic absorption spectrophotometry. Two samples were investigated this way, and parallels



Table 2. Chemical analyses of the contact rocks around the Innset massif. Composition of the spots is compared with cordierite.

	I-14M	I-14B	I-14S	I-16M	I-16B	I-16S	I-11	I	II	III	IV
SiO <sub>2</sub>	55.30	54.70	54.45	57.15	57.20	57.10	67.40	67.35	47.69	52.8	54.0
Al <sub>2</sub> O <sub>3</sub>	17.40	18.45	20.45	17.80	18.50	20.50	11.90	13.40	32.52	22.4	22.7
Fe <sub>2</sub> O <sub>3</sub>		2.53			1.71		2.21	2.23			
FeO		5.96			6.38		4.67	5.37			
Fe <sub>2</sub> O <sub>3</sub> (tot.)	9.70	9.15	8.80	9.40	8.80	8.60	7.40	8.20	8.67	9.4	9.2
MnO	0.10	0.09	0.09	0.10	0.09	0.09	0.10	0.09	0.04	0.08	0.08
MgO	5.75	5.60	5.00	5.30	4.95	4.90	4.40	5.10	7.56	6.3	6.0
CaO	1.90	1.90	1.75	2.15	1.95	1.00	3.65	1.00	0.52	1.4	1.6
Na <sub>2</sub> O	3.90	3.70	2.25	3.50	3.40	2.10	3.25	2.80	0.53	2.8	2.6
K <sub>2</sub> O	3.55	4.20	5.30	3.15	3.75	4.50	1.00	2.00	0.42	2.5	2.2
Ign. loss	1.97	2.25	2.97	1.76	2.35	2.84	1.81	1.53	2.40	2.1	2.0
	99.57	99.38	101.06	100.31	100.28	101.63	100.39	100.87	100.35	99.8	100.4

M = matrix, B = bulk composition, S = spots.

I-14: Spotted argillite.

I-16: Spotted argillite.

I-11: Unspotted greywacke.

I: Greywacke, south-east of Oppdal, 10 km south of the Innset massif.

II: Cordierite, composition taken from Deer, Howie & Zussman (1966).

III:  $\frac{1}{3}$  of cordierite (II) +  $\frac{2}{3}$  of matrix (I-14M).

IV:  $\frac{1}{3}$  of cordierite (II) +  $\frac{2}{3}$  of matrix (I-16M).

were run of spots, matrix and bulk composition from each sample, along with one unspotted greywacke from within the same contact metamorphosed zone, and one greywacke taken approximately 10 km away from the contact zones. The results are given in Table 2.

Even though the proportions of the different minerals vary considerably between spots and matrix, their chemistry shows only minor differences. Because of the relatively imprecise preparation method, the only certain trends which can be taken from Table 2 are higher Al and K and lower Na in the spots than in the matrix.

The chemical composition of the spots does not coincide with any actual minerals. However, the abundance of inclusions of matrix minerals in the spots shows that the original porphyroblasts must have been highly poikilitic. By assuming that the poikiloblasts were originally cordierite, different ratios of matrix to cordierite (composition taken from Deer, Howie & Zussman 1966) can be tested against the spots.

By combining  $\frac{2}{3}$  matrix from the analysed samples with  $\frac{1}{3}$  cordierite (a fairly reasonable figure for the spots as seen in thin section), a composition quite close to the analysed spots is obtained (Table 2). The only really implausible value is given by potassium, a mobile element which probably entered the spots during the pinitization process.

Thin sections of the analysed samples were modally analysed in order to plot in an ACF diagram. The method used, which is based on chemical and mineralogical composition, is described by Winkler (1967). Polished

Table 3. Modal analyses of two spotted argillites (I-14 and I-16) and one unspotted greywacke (I-11).

	I-14	I-16	I-11
Albite/quartz	38.1	44.1	50.2
Amphibole			16.1
Epidote	2.2	1.0	12.4
Biotite	30.1	29.4	7.6
Muscovite/sericite	16.9	12.9	
Chlorite	10.6	10.6	12.9
Apatite	0.1		0.1
Tourmaline		0.1	
Magnetite	0.4	0.4	0.1
Hematite	0.6	0.6	0.2
Pyrite	0.8	0.7	0.3
Chalcopyrite	0.2	0.2	0.1
	100.0	100.0	100.0

sections were made for determination of the opaque minerals. The modal analyses are listed in Table 3, and the ACF plots shown in Fig. 3. By using the diagram for hornblende–hornfels facies (Winkler 1967), one of the spotted samples plots within the andalusite–anorthite–cordierite sub-triangle, the other within the cordierite–anorthite–talc, anthophyllite, cummingtonite sub-triangle, while the unspotted greywacke plots in the sub-triangle containing hornblende, actinolite and tremolite.

The ACF plots thus strongly suggest that the spots are pseudomorphs after cordierite. In a general way the diagram also explains why the interbedded greywackes, in contrast to the spotted argillites, contain common hornblende  $\pm$  actinolite, as the stability field of these amphiboles is separated from the stability field of cordierite by the tie-line between the F corner and anorthite.

It can also be seen from the diagram that small variations in the A value ( $\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$  corrected for feldspar, biotite and muscovite) will give contact-metamorphic argillites containing cordierite along with or without andalusite, as observed in the spotted argillites south-east of the Innset massif.

## Physical conditions during intrusion

### *South-eastern side*

The contact-metamorphic rocks are affected by a later regional metamorphism (discussed later) which has given rise to minerals like chlorite, epidote, etc. These lower grade minerals grew at the expense of earlier higher grade contact minerals, so it is therefore difficult to determine exactly the original mineral assemblages of the different contact-metamorphic rocks previously described. However, the highest grade contact-metamorphic mine-

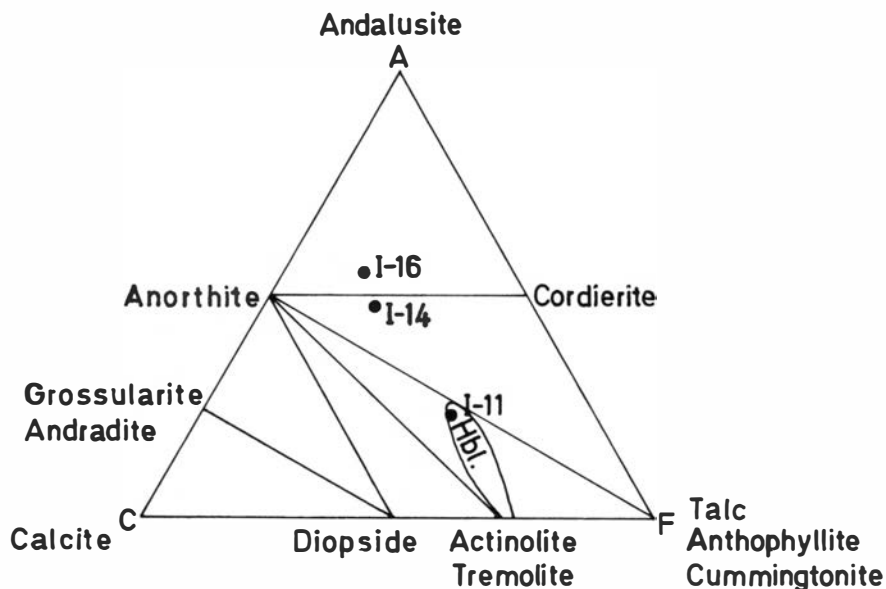


Fig. 3. ACF plots of two spotted argillites (I-14 and I-16) and one unspotted greywacke (I-11).

erals identified within the different zones south-east of the Innset massif are listed below. A universal-stage is used for determination of some of the minerals.

*Inner zone.* – Hornfels (derived from greywacke): Plagioclase (An 50) + quartz + hornblende  $\pm$  cummingtonite.

Hornfels (derived from argillite): Plagioclase (An 50) + quartz + cordierite  $\pm$  andalusite  $\pm$  orthoamphibole.

*Outer zone.* – Unspotted greywackes: Plagioclase (altered to saussuritized albite) + quartz + hornblende  $\pm$  actinolite.

Spotted argillites: Plagioclase (An 28) + quartz + cordierite (pseudomorphs)  $\pm$  andalusite  $\pm$  orthoamphibole.

The meta-argillites all have mineral assemblages typical of contact metamorphism. The amphibole bearing metagreywackes have mineral compositions which in Barrovian-type regional metamorphic rocks would have been accompanied by almandine (Winkler 1967).

According to Hensen & Green (1971), the ratio  $100 \text{ MgO}/(\text{MgO} + \text{FeO})$  (molecular proportions) of the metamorphosed rock is important for the stability range of almandine garnet. For the analysed contact rocks south-east of the Innset massif (Table 2, I-11, I-14 and I-16), this ratio is close to 60, and the experimental data of Hensen & Green (1971, 1972) show

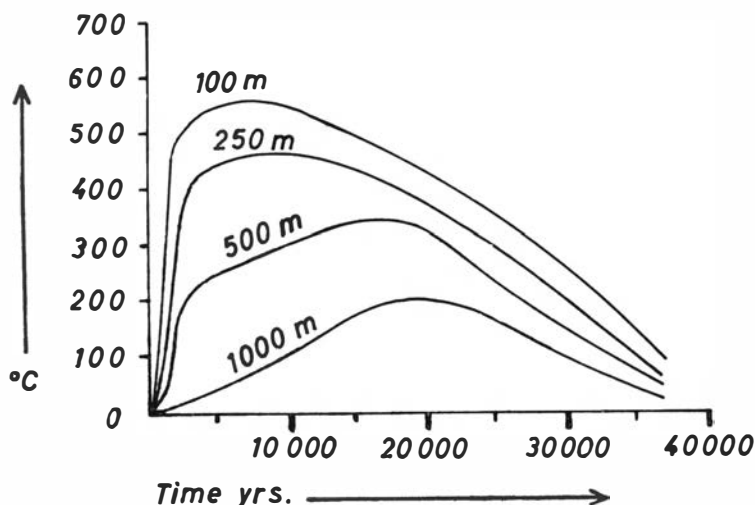


Fig. 4. Conductive heat transfer: Variation of temperature with time for various distances from the contact of an igneous sheet 1000 m thick, after Jaeger (1957).

that almandine garnet will not form in these rocks under conditions of contact metamorphism because the pressure is too low.

Thus, the inner zone of equigranular hornfelses, the spotted argillites and the interbedded unspotted greywackes south-east of the Innset massif, according to their mineral compositions, were all formed under the conditions of the hornblende-hornfels facies. Why then the different development of these three types of contact rocks?

The differences between the cordierite bearing argillites and the amphibole bearing greywackes were explained on p. 22 as a result of differences in bulk chemical composition between the argillites and the greywackes. The textural differences between the cordierite hornfelses and the spotted argillites, however, must have been caused by physical differences during their formation.

Jaeger (1957) has calculated temperature distributions around cooling intrusions by assuming conductive heat transfer. The following general statements are important for the discussion below and are in full agreement with corresponding mathematical analyses performed by Reilly (1958). The further from the contact, the lower the increase in temperature, the later the influence of the intrusion is felt, and the *slower* the temperature rises. This is illustrated in Fig. 4, taken from Spry (1969) after Jaeger's (1957) data.

The formation of cordierite in the contact zones must have started with nucleation, as cordierite could hardly have existed in the original geosynclinal sediments. The formation of a nucleus can only take place after a certain energy barrier is surpassed.

For the inner contact zone, the energy barrier for nucleation of cordierite was rapidly exceeded, as the temperature here was rather abruptly increased

to temperatures appreciably higher than the actual minimum formation temperature for cordierite (pp. 27–28). The result must have been an instantaneous simultaneous nucleation of cordierite at all possible points in the inner contact sediment.

As the energies required for crystal growth are generally less than those for nucleation (Spry 1969), cordierite started to grow on the nuclei as soon as these were formed, without further development of new nuclei. The inner contact sediments therefore grew many rather small cordierite crystals. The prolonged high temperature of this zone also made some of the pre-existing minerals grow, and as a result the texture was generally coarsened. The resulting recrystallized sediments are seen today as equigranular medium-grained hornfels.

The outer zone, in contrast to the inner zone, was exposed to an extremely slow increase in temperature. Actually several thousands of years passed before the maximum temperature was obtained. As the energy barrier for nucleation of cordierite was slowly surpassed, some few nuclei were formed. The lower energies required for crystal growth than for nucleation, as soon as some nuclei were formed, caused cordierite crystals to grow on these existing nuclei while further nucleation ceased. As a result, a porphyroblastic rock developed, containing relatively few, scattered, big cordierite crystals.

The lower maximum temperature as compared to the inner zone, and the limited duration of this elevated temperature (Fig. 4), made only minor crystal growth possible for some of the pre-existing minerals. The matrix of the spotted argillites is therefore markedly finer-grained (0.04 mm) than that of the inner zone of hornfels (0.15 mm).

The reason that cordierite in the outer zone has formed large isolated crystals thus seems to be more a function of difficulty of nucleation than ease of growth.

#### *North-western side*

The highest-grade contact metamorphic minerals preserved north-west of the Innset massif are plagioclase (An 48) + quartz + biotite  $\pm$  hornblende  $\pm$  actinolite. Minerals like cordierite, andalusite, anthophyllite and cumingtonite were not observed.

The mineral assemblages of the contact zone north-west of the massif thus fit the lower to middle part of the Barrovian-type almandine-amphibolite facies (B 2.1 – B 2.2) as well as the hornblende–hornfels facies (Winkler 1967).

Extensive field work in this area has never revealed an outer zone of spotted argillites, although the sediments are the same alternating greywackes, sandstones and siltstones as south-east of the massif. The spotted argillites are so conspicuous that they could hardly have been overlooked. This absence of cordierite north-west of the Innset massif could be explained in two ways.

1. Different pressure and/or temperature on the two sides of the massif during contact metamorphism.

The sediments which surround the Innset massif dip some 60° south-east. As mentioned on p. 31, the massif has taken part in the main deformation of the area so that the original orientation of the intrusion is uncertain.

By assuming that the north-western side of the Innset massif was originally the lower side of the intrusion, calculations based on rock thicknesses show that the load pressure along this contact must have been more than 2000 bars higher than at the south-eastern (upper) contact. This difference in pressure might explain why cordierite was formed only near the upper contact.

From Hensen & Green (1971–1972), however, it is evident that sediments with a composition like the analyzed samples from the south-east side of the Innset massif by low *P* will contain cordierite alone. By increasing *P*, cordierite and almandine garnet will coexist over a comparatively wide pressure range before cordierite becomes unstable with further increasing *P*, and only garnet continues to grow. As cordierite and almandine garnet are both absent near the north-western contact, a higher load pressure at this contact as compared to the south-eastern one, can hardly explain the absence of cordierite north-west of the Innset massif, if the chemistry of the sediments is the same on either side of the intrusion.

2. A general difference in chemical composition of the metasediments on either side of the Innset massif.

The original chemistry of the metasediments south-east of the Innset massif could possibly have been metasomatically altered during intrusion. When comparing the spotted argillites with the unspotted greywackes south-east of the massif, however, the only really anomalous oxide is  $\text{Al}_2\text{O}_3$  (Table 2), and this is among the least mobile of components. It is therefore unlikely that the cordierite–andalusite rocks were formed by metasomatism.

The high contents of FeO and MgO in the metasediments seem to have been caused by their derivation from the basic volcanics of the Støren group. To test this, one sample from the same metasediments taken approximately 10 km south of the contact of the Innset massif was analysed. As seen from Table 2, the FeO and MgO content of this sample is very near that of the spotted argillites, and slightly higher than for the contact greywacke.

Even if the metasediments on either side of the Innset massif, both macroscopically and microscopically, have the same general appearance, the absence of cordierite and almandine near the north-western contact seems to be caused by primary differences in chemistry between the sediments near the south-eastern and the north-western contact. This is also reflected in the different development of the monoclinic amphiboles of the two areas (pp. 18–19).

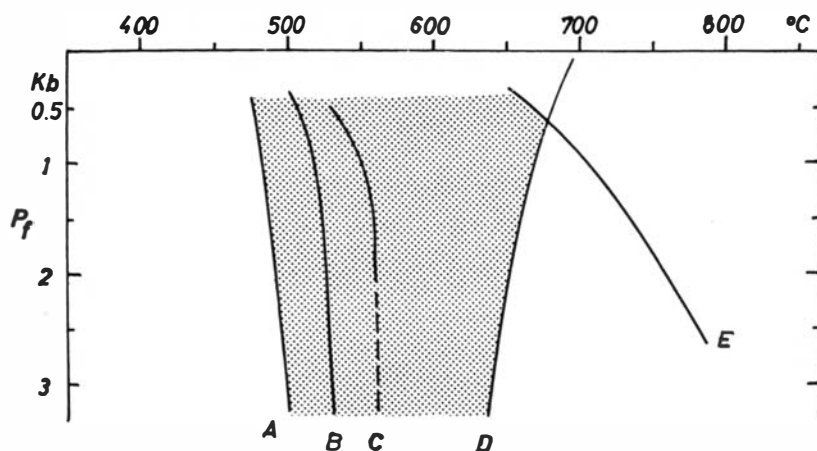


Fig. 5. Dotted area shows the possible pressure/temperature field for formation of the contact rocks south-east of the Innset massif. Curves after Winkler 1967. ( $P_f$  = the pressure of the fluid phase.) Important reactions: A. Pyrophyllite  $\rightleftharpoons$  andalusite + quartz +  $H_2O$ . B. Chlorite + muscovite + quartz  $\rightleftharpoons$  cordierite + biotite +  $Al_2SiO_5$  +  $H_2O$ . C. Al-rich chlorite + quartz  $\rightleftharpoons$  gedrite + cordierite +  $H_2O$  and chlorite + tremolite + quartz  $\rightleftharpoons$  hornblende + anthophyllite +  $H_2O$ . D. Andalusite  $\rightleftharpoons$  sillimanite. E. Formation of orthopyroxene.

The different chemistry possibly reflects alteration with time of the source rocks for the Krokstad sediments, as the sediments near the south-eastern contact are most probably older than those near the north-western contact.

### Pressure and temperature conditions on the south-east side

As already stressed, the minerals of the contact aureoles south-east of the Innset massif indicate hornblende-hornfels facies. Fig. 5, drawn from data given by Winkler (1967), shows the possible pressure/temperature field of formation of these contact rocks. As the inversions orthoamphibole  $\rightleftharpoons$  orthopyroxene and andalusite  $\rightleftharpoons$  sillimanite are never observed around the contact, it is seen from the figure that the maximum temperature by the contact ( $675^\circ\text{C}$ ) is obtained by a pressure of 0.6 kilobar (crossing point of lines D and E in Fig. 5). The minimum temperature at the outer margin of the spotted argillites, defined by formation of andalusite, is somewhat less than  $500^\circ\text{C}$  (line A).

Winkler (1967) refers to Jaeger (1957), who has calculated the temperature in rocks adjacent to intrusions. The calculations are based on the assumption that heating of the country rock is due entirely to conductivity. In general it is concluded that at the immediate contact, the temperature of the country rock is somewhat greater than 60 % of the intrusion temperature with addition of the temperature of the country rock prior to intrusion ( $T_c$ ). At a distance equal to one half of the thickness of the intrusion, the

Table 4. Temperature distribution within the contact zones based on conductive heat transfer (Jaeger 1957), compared with equilibrium temperatures for observed diagnostic mineral reactions. (The outer margin of the spotted argillites is some 4.5 km away from the contact.)

	Intrusion temperature	Temperature at the contact	Temperature 4.5 km from the contact
Acid part	800°C	530°C	320°C
Basic part	1100°C	710°C	420°C
Basic part, based on contact minerals		<675°C	>480°C

temperature is increased only by one third of the intrusion temperature +  $T_c$ .

The thickness of the Innset massif is calculated as roughly 9 km. As mentioned, the intrusion ranges from trondhjemitic (quartz biotite dioritic) to noritic in composition. The acid members are concentrated mainly in the western parts, and the intermediate and basic members in the eastern parts of the massif. The outer zone of spotted argillites is only found south-east of the eastern part of the massif, while the inner zone of equigranular cordierite bearing hornfels continues south-east of the western parts (Fig. 1).

According to Winkler (1967, p. 80) a reasonable intrusion temperature for granites is some 700–800°C, and for gabbroic magma some 1200°C. It is thus possible to calculate the temperatures of the country rocks around the Innset massif by assuming that the western, trondhjemitic parts had an intrusion temperature of approximately 800°C, and the eastern, more basic parts had a mean intrusion temperature of approximately 1100°C. By assuming a pressure of 0.6 kilobar for this south-eastern contact zone, which would give the maximum stability temperature for the presence of ortho-amphibole and andalusite (Fig. 5), and a normal thermal gradient prior to intrusion of 20°C/kilometre (20°C/250 bar), the figures given in Table 4 have been calculated. The table compares the temperatures calculated this way for the immediate contact and the outer margin of the spotted argillites, with the corresponding temperatures estimated from the occurring contact minerals.

As a rough estimation, agreement between the figures is good. The calculated contact temperature, however, is somewhat too high for the basic part (710°C instead of less than 675°C). On the other hand, at a distance of 4.5 km from the contact, at approximately the outer limit of the spotted argillites, the theoretical temperature is somewhat too low, even to form andalusite, e.g. 420°C instead of 480°C. This last error becomes even more pronounced when the younger folding, which has probably effected a shortening of these contact zones, is taken into account.



However, this area is intruded by a number of trondhjemite intrusions, the biggest of which are marked on the map (Fig. 1); these to some extent must have compensated the shortening of the crust caused by folding. If these trondhjemites are more or less contemporaneous with the intrusion of the Innset massif, they have also transmitted heat to the country rocks during the evolution of the contact aureoles.

Another feature which must be taken into account is that the opdalite-trondhjemite rocks nearly always carry primary biotite (Goldschmidt 1916). This mineral, as was also pointed out by Barth (1962), shows that the magma must have had a relatively high water content. Under a pressure of 0.5 kilobar, a granitic melt can contain about 4 % water (Barth 1962, p. 127), which effectively reduces the melting temperature of the magma. The intrusion temperature of the Innset massif may therefore have been somewhat less than the theoretical figures given in Table 4, thus giving a somewhat lower temperature for the formation of the inner zone of contact hornfelses, more in agreement with the observed minerals of this zone.

For the outer parts of the spotted argillites, however, the result may have been the opposite. Hori (1964) has shown that heat transferred outward from a cooling intrusion by magmatic waters – a feature not considered in the calculations of Jaeger (1957) – is significant and that the width of the resultant aureole may thus be greatly increased.

The mineral assemblages as well as the width of the contact aureoles south-east of the Innset massif are thus in good agreement with the theoretically expected figures for temperatures and distribution of heat around an intrusion of this size.

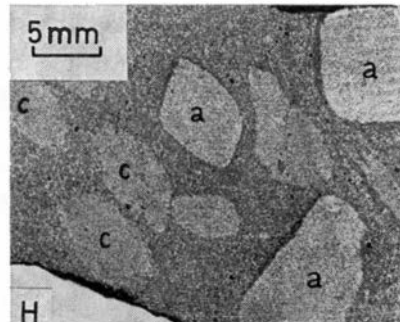
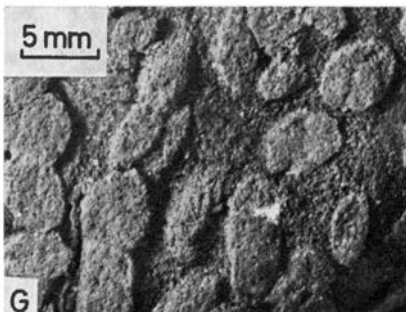
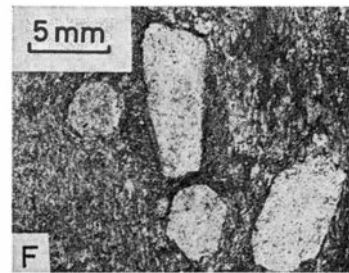
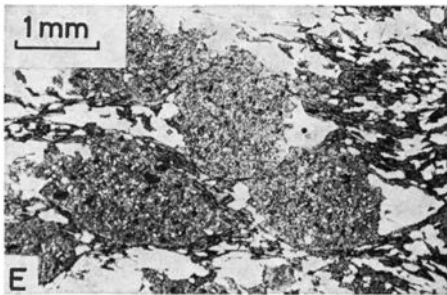
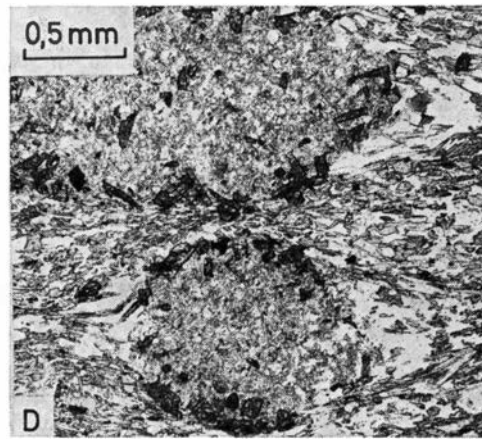
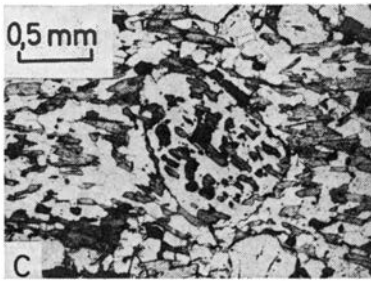
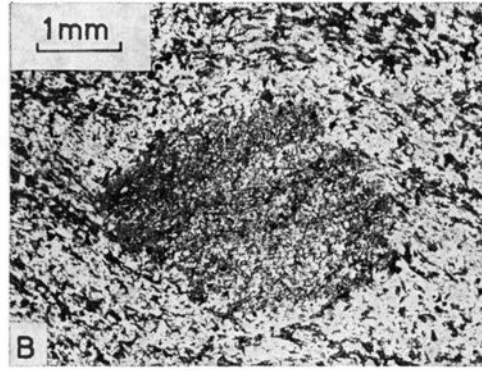
### Intrusion in relation to deformation episodes

Two deformation phases ( $F_1$  and  $F_2$ ) dominate the area. The main structures were formed during the oldest  $F_1$  deformation, which is characterized by mainly north-east trending isoclinal to tight folds, accompanied by a marked axial planar schistosity which is the regional schistosity of the area. The younger  $F_2$  deformation is mostly seen as east-west trending minor folds and crenulations deforming the older  $F_1$  structures.

The following discussion is based on principles given by Zwart (1962).

The  $F_1$  structures which dominate the area are clearly deflected by the Innset massif; the  $F_1$  foliation bends smoothly around the massif, conformable to the major outlines of the intrusion.

On a smaller scale, the same feature is seen in thin sections. As a result of the flattening of the matrix around pre-existing porphyroblasts, the  $F_1$  foliation is deflected around the contact porphyroblast pseudomorphs of the spotted argillites (Fig. 6D,E). Primary bedding, usually not coinciding with the foliation, is sometimes seen to continue through the porphyroblasts (spots), a clear indication of the stationary growth of the porphyroblasts.



This is shown in Fig. 6A, where primary bedding is well preserved, while the  $F_1$  foliation is rather vague.

Post-crystalline rotation of the porphyroblasts (spots) is a common feature, possibly a result of laminar flow connected to the  $F_1$  deformation. Fig. 6B shows a rotated spot linearly intersected by the primary bedding, while Fig. 6C shows a rotated cordierite crystal from the inner zone of equigranular hornfelses.

Flattening of the matrix during  $F_1$  often forms pressure shadows in the plane of the  $F_1$  foliation around the porphyroblasts (spots) (Fig. 6D,E).

The  $F_1$  structures are often defined by the minerals (especially chlorites) formed during the regional metamorphism. The almandine garnets of the eastern area (Fig. 1) show clear signs of synkinematic growth during  $F_1$ . The  $F_1$  foliation to some extent bends around them, but is mostly clearly truncated at the garnet borders (Fig. 7, cf. Zwart 1962, Fig. 1). The kyanite, which in this eastern area sometimes replaces andalusite, was most probably also formed during  $F_1$ .

From what has been said above there is sufficient evidence to postulate that the intrusion of the Innset massif, and consolidation of this body, took place before the main deformation ( $F_1$ ) of the area. The  $F_1$  structures around the massif show that the intrusion must have acted as a relatively rigid and competent body during this deformation episode. This is consistent with observations of the  $F_1$  structures in relation to the minerals formed by contact metamorphism south-east of the intrusion, which show that these minerals are clearly pre- $F_1$ . The spots during  $F_1$  must have been porphyroblasts, not pseudomorphs, as they have acted as competent bodies during the flattening of the matrix around them.

The above statements also support the assumption that the regional metamorphism, mainly in the greenschist facies, but for the eastern area in the almandine-amphibolite facies, took place contemporaneously with the main deformation period  $F_1$ . The later  $F_2$  deformation is possibly responsible for scattered chlorite flakes, which are occasionally observed oriented in an east-west direction.

### Age of intrusion

The Innset massif is clearly younger than the Krokstad sediments which are intersected by the intrusion, that is, younger than Llandeillian. On the other hand, as the Innset massif was already consolidated and the contact aureoles

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Fig. 6. A. Spots linearly intersected by primary bedding. (Thin section.) B. Rotated spot linearly intersected by primary bedding. (Thin section.) C. Rotated cordierite crystal from the inner zone of even grained hornfelses. (Thin section.) D, E. Pressure shadows in the plane of foliation around spots. Note deflection of the foliation around the spots. (Thin section.) F, G. Six-sided 'idiomorphic' spots. (Hand specimen.) H. Square to orthorhombic spots (a) pseudomorphs after andalusite. More vaguely developed spots after poikilitic cordierite (c). (Sawn hand specimen.)

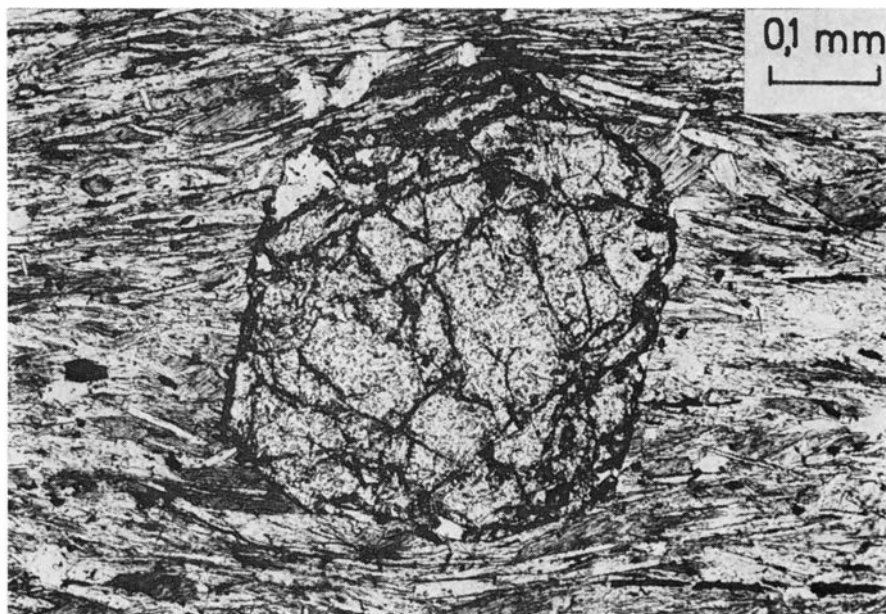


Fig. 7. Synkinematic ( $F_1$ ) garnet from the eastern, more strongly regional metamorphosed area.

developed by the time of the  $F_1$  deformation, the intrusion must have taken place an appreciable period of time before this deformation. As the Devonian deposits at Rørrangen are not affected by  $F_1$ , while the younger beds of the Trondheim region are folded, this deformation period must have taken place towards the end of the Silurian.

The intrusion of the Innset massif thus must have taken place some time between Llandeillian and Upper Silurian, probably some 420–470 million years ago.

This age is not in agreement with the K-Ar determination of 355 million years published by Broch (1964). The K-Ar age probably reflects the latest metamorphism of the area because four different rocks from the Oppdal–Innset area all give ages between 355 and 388 million years, which is certainly much less than the deposition time of the Støren group and the other rocks of the area, except possibly for the metasomatic formation of the augen gneisses.

In a recent paper Birkeland & Nilsen (1971) described contact aureoles around gabbroic intrusions in the eastern part of the Trondheim Region (e.g. the Hyllingen and Øyungen gabbros). They reached a conclusion similar to the present author in that they consider the contact aureoles to have been formed pre- to early syn- $F_1$ .

This means that at least some of the major intrusions of the Trondheim Region are older than most of the minor trondhjemite intrusions of the same area, as these are usually not affected by the  $F_1$  deformation.

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