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Structure, mineralogy, chemistry and economic potential of calcitic marble in the Geitfjellet-Bukkafjellet area, Nord-Trøndelag

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RAPPORT

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Sammendrag:

Forekomstene av kalkspatmarmor i Geitfjellet-Bukkafjellet-området sørvest for Grong i Nord-Trøndelag representerer en sammenfoldet avsetning som hører til bergarter i Sevedekket. Marmoren er en ren og grovkornet kalkspatmarmor med kvarts, muskovitt, flogopitt og tremolitt som de viktigste spormineralene. 14 av 29 prøver fra et område på 400 m x 400 m har CaO-innhold over 55 vekt%. Dette tilsvarer 98 % $CaCO_3$ (kalkspat). I de fleste prøvene er MgO-innholdet høyere enn summen av de andre oksydene (utenom MgO og CaO). Dette betyr at marmoren har en $MgCa(CO_3)_2$-komponent, men siden MgO-løseligheten i kalkspat ser ut til å være omkring 1 % (tilsvarer ca. 4.5 % dolomitt), er fri dolomitt tilstede i bare et fåtall av prøvene. Det totale karbonatinnholdet overstiger 99 % i mer enn to tredjedeler av prøvene og basert på målinger av 6 utvalgte prøver ser det ut til at hvithets-verdien (R 457) overstiger 90 % i halvparten av prøvene. De reneste partiene av marmoren har FMX- og R 457-verdier på henholdsvis 97 % og 95 %.

Bergartsvariasjonene er uregelmessige, og den kompliserte tektonikken reduserer mulighetene for å finne enkle og forutsigbare mønstre. Kontinuerlig prøvetaking i form av kjerneboring er påkrevet i en eventuell videre undersøkelse av det området som er dekket av overflateprøveprofilene. Et område lenger vest i det samme marmorfeltet på 1.5 x 0.5-1.2 km ser lovende ut, og bør undersøkes ved overflateprøvetaking og kjemisk analyse.

Emneord: marmor	industrimineraler	
kalkspat		
dolomitt		fagrapport

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Reidar G. Trønnes

ABSTRACT

The Geitfjellet–Bukkafjellet calcite marble deposit southwest of Grong in Nord-Trøndelag represents a tectonically thickened body within multiphase folded supracrustals belonging to a Seve Nappe equivalent. The accessory silicate mineralogy of the coarse grained marble is dominated by quartz, muscovite, phlogopite, and tremolite. 14 of 29 samples from an area measuring about 400m by 400m have CaO-contents of more than 55 weight %, corresponding to more than 98 % $CaCO_3$. In most of the samples, MgO exceeds the sum of the remaining oxides and is positively correlated with the contents of Si, Al and K, indicating that the $CaMg(CO_3)_2$-component is present. Detailed mineralogical observation and calcite analyses show that the MgO-solubility in calcite in these marbles was about 1 wt%, corresponding to 4.5 wt% dolomite. Free dolomite is therefore present in only about 5 of the 29 samples. The estimated total carbonate content exceeds 99 wt% in 20 of the samples. In the purest calcite marble, the light reflectance values FMX, FMY, FMZ and R457 reach 97, 97, 95 and 95 %, respectively. Based on measurement of a selection of 6 samples and the observed correlation between CaO-content and reflectivity, the FMX- and R457-values are expected to exceed 90 % in about half of the samples.

The petrochemical variation is irregular, and the complex tectonic style of the area reduces the possibility of establising simple and predictible spacial patterns. Continuos sampling in the form of drillcores seems required in the possible further evaluation of the limited area covered by surface samples. At least one other area within the 1.5 by 0.5–1.2 km marble field appears promising, and should be investigated by surface sampling and chemical analysis.

INTRODUCTION

As part of NGU's efforts to compile and evaluate information on Norwegian carbonate resources, a concentrated study of the carbonates in the Nord-Trøndelag and Fosen area was initiated in July 1992. A field evaluation of known carbonate rock units was undertaken in the summer of 1992. During this reconnaissance evaluation, a portion of the calcite marble deposits in the Seve Nappe equivalent (Skjøtingen Nappe), 5–6 km west of Formofoss were recognized as unusually pure. These marble units are shown on the preliminary 1:50 000-scale bedrock map (map sheet Grong, 1823-4) compiled by Roberts (1987) but they have not previously been evaluated with respect to their economic potential. The lack of previous investigations of these mables is probably mainly due to their location at an altitude of about 600 m and with a distance of at least 3 km to the nearest road.

The chemical analyses of two pure samples from the reconnaissance visit indicated about 99% $CaCO_3$, and it was decided to carry out detailed mapping based on a magnified arial photograph (1:5000), combined with surface sampling, and mineralogical and chemical analyses. The field work was carried out during a 4-day period from September 30 to October 3, and the results are presented in this report.

TECTONOSTRATIGRAPHY, STRUCTURE AND METAMORPHISM

The carbonates in the Nord-Trøndelag and Fosen area are confined to three different tectonostratigraphic levels: in both the Seve and the Køli Nappe equivalents of the Upper Allochton and in the Helgeland Nappe Complex of the Uppermost Allochton (Figure 1). The Geitfjellet–Bukkafjellet marble horizons occur in the eastern part of the Seve (Skjøtingen) Nappe about 10 km southwest of Grong. The Seve equivalent nappe units in the Trøndelag area are present as isoclinally folded bands withinin the Vestranden Gneiss Complex (VGC) and as more extensive thrust sheets on the southeastern side of the Møre–Trøndelag Fault zone (MTFZ). These thrust sheets are often in direct contact with the overthrust Køli nappes.

Figure 1 may give the impression that the Seve supracrustals occur in simple downfolded synforms in the basement (Parautochton or Lower Allocthon) of the VGC. As pointed out by Sollie (1989), however, the zones of Seve rocks commonly include smaller scale repetitions of basement gneiss and supracrustals resulting from isoclinal folding. Based on an investigation of the area containing Seve (Skjøtingen Nappe) equivalent supracrustal rocks southwest of Grong, Winge (1989) developed a structural interpretation similar to that of Sollie (1989). Figure 2 shows the distribution of the lithological units along the western margin of map sheet Grong (M711, 1:50000) south of Geitfjellet, and Figure 3 is a simplified schetch map showing the surface pattern of the marble horizons over a somewhat wider area. The two cross sectional profiles in Figure 3 are simplified versions of the figures 6.12 and 6.13 in Winge (1989) and serve as illustrations of the fold pattern. An early isoclinal F2-episode post-date the (thrust) emplacement of the Seve supracrustal rocks on the basement and is followed by a more open folding (F3). The seemingly massive marble body west of Konradtjørna, covers a surface area of about 1 km^2 and has been tectonically thickened, possibly by plastic flow.

As part of the evaluation of the Konradtjørna marble deposit, a relatively detailed mapping, using a magnified arial photograph (1:50000), resulted in Figure 4. The orientational pattern of marble and wallrock foliation and of the marble–wallrock contacts presented in Figure 4 is consistent with the map of Winge (1989). The marble–wallrock contacts and the marble foliation strikes ENE–WSW with NNW-dips in the western and central parts of Figure 4. In the eastern portion the strike is NNW–SSE to NNE–SSW with dips towards east. Both the F2 and F3 fold axes and the corresponding lineation (L3) plunges towards northeast (Winge, 1989).

The metamorphic evolution of the area is characterized by kyanite growth in pelitic rocks during an early high pressure phase (M1, corresonding to F1), followed by high temperature metamorphism accompanied by sillimanite growth (M1–M2, Winge, 1989). The later deformation events are characterized by gradually decreasing pressures and temperatures and the growth of staurolite (M1-M2), garnet and hornblende (M2–M3), biotite, plagioclase and titanite (M1–M4), light mica and epidote (M3–M4), actinolite (M4), chlorite (M4), and stilpnomelane (M5). Winge (1989) also ascribed the growth of tremolite in the marbles to the earliest high pressure deformation period.

MINERALOGY, MINERAL CHEMISTRY AND PETROCHEMISTRY

Sampling

Based on the initial mapping, it appears that a 0.16 km^2 equidimensional area of the central massive carbonate body immediately south and west of the thin gneiss horizon west of Konradtjørna contains the purest carbonate. In order to characterize the chemical variation within this portion of the deposit, 27 samples were collected over 3 profiles, 100–200 m apart (Figure 4). The samples, labelled K-1 to K-27, and located on Figure 4, comprised 2–5 rock chips (1–3 kg) each, and were taken from suitable outcrops about 50 m apart along the profiles. Samples labelled with the prefix Gr- were taken from other parts of the carbonate deposits and are located on Figure 2 and/or Figure 4.

Mineralogy

The marbles are mostly granular, allotriomorphic, and rather coarse grained. The grain size varies from 0.5 to 5 mm, with an average for the whole marble area of 2–4 mm. The coarse grain size of calcite makes the rock friable. Banding and parallel orientation of flakey and long-prismatic minerals are most pronounced in the the marginal parts of the large and massive marble body and in the thin peripheral marble horizons. These peripheral parts are generally richer in silicate minerals than the central parts of the marble massif. Even the grain size appears to some extent to be correlated with the position and composition of the of the sample: the whitest and purest carbonate portions in the central parts have average grain size of 4-5 mm and hardly any preferred orientation (Gr-1, K-16, K-20, K-21).

The mineralogy is dominated by calcite, but small amounts of dolomite occur in some of the samples. The amount of dolomite is broadly correlated with the amount of silicate minerals. The dolomite occur as 50–200 µm grains, often as intergranular strings between the larger calcite grains, and as 1–15 µm exsolution patches within the calcite grains. The distribution and shape of these intracrystalline dolomite grains is goverened by the crystallography of the host calcite (Figure 5). In the portions of the marble where the MgO-content is sufficient to saturate the calcite, the 1–15 µm dolomite exolutions occur in irregular swarms with unexsolved calcite in between.

Ubiquitous silicate minerals are quartz, muscovite, phlogopite, and tremolite, as well as minute amounts of clinochlore, talc, and titanite. Scattered grains of anorthite, intermediate plagioclase and potassic feldspar have been observed. Various silicate-carbonate mineral associations are illustrated by the back-scattered electron images of Figures 6–8. As shown in Figures 7 and 8, the tremolite is of a distinctly coarse-grained (100–200 µm across) and nonfibrous type. A major part of the contents of Fe, Ti and P is confined to scattered accessory grains of pyrite, magnetite and/or heamatite, rutile, and apatite.

Mineral chemistry and Mg-solubility in calcite

Representative analyses of the silicate minerals along with analytical specifications are given in Table 1. The minerals are characterized by very high Mg/Fe-ratios. Muscovite has a small phengitic component, and the phlogopite is characterized by a combination of Al-tschermak and muscovite (Al-dioctahedral) substitutions. Also the tremolite has a small Al-tschermak component.

Both the larger dolomite grains and the small exsolved intracalcite dolomite exsolutions are completely stoichiometric with Ca=Mg (atomic) and up to 0.35 weight % FeO. The calcite contains a maximum of 0.01 wt % FeO but has a variable MgO-content ranging from less than 0.3 to 2 wt%. From the analyses of calcite in low-MgO, dolomite-free samples, and both within and outside the dolomite exsolution swarms in MgO-saturated rocks (Figure 5), a rough picture of the MgO-saturation level in calcite has emerged. The calcite in rocks with dolomite exolution has MgO-contents of 1.5–2.0 wt% in grains without dissolved dolomite and 0.5–1.0 wt% in grains that are within swarms of exsolved dolomite. This indicate that the solubility level of MgO in calcite is about 1 wt%. The apparent variation in solubility on a local scale (between different samples within the same marble deposit) probably results from a combination of local variations in the conditions of final equilibration and kinetic (non-equilibrium) effects.

Petrochemistry and normative mineralogy

The major element composition of the 27 K-samples and 4 of the Gr-samples was determined by X-ray flourescence spectrometry (XRF). The data along with a brief description of the analytical procedure and detection limits are given in Table 2a. The analytical accuracy and precision are evaluated from triplicate analyses of two synthetic carbonate standards (Table 2b). The accuracy (1 standard deviation) is typically lower than 2 % of the oxide present, even at the level of 0.05 wt%, and the precision is almost invariably higher than the accuracy.

The chemical data are shown as a function of position along the sampled profiles (Fig. 4) in Figures 9 and 10. CaO is about 55 % for most of the samples, especially along the southern profile. MgO is equal to or somewhat greater than the oxide total – (MgO + CaO + CO_2). Some of the MgO must be present in silicate minerals, especially phlogopite and tremolite.

The variation of the silicate mineral content, and therefore the proportion of silicate-bound MgO, can be evaluated by first considering Fig 10. SiO_2 is invariably higher than Al_2O_3, which in turn exceeds K_2O, and there is a positive correlation between these oxides and MgO. This is consistent with the observation that muscovite is always present. Phlogopite accomodates about equal amounts of K_2O and Al_2O_3, and muscovite balances the excess Al_2O_3.

The most important Mg-bearing silicates are phlogopite and tremolite, with ratios of MgO / other oxides (including H_2O) of 0.33 and 0.41, respectively. The excess MgO relative to the oxide total – (MgO + CaO + CO_2) therefore confirms the presence of MgO in the carbonate phase. Fig 11 presents a normative mineralogy of the samples calculated from simplified stoichiometric assumptions (normative calcite and dolomite are in the form of 100 % $CaCO_3$ and $Mg_{0.5}Ca_{0.5}CO_3$, respectively). Based on the significant contents of quartz and muscovite, the positive correlation between MgO, SiO_2, Al_2O_3, and K_2O, and the ratio of MgO/other oxides of 0.3–0.4 in phlogopite and tremolite, it was assumed that one quarter of the total MgO is confined to the silicates. The theoretical dolomite content (including dolomite in solution in calcite) was then calculated from the remaining MgO, and calcite was calculated from the CaO that is not confined to the dolomite. Figure 11 shows that only 5 of the samples have normative dolomite content exceeding 4.5 wt%, which is the dolomite solubility in calcite corresponding to a MgO-solubility of 1 wt%. Free dolomite might be expected in such samples based on these simple assumptions. Although a mineralogical study has only been carried out on 4 of the samples shown in Fig 11 (as well as on 7 of the Gr-samples), it appears that the procedure provides a guide to the occurrence of free dolomite.

The contents of Fe and Ti varies independantly of the correlated Si-Al-K-Mg-variation, indicating that pyrite, magnetite/heamatite, rutile, and tianite are main carriers of these elements.

Acid soluble MgO and CaO, trace elements and light reflectivity

Acid soluble MgO and CaO, trace elements, light reflectivity and grain size distribution of the corresponding sample powder were measured in 6 selected samples. The results, accompanied by brief descriptions of the analytical procedures, are presented in Tables 3 and 4 and Figure 12. The acid insoluble analyses of MgO and CaO are not as accurate as the corresponding XRF-analyses, and the two data sets are therefore indistinguishable from each other within the accuracy. The trace elements are, as expected, present in very low abundances, with 20 of the 31 measured elements below the detection limit in all of the samples.

The grain size distribution of the sample powder used for chemical analysis and reflectivity measurements was investigated by initial wet sieving to determine the mass fraction less than 63 mm, followed by sedimentation analysis using a SediGraph 5100 V3.02 instrument. The resulting grain size distribution is shown in Figure 12. In spite of the use of a deflocculant agent (sodium hexa-metaphosphate), it appears that flocculation of the very finest particles (< 3.5μm) did occur, causing the abrupt termination of the grain size – mass distribution curves.

The reflectace values for the filters FMX (red – amber), FMY (green), FMZ (blue), and R457 (brightness) are listed in Table 4. As expected, there is a clear positive correlation between the reflectance level and the CaO-content. Brightness values of 94–96 are very good for raw materials for the filler industry.

EVALUATION OF THE ECONOMIC POTENTIAL

The tectonically thickened marble massif west of Konradtjørna in the Geitfjellet–Bukkafjellet area represent a significant carbonate resource. A true tree-dimensional picture of the deposit can only be obtained by core drilling, but Figure 3 gives an interpretational cross section through the deposit. It is not likely, however, that the *total* tonnage of carbonate will determine the feasibility of an industrial mineral exploitation of the marble deposit. A tonnage calculation involving the uppermost 10 m of the deposit over the 400m by 400m sampled area results in 4.4 mill. metric ton.

The chemical and norm-mineralogical profiles presented in Figures 9–11 illustrates the variation on a 50–400 m scale (50–200 m distace between samples along and between profiles, respectively). Exploitation of this deposit, located at an altitude of about 600 m and 13–15 km from the railway and highway at Grong, will depend on the identification of regularly shaped and reasonably large portions of the marble deposit with composition corresponding to the samples

Gr-1 and K-14, 16, 17, 8, 5, 2, 1, 20, 21, 24 and 25. The present study has not located any specific area that appears especially promising in this respect. The variation along the profile from K-20 to K-27 is less pronounced than that along the other profiles. The purity of the sampled marble along this profile is also relatively high, although the samples K-22, 23, 26 and 27 have CaO-contents below 55 % and most likely brightness values below 90 % (K-27 has an R457-value of 88.0 %).

An ideal situation in a structurally simple area would be to establish relationships between the stratigraphy and composition of the deposit. In the area west of Konradtjørna, however, the marble deposit is tectonically thickened, possibly in part by plastic flow. This reduces the chances of establishing simple and predictable relations. A relatively extensive drilling program seems required to locate and define the three-dimensional form of high-grade portions of the marble deposit. The stuctural complexity may imply that evenly shaped zones of sufficient size and purity for profitable mining is difficult to find.

Somewhat lower grade marble from the Geitfjellet–Bukkafjellet deposit appears suitable as a raw material in a mechanical concentration plant. The silicate minerals occur mostly in relatively coarse aggregates (Figures 6–8), whereas the minute amounts of pyrite and Fe-Ti-oxides occur as tiny, scattered grains. An efficient separation of dolomite, however, would be nearly impossible, since much of this mineral is present as exsolution grains only 1–15 µm across.

The friability of the coarse grained marbles will presumably make them unsuitable as raw material in calcination processes. The energy input required in the crushing and grinding of such marbles, however, is expected to be low.

The location of the Geitfjellet–Bukkafjellet marble deposit is unfavourable. The transportation costs will be high, and the location at 600 m altitude will limit the efficiency of quarry or mine operation (only summer month operation may be desirable). The opening investment will include the construction of a 3 km long road, and the likely upgrading of the 6–7 km long Geitfjellet road towards Grong. The location may also prove unfavourable from an environmental point of view. Outdoor activity interests will likely oppose a quarry development west of Konradtjørna, but it is beyond the scope of this report to evaluate this factor. The carbonate bedrock in this area forms the basis for interesting karst topography along some of the minor rivers and streams. The marble area has also special botanical and possibly zoological values.

REGIONAL IMPLICATIONS AND RECOMMANDATIONS FOR FURTHER INVESTIGATIONS

The present documentation of the high purity, high metamorphic grade and relatively large volume of the Geitfjellet–Bukkafjellet marble deposit strengthens the position of the Seve nappe equivalent as host for carbonate resources in the Nord-Trøndelag and Fosen area. This observation will have important consequences for the further prospecting and evaluation of the resource inventory.

Within the Geitfjellet–Bukkafjellet marble deposit, further investigations, including surface sampling, should be carried out to ascertain whether other areas further west than the 400m by 400m sampled area has equal or higher purity of calcite. The mapping in 1992 indicated that the half-moon-shaped area south of the major NE-SW-trending fault zone (Figures 2 and 4) has a relatively high content of impurities, but that areas 1.0–1.3 km WSW of Konradtjørna may be of good quality.

If, in the light of market situation and estimated cost of quarrying and transportation, the results from the sampling in 1992 is considered interesting, a core drilling program should be carried out. Such a program should attempt to locate and define higher grade zones within the sampled area. An integral part of such a program will also be the construction of a detailed map (e.g. scale 1:1000, contour interval of 1 m) based on arial photography and a measured surface grid.

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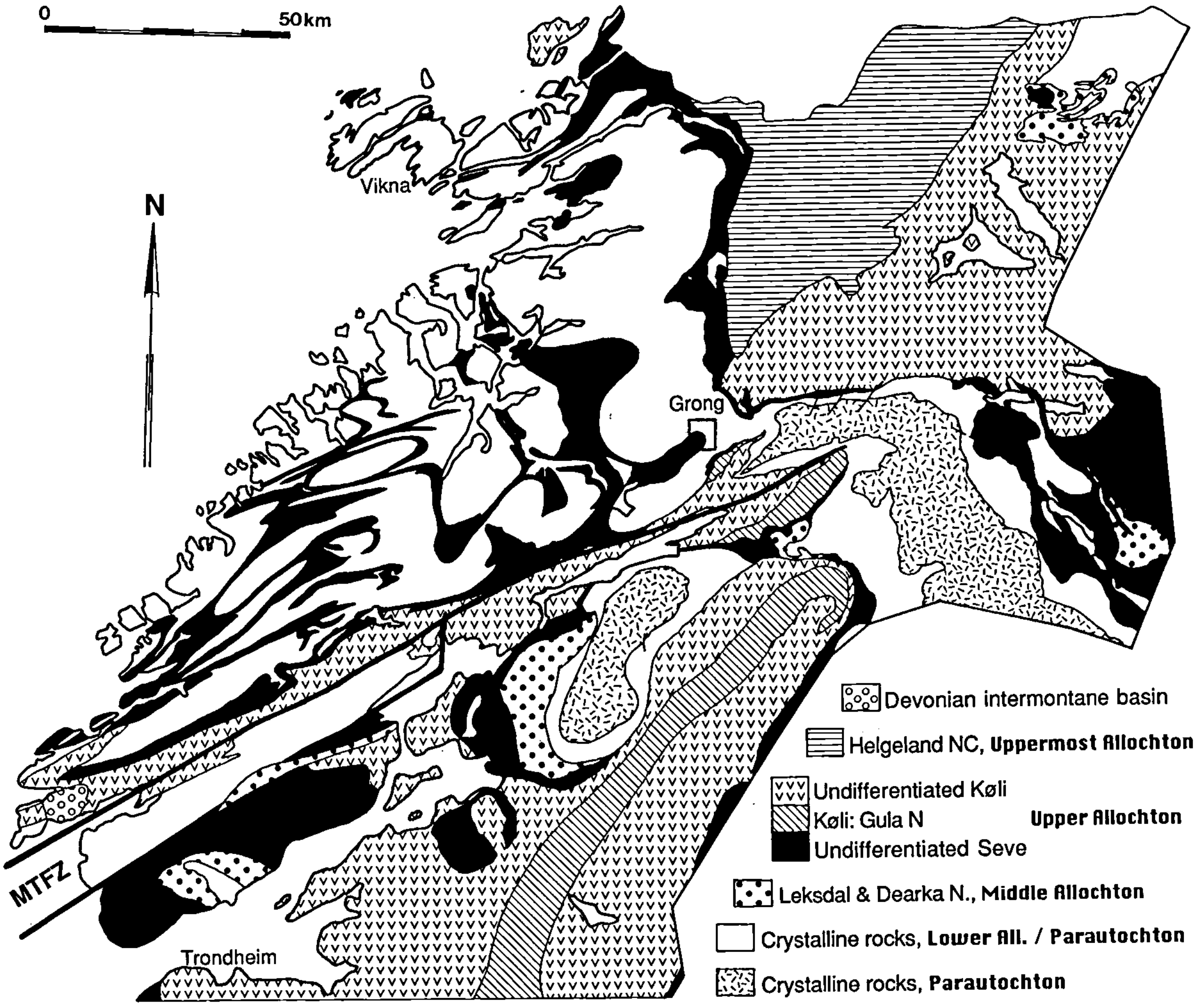
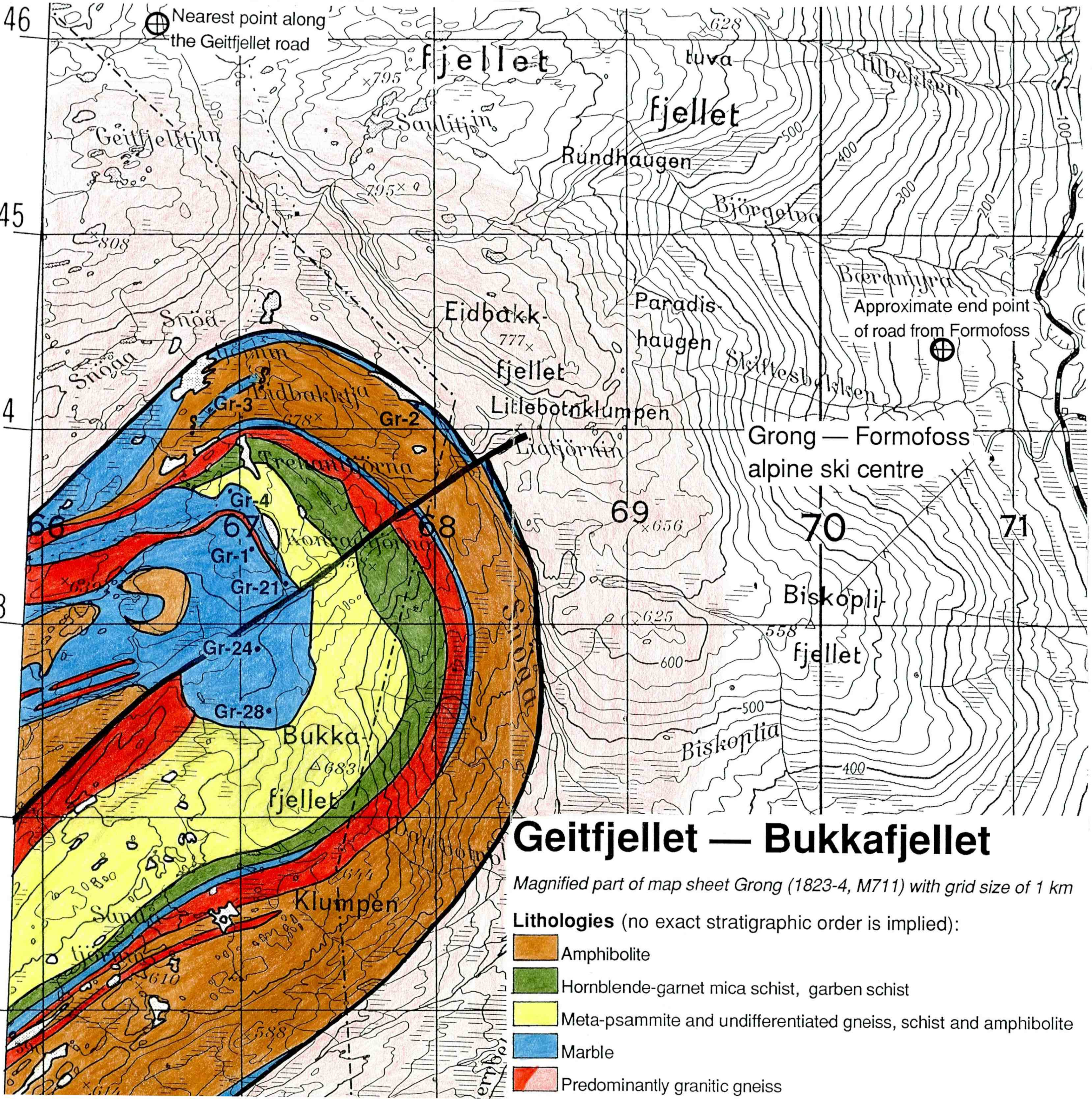


Figure 1. Tectonostratigraphic map of Nord-Trøndelag and Fosen based on Gee et al. (1985), Roberts (1989), Sollie (1989) and Dallmeyer et al. (1992). MTFZ: Møre–Trøndelag Fault Zone; N: Nappe; NC: Nappe Complex. The Vestranden Gneiss Complex is the area northwest of the MTFZ and west the Helgeland NC. The indicated rectangular area immediately south of Grong is the area of Figure 2.

Figure 2. Geological map of the Geitfjellet-Bukkafjellet area based on Roberts (1987) and Winge (1989). Gr-1 to Gr-28 are sample localities.

Fig. 2



Geitfjellet — Bukkafjellet

Magnified part of map sheet Grong (1823-4, M711) with grid size of 1 km

Lithologies (no exact stratigraphic order is implied):

- 🟫 Amphibolite
- 🟩 Hornblende-garnet mica schist, garben schist
- 🟨 Meta-psammite and undifferentiated gneiss, schist and amphibolite
- 🟦 Marble
- 🟥 Predominantly granitic gneiss

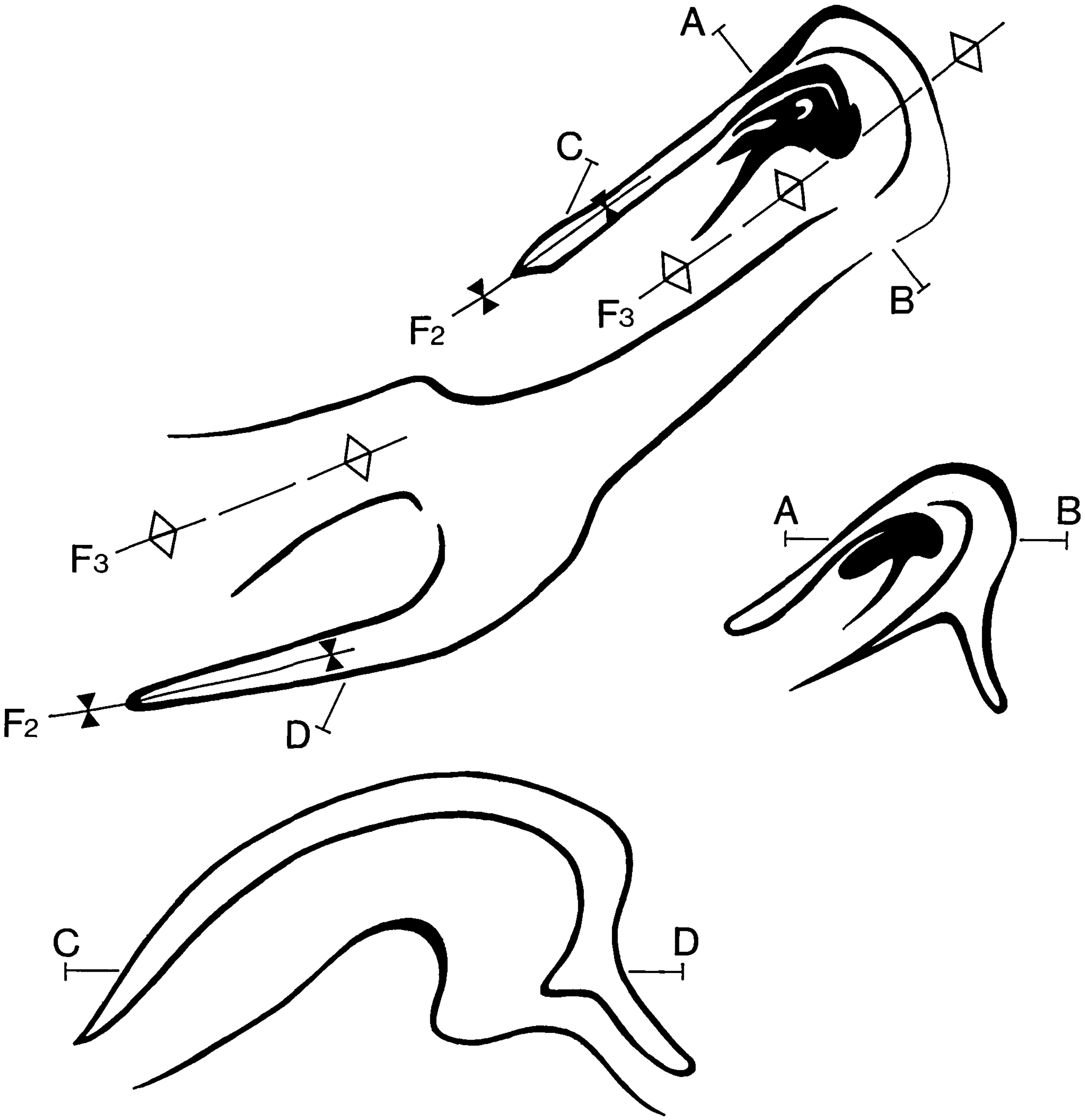


Figure 3. Schematic interpretational sketch illustrating the style of folding in the Geitfjellet–Bukkafjellet area. The only lithological units shown on the map and two profiles are the marble horizons. See text for discussion of the deformation phases. Based on Winge (1989).

Figure 4. Geological map on magnified aerial photographic base, showing the results from the current detailed investigation. The orientation of foliation and marble-wallrock contacts is indicated by strike and dip symbols. Numbers 1 to 27 indicate the localities of the samples K-1 to K-27.


Geitfjellet–Bukkafjellet
M 1:5000
0
300 m
Gneiss, amphibolite
Marble
N
Trekant-tjørna
Konrad-tjørna
Gr-36
Gr-21
Gr-24
Gr-28
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
30° 65g
35° 65g
30° 65g
30° 70g
40° 45g
35° 80g
30° 55g
30° 55g
30° 95g
55° 60g
25g
55°
35° 90g
35° 85g
15° 80g
160g 30°
30° 110g
185g 25°
25° 85g
40° 170g
35° 160g
105g 30°
40° 155g
120g 25°
170g 35° 45 170g
35° 160g
50 180g
185g
10g

Fig. 4

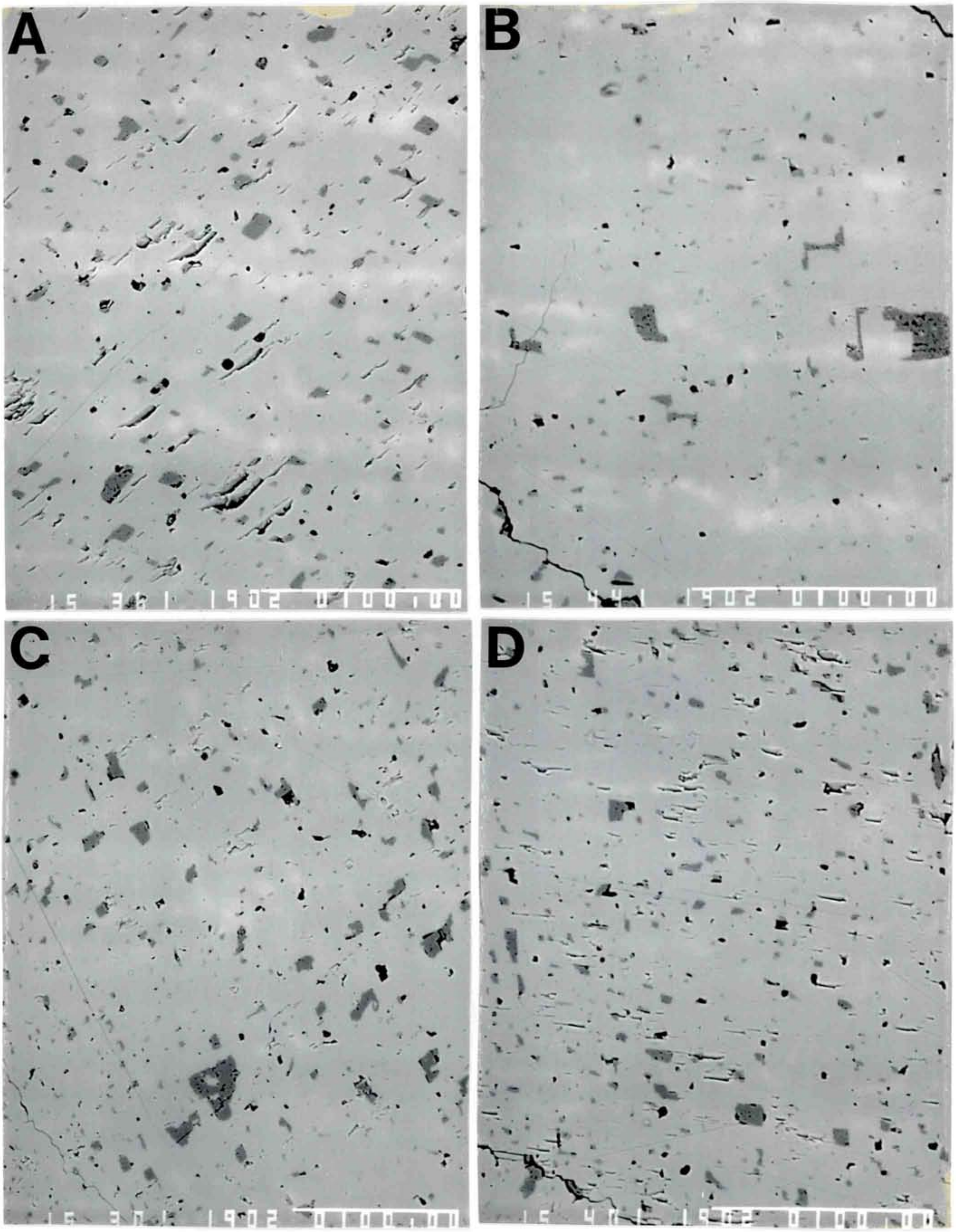


Figure 5. Back-scattered electron (BSE) images of calcite (high BSE-intensity, high brightness) with small dolomite (lower brightness) exsolutions. The scale bars of the BSE-images in Figures 5–8 are all 100 μm. Note that the shape and spacial distribution of the dolomite exsolutions are crystallographically determined. **A** and **B** are from K-7 and **C** and **D** from Gr-21.

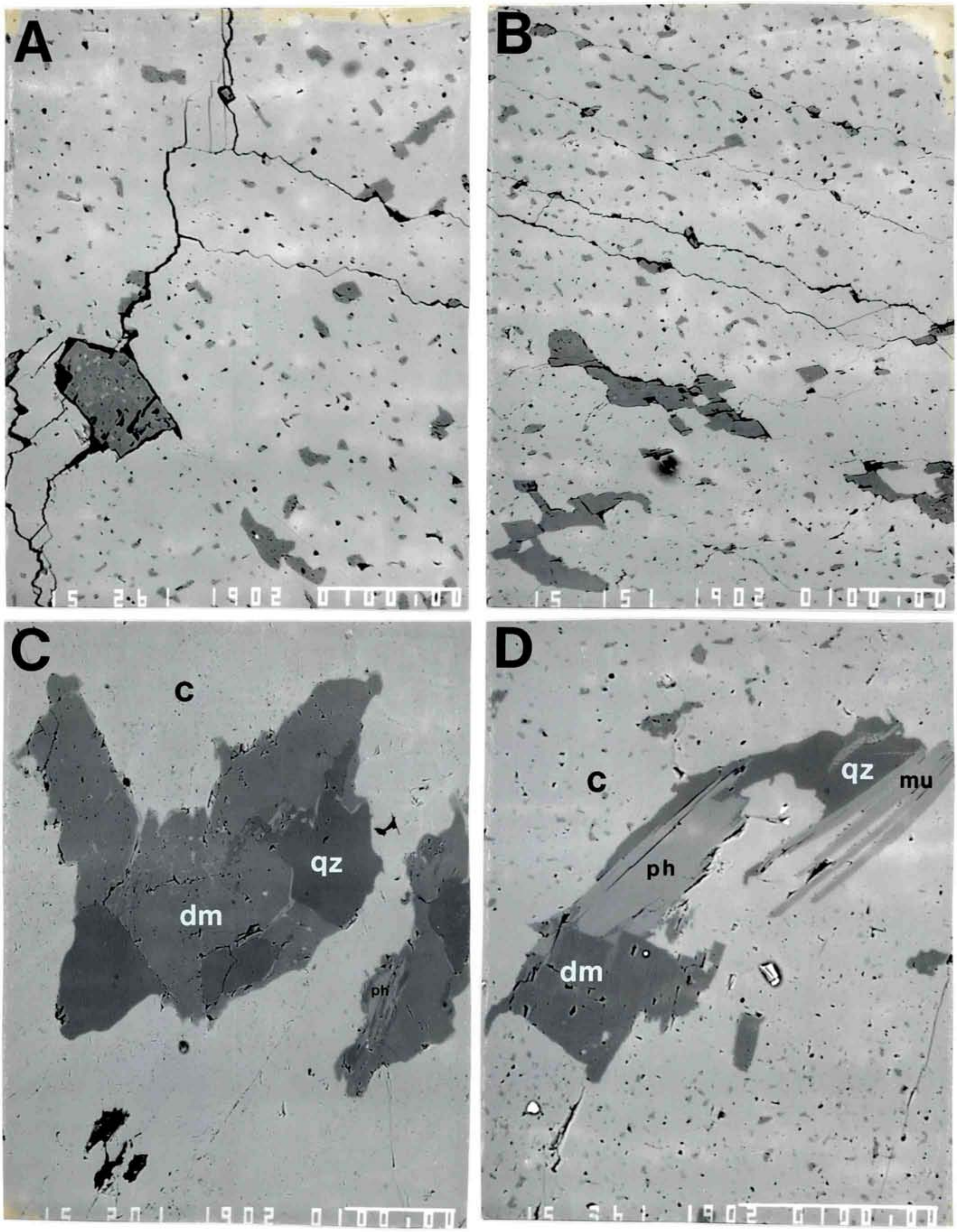


Figure 6. **A** and **B** (K-7): Dolomite (darker) exsolutions in calcite with additional larger dolomite grains. Note the tiny calcite inclusions in the largest dolomite grain in A. **C** (Gr-2) and **D** (Gr-4): Calcite (c), dolomite (dm), quartz (qz), phlogopite (ph) and muscovite assemblages.

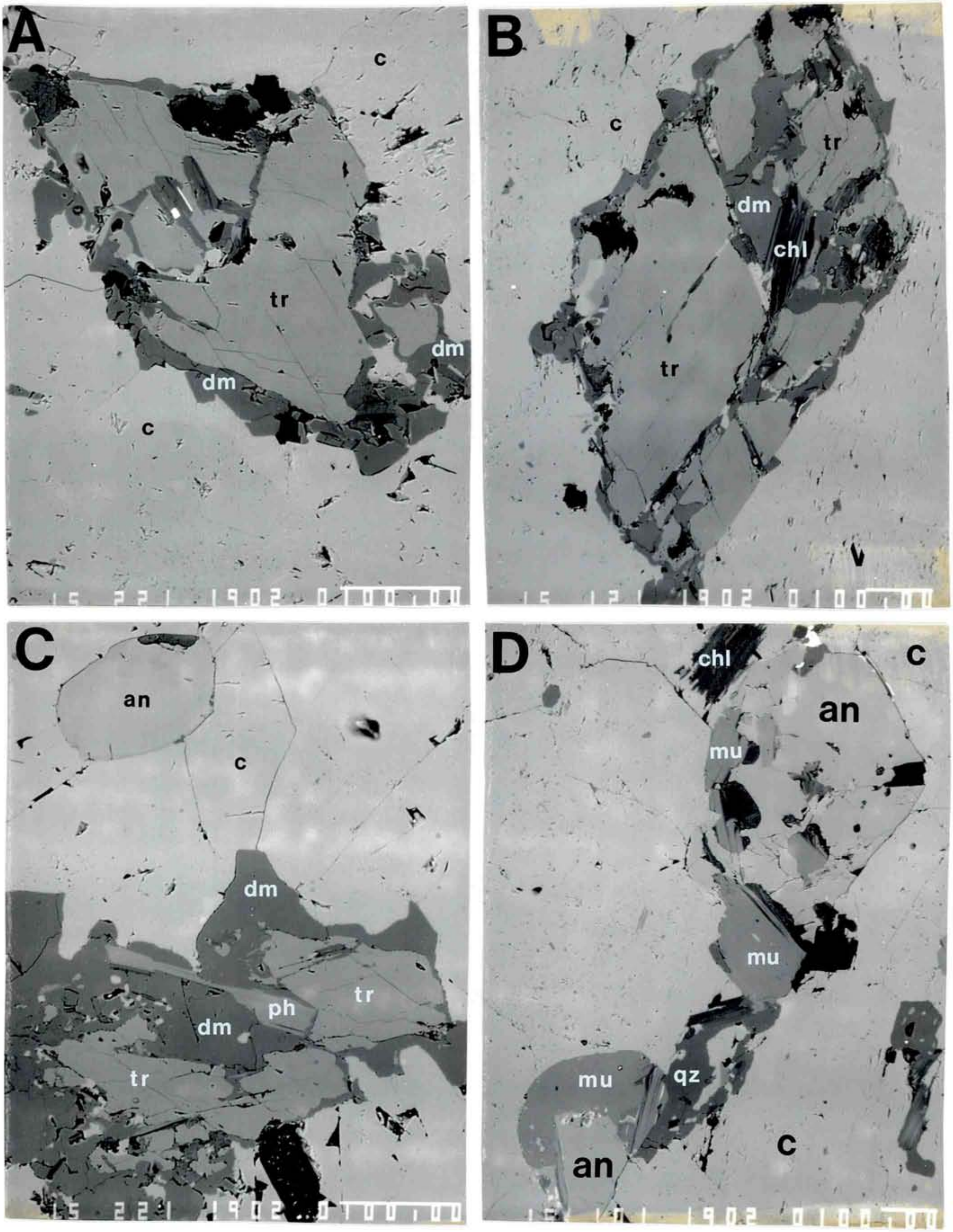


Figure 7. **A** and **B** (Gr-3): Intergrowths of tremolite (tr), dolomite and chlorite (chl) in calcite. In **A**, a tiny rectangular magnetite grain (very high brightness) occurs within an elongate dolomite area inside tremolite. **B** (Gr-4) and **C** (Gr-36): Assemblages containing anorthite (an). Other abbreviations as in Figure 6.

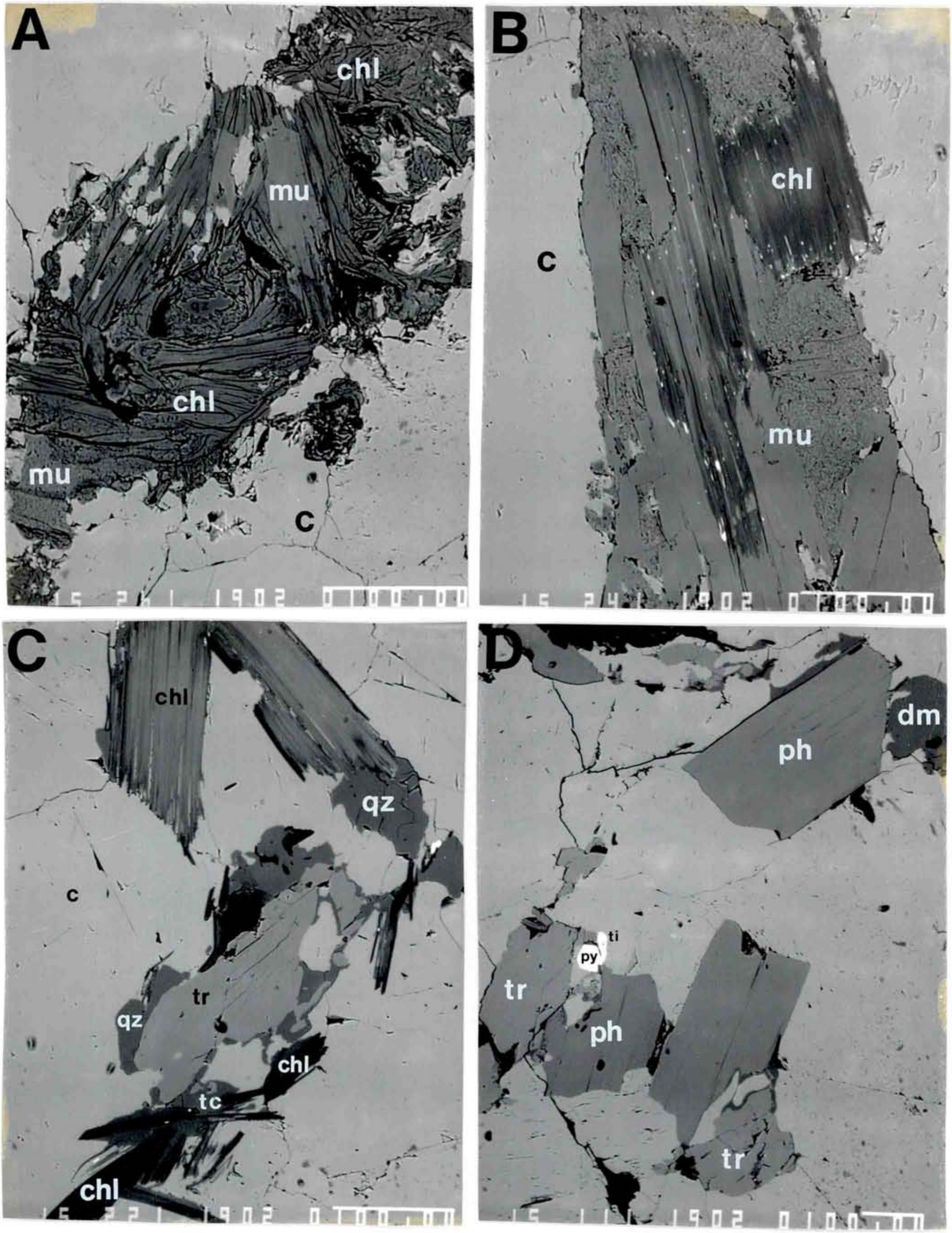


Figure 8. **A** (Gr-2) and **B** (Gr-3): Muscovite–chlorite intergrowths. Note the central quartz grains in **A** and the tiny rutile grains (very high BSE-brightness), mostly along the irregular margins of the the chlorite in **B**. **C** (Gr-21) and **D** (Gr-28): Diverse silicate–carbonate mineral aggregates including talc (tc) in **C** and pyrite (py) and titanite (ti) in **D**. Other abbreviations as in Figures 6 and 7.

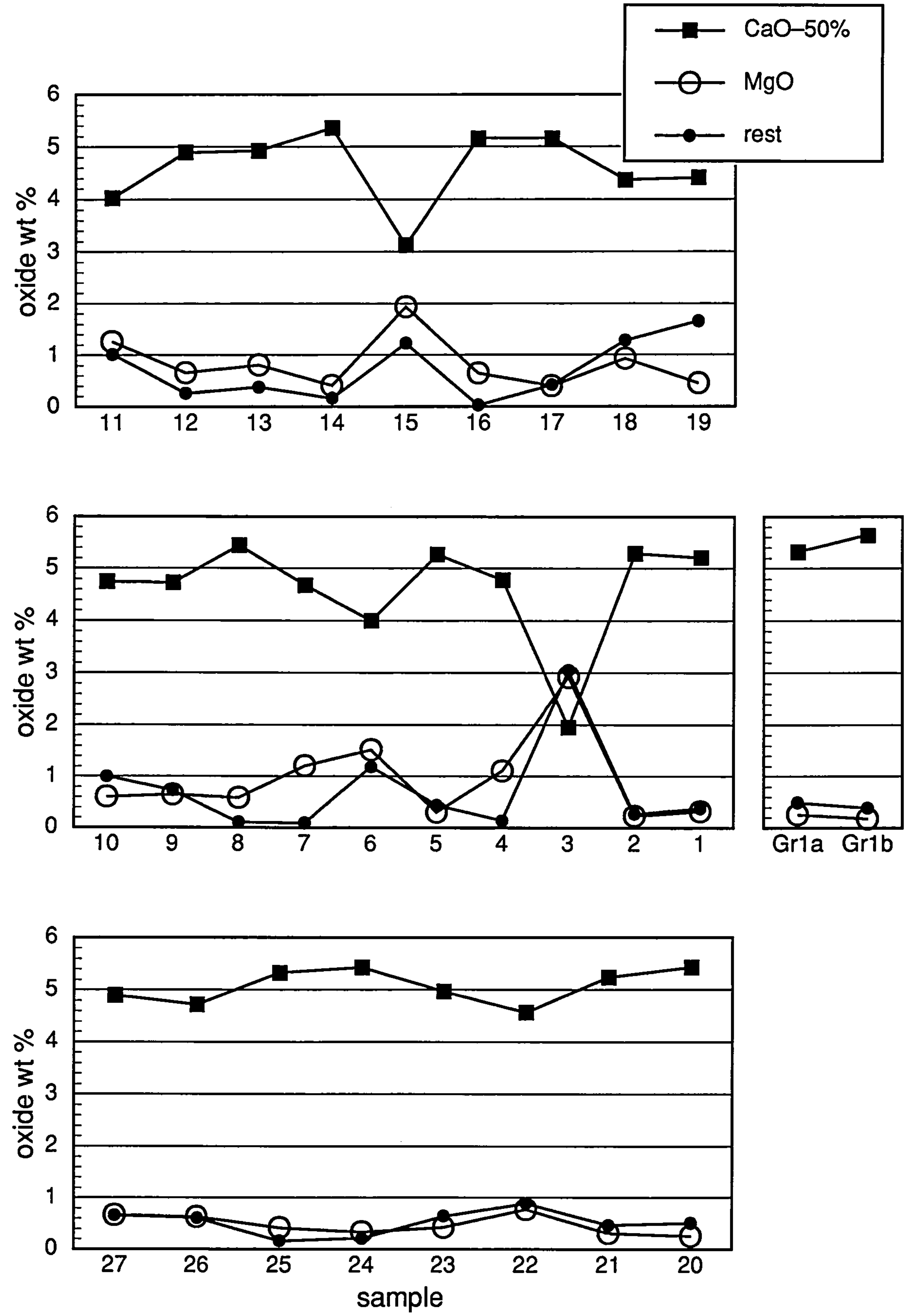


Figure 9. Chemical variation (weight %) along three profiles west of Konradtjørna based on XRF-analyses. See Figures 2 and 4 for the location of the samples Gr-1 and K-1 to K-27 (labelled 1 to 27 in Figures 4 and 9–11). CaO–50% is used in order to plot the CaO-values spatially close to the MgO-values without using a logarithmic scale. The "rest"-values represent the sum of all of the oxides other than MgO, CaO, CO_2 and H_2O.

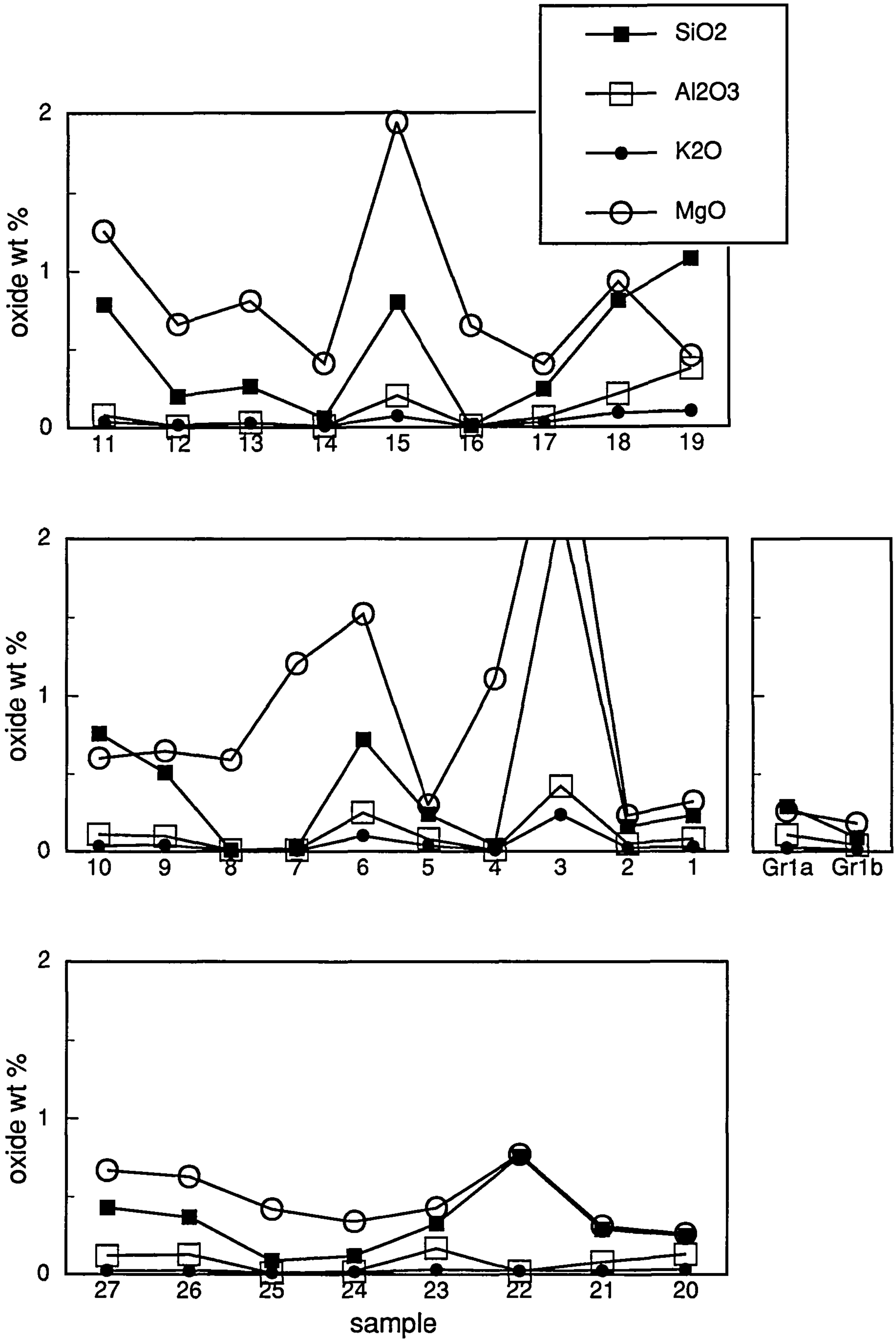


Figure 10. Chemical variation (weight %) as in Figure 9.

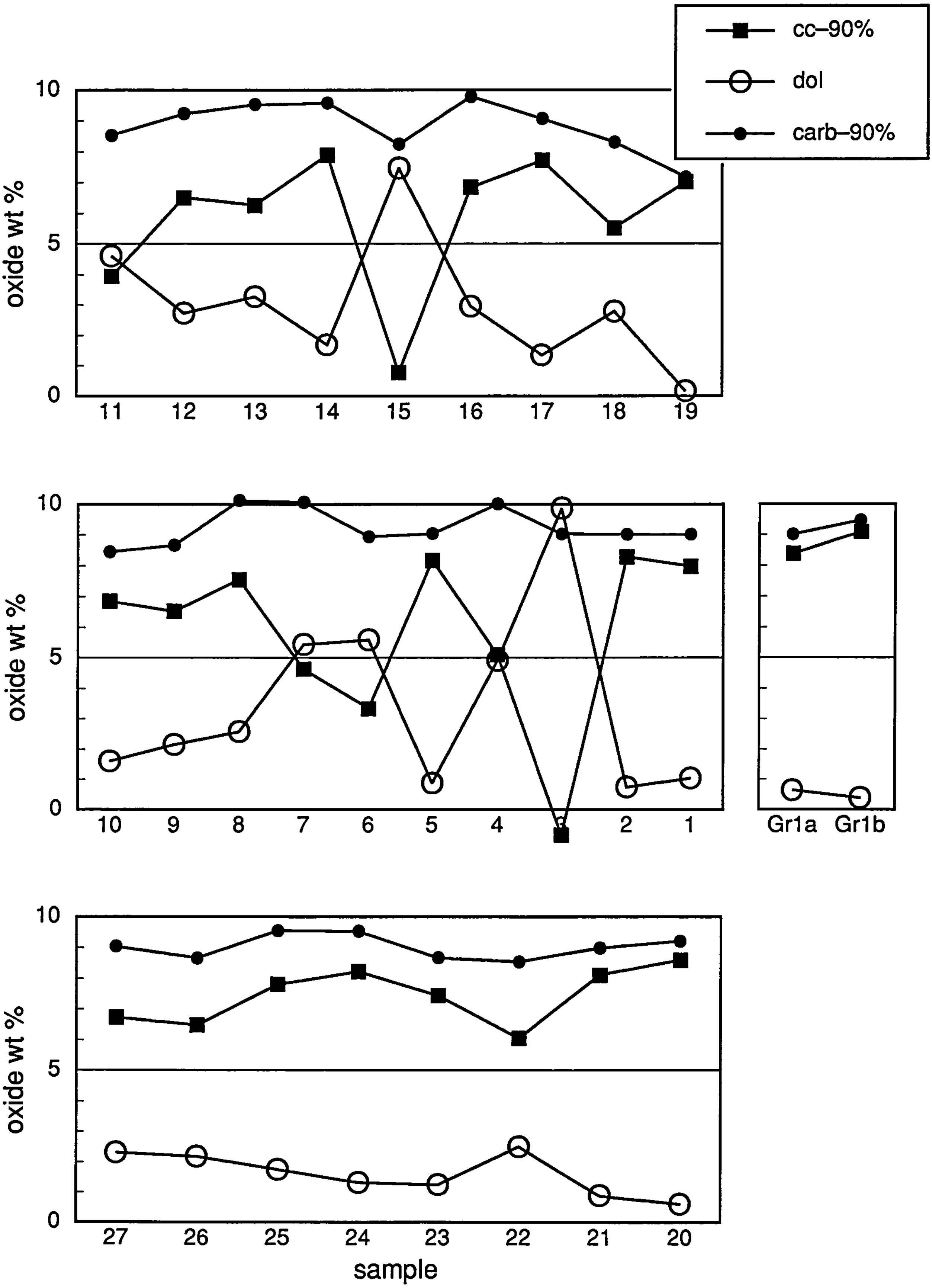


Figure 11. Normative mineralogy (weight %) corresponding to the chemical variation of Figures 9 and 10. Calcite–90% (cc–90%) and total carbonate–90% (carb–90%) are used to move the calcite and total carbonate trends close to the dolomite (dol) trend in a linear diagram. See the main text for the assumptions behind the norm calculation. The solubility of dolomite in calcite appears to be about 4.5 % in these rocks (corresonding to 1% MgO), and only the 6 samples with plotted "dolomite"-values of more than 4.5 % are expected to have free dolomite.

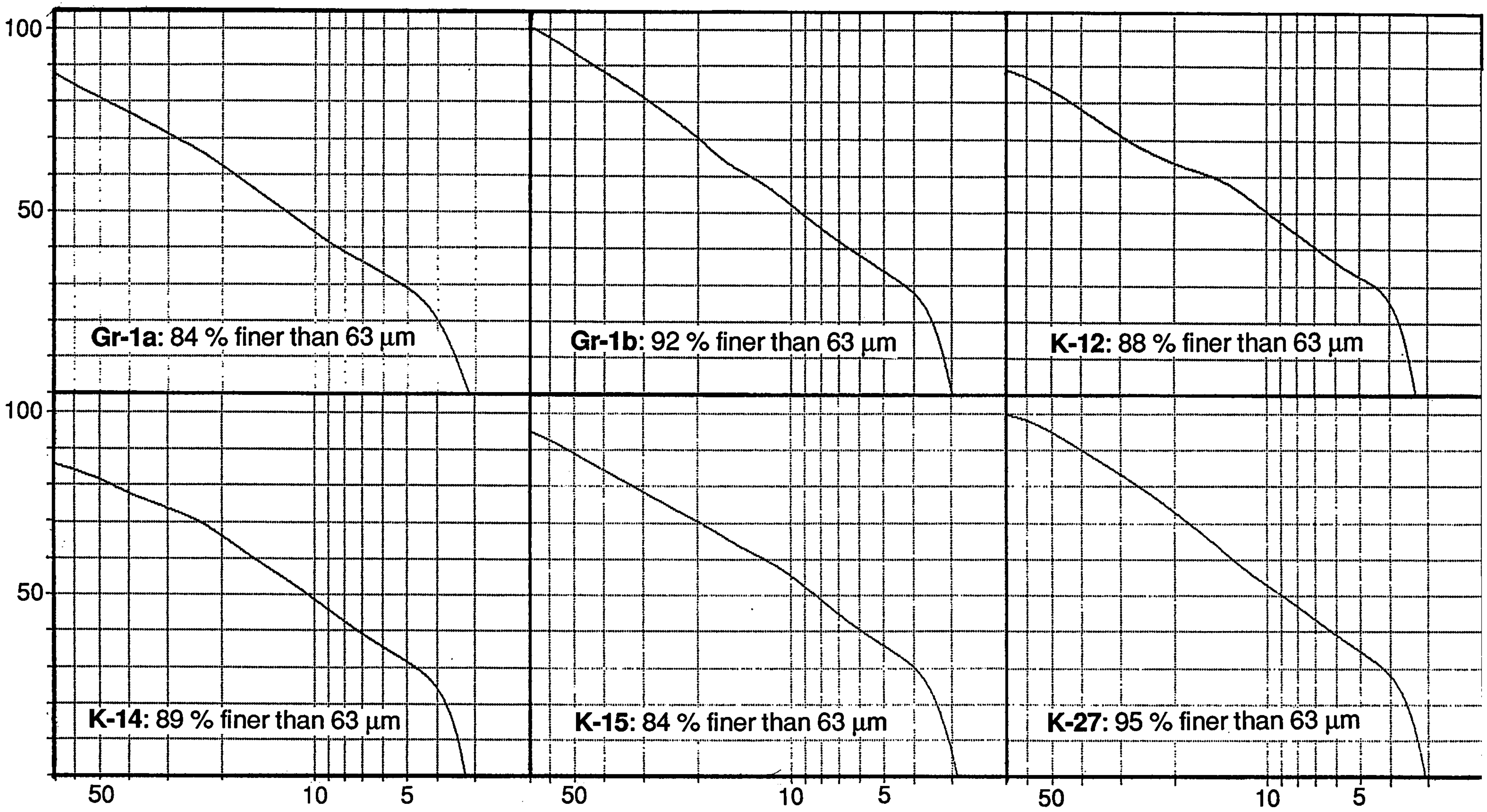


Figure 12. Grain size distribution of sample powder used for reflectance measurements. The vertical axis is: **Cumulative mass finer than (%)** and the horizontal axis is: **Grain size in the form of equivalent spherical diameter (µm).**

Table 1. Representative silicate mineral compositions

	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Total	Si	Al^{IV}	Al^{VI}	Mg+Fe	Ca	Na+K
Muscovite:														
Gr-1a	46.4	36.5	0.27	0.85	0.18	0.36	10.8	95.36	6.140	1.860	3.833	0.198	0.026	1.915
Gr-36	47.2	35.3	0.19	1.83	0.05	0.49	10.9	95.96	6.212	1.788	3.687	0.380	0.007	1.955
Phlogopite:														
Gr-3	41.5	17.7	0.50	24.9	0.34	0.13	10.9	95.97	5.733	2.267	0.615	5.185	0.050	1.956
Gr-4	42.1	15.8	0.30	26.1	0.08	0.25	10.8	95.43	5.834	2.166	0.419	5.435	0.012	1.979
Gr-36	41.9	16.7	1.09	25.3	0.03	0.21	10.5	95.73	5.802	2.198	0.527	5.348	0.004	1.911
Tremolite:														
Gr-3	58.4	3.34	0.33	23.5	13.1	0.23	0.16	97.95	7.882	0.118	0.237	4.765	1.894	0.088
Gr-4	57.5	3.34	0.22	23.1	13.4	0.19	0.15	97.90	7.772	0.228	0.304	4.679	1.941	0.076
Talc:														
Gr-3	63.2	0.36	0.14	31.1	0.29	0.11	0.05	95.25	7.993	0.007	0.047	5.877	0.039	0.035
Chlorite:														
Gr-3	29.9	23.1	0.62	33.0	0.07	0.02	0.21	86.92	5.560	2.440	2.623	9.243	0.014	0.057

Oxide abundances are in weight percent. Mineral formula units (cations) are normalized to 24, 24, 23, 24, and 28 oxygen atom equivalents for muscovite, phlogopite, tremolite, talc, and chlorite, respectively.

The minerals were analyzed with a Jeol 733X Superprobe instrument using 4 wavelength-dispersive spectrometers, accelerating voltage of 15 kV, probe current of 15 nA, counting time of 10 seconds, and a raster mode of analysis. The raw data were corrected using the Jeol ZAF-correction program and stadardization was based on natural mineral standards (wollastonite for Si and Ca, olivine for Mg and Fe, kyanite for Al, albite for Na and orthoclase for K). The reported analyses represent averages of 3-8 spot analyses. The average precison (1σ) is generally better than 1 % for oxides with total abundances of 30-60 wt%, better than 3 % for oxides at the 5-30 wt% abundance level, and better than 8 % for the minor and trace oxides. Based on repeated analyses of standards the analytical accuracy is estimated to be similar to the precision.

Table 2a. Major element analyses

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	P_2O_5	TiO_2	MnO	K_2O	Σ–MgO–CaO–CO_2
Gr-1a	0.29	0.11	0.05	0.26	55.32	*nd*	110	20	260	0.49
Gr-1b	0.09	0.04	0.05	0.18	55.64	*nd*	90	40	130	0.39
Gr-21	3.06	0.39	0.07	1.83	51.43	0.01	630	60	690	3.67
Gr-36	4.27	1.57	0.57	2.53	48.82	0.02	780	210	3030	6.83
K-1	0.23	0.08	0.02	0.32	55.21	*nd*	120	50	280	0.38
K-2	0.16	0.05	0.02	0.23	55.29	*nd*	90	30	240	0.27
K-3	2.19	0.42	0.16	2.92	51.96	0.01	240	90	2360	3.05
K-4	0.04	*nd*	0.06	1.11	54.78	*nd*	90	170	100	0.14
K-5	0.24	0.08	0.06	0.30	55.27	*nd*	80	90	390	0.44
K-6	0.72	0.25	0.09	1.52	54.00	*nd*	190	120	1010	1.19
K-7	0.02	*nd*	0.05	1.21	54.68	*nd*	80	80	70	0.09
K-8	*nd*	*nd*	0.09	0.59	55.44	*nd*	50	80	50	0.11
K-9	0.51	0.10	0.04	0.65	54.73	*nd*	220	100	430	0.73
K-10	0.76	0.11	0.05	0.60	54.75	0.01	180	130	350	1.00
K-11	0.79	0.08	0.08	1.26	54.03	*nd*	220	90	370	1.02
K-12	0.20	nd	0.03	0.66	54.90	*nd*	80	80	180	0.26
K-13	0.26	0.03	0.03	0.81	54.93	0.01	50	120	290	0.38
K-14	0.06	nd	0.07	0.41	55.36	*nd*	110	130	100	0.16
K-15	0.80	0.20	0.10	1.94	53.13	*nd*	330	240	710	1.23
K-16	*nd*	*nd*	0.01	0.65	55.16	*nd*	90	70	50	0.03
K-17	0.24	0.06	0.06	0.40	55.16	*nd*	160	100	290	0.42
K-18	0.81	0.21	0.13	0.93	54.37	*nd*	220	170	890	1.28
K-19	1.08	0.37	0.07	0.45	54.41	*nd*	380	70	980	1.66
K-20	0.25	0.13	0.08	0.26	55.43	*nd*	150	50	310	0.51
K-21	0.29	0.08	0.05	0.31	55.24	*nd*	180	30	250	0.47
K-22	0.76	0.02	0.06	0.77	54.57	*nd*	230	40	230	0.89
K-23	0.33	0.17	0.08	0.43	54.97	*nd*	210	80	310	0.64
K-24	0.12	0.02	0.04	0.34	55.43	*nd*	80	40	160	0.21
K-25	0.09	*nd*	0.04	0.42	55.33	*nd*	120	50	110	0.16
K-26	0.37	0.13	0.07	0.63	54.72	*nd*	80	30	250	0.61
K-27	0.43	0.12	0.06	0.67	54.90	*nd*	130	100	240	0.66

Measurements by a Phillips PW1480 X-ray fluorescence spectrometer on glass disks made by fusing the sample and $Li_2B_4O_7$ in the ratio 1:7 (analyst: B. Nilsen). Oxide concentrations are in weigth percent, except for TiO_2, MnO and K_2O in weight parts per million. *nd*, not detected. Na_2O-concentrations are below the detection limits of 0.1 % for all of the samples. The detection limits for SiO_2, Al_2O_3, and P_2O_5 are 0.01 %. Table 2b illustates the analytical accuracy and precision.

Table 2b. Accuracy and precision of major element analyses illustrated by triplicate analyses of two synthetic standards

		SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	P_2O_5	TiO_2	MnO	K_2O
KST-22	*accepted*	*0.67*	*0.15*	*0.043*	*0.01*	*55.49*	*0.028*	*0.003*	*65*	*4*	*550*
	run 1	0.66	0.16	0.05	0.02	55.29	<0.1	<0.01	80	<20	540
	run 2	0.65	0.15	0.05	0.01	55.29	<0.1	<0.01	110	<20	540
	run 3	0.65	0.16	0.05	0.03	55.28	<0.1	<0.01	110	<20	540
KST-29	*accepted*	*30.03*	*6.02*	*3.155*	*1.345*	*31.99*	*2.155*	*0.215*	*700*	*1600*	*22200*
	run 1	30.04	6.11	3.14	1.31	31.94	2.13	0.20	680	1610	22290
	run 2	30.06	6.06	3.13	1.31	31.93	2.15	0.20	680	1610	22310
	run 3	30.15	6.09	3.13	1.32	31.93	2.11	0.20	690	1610	22350

The repeated measurements of the two synthetic standards were performed in sequence at the start of the analysis session.

Table 3. Acid soluble MgO and CaO (weight %) and trace elements (weight ppm)

Sample	MgO	CaO	F	V	Ni	Zn	Rb	Sr	Ba	Y	Zr	Yb	U
Gr-1a	0.7	55.3	2500	11	6	6	7	144	11	7	11	<10	14
Gr-1b	0.7	55.5	2700	13	5	6	6	96	<10	6	9	<10	13
K-12	0.9	55.0	6700	15	6	<5	<5	319	20	<5	6	15	13
K-14	0.6	55.4	6500	10	6	29	<5	193	21	<5	6	11	66
K-15	1.7	53.2	6600	16	5	<5	<5	293	20	<5	10	<10	<10
K-27	1.0	54.5	6700	25	16	7	<5	344	18	<5	8	15	43

CaO and MgO were determined by dissolving the sample powder in diluted HCl (1:4) during heating followed by titration with EDTA (analyst: J. Røste). The trace element concentrations were measured on a Phillips PW1480 X-ray fluorescence spectrometer on pressed pellets containing 5.4 g sample + 1.2 g Hoechst C wax (analyst: B. Nilsen). The following elements were measured but not detected (detection limits in ppm in brackets): S and Cl (1000); W (30); Sc, Co, Ga, As, Ag, Cd, Sn, Sb, La, Ce, Nd, Pb, and Th (10); Cr, Cu, Mo, Nb, (5).

Table 4. Reflectance values and CaO-contents (from XRF)

Sample	FMX	FMY	FMZ	R457	CaO
Gr-1a	96.6	96.1	93.6	93.6	55.32
Gr-1b	97.2	96.9	95.2	95.2	55.64
K-12	91.3	90.9	88.3	88.4	54.90
K-14	94.9	94.8	94.0	94.1	55.36
K-15	85.7	84.9	80.7	80.8	53.13
K-27	90.3	89.9	88.0	88.0	54.90

Measured on pressed powder pellets, using a Zeiss Elrepho Mat DFC5 and a $BaSO_4$-standard (DIN 5033). The grain size distribution of the sample powder is shown in Figure 12. Analysts: J. Røste and K. Solem.