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Origin of quartzo-feldspathic supracrustal rocks from the central part of the Nagssugtoqidian mobile belt of West Greenland

by

Anders Rehkopff

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Origin of quartzo-feldspathic supracrustal rocks from the central part of the Nagssugtoqidian mobile belt of West Greenland

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Abstract

The Marranguit–Kangilerssua supracrustals constitute a sequence of variable supracrustal lithologies intensely folded into surrounding orthogneisses and metamorphosed under granulite facies conditions. No field or petrographic evidence indicates the original nature of the individual supracrustal rock types.

Fortynine samples from the quartzo-feldspathic part of the supracrustals have been analysed for major elements and the trace elements Cr, Co, Ni, Cu, Zn, Rb, Sr, Zr and Ba. Ten different geochemical discrimination methods indicate that both metasedimentary and metaigneous material are present. The metaigneous rocks possess typical calc-alkaline differentiation trends and were originally extrusives. Mixing-zones between metasedimentary and metavolcanic material are interpreted as reflecting a pyroclastic nature of some of the metavolcanic rocks.

The quartzo-feldspathic part of the M–K supracrustals is dominated by greywacke/lithic arenite with subordinate intercalations of mudstone and single layers or lensoid bodies of subarkose and sublithic arenite. The greywacke/lithic arenite grade into calc-alkaline pyroclastics, which vary in composition from rhyodacite to rhyolite. Associated quartz-andesitic and dacitic extrusives occur throughout the supracrustal formation, which in addition contains thin layers of limestone, basic and ultrabasic rocks.

The supracrustals may be either Archaean or Proterozoic in age.

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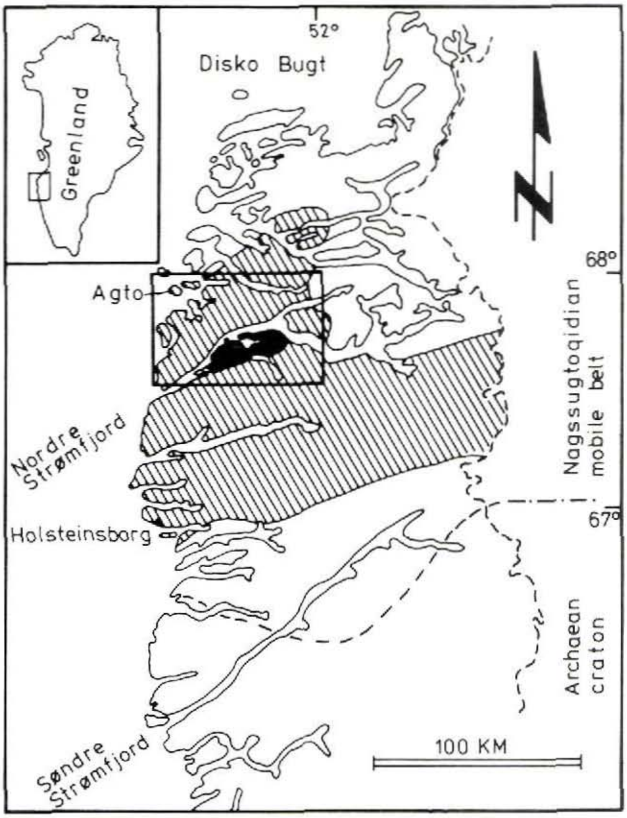


Fig. 1. The Nagssugtoqidian mobile belt of West Greenland. The ruled area is the granulite facies 'Isortoq' complex, bordered to the north and south by the 'Egedesminde' and 'Ikertoq' (amphibolite facies) complexes respectively (Ramberg, 1948). The Marranguit–Kangilerssua area within the map sheet Agto 67 V.1 Nord (boxed) is shown in black.

INTRODUCTION

The Marranguit–Kangilerssua (M–K) area is situated in the Nordre Strømfjord region (*Agto map sheet 67 V.1 Nord, 1:100 000) in the central part of the Nagssugtoqidian mobile* belt of West Greenland (figs 1 and 2), and belongs to the granulite facies Isortoq complex of Ramberg (1948). The northern parts of the area, the Marranguit and Nûk peninsulas, are within the Nordre Strømfjord shear zone (Bak *et al.*, 1975). Lithologies in the M–K area are similar to lithologies in other parts of the Nordre Strømfjord region (Olesen *et al.*, 1979; Getreuer & Rehkopff, 1980), and are characterised by two main lithologies:

(1) Monotonous, tonalitic to granitic gneisses.

(2) A heterogeneous sequence of rapidly alternating lithologies of garnet, sillimanite, cordierite, pyroxene and graphite-bearing quartzo-feldspathic gneisses and schists plus marbles and calc-silicate rocks.

Concordant amphibolites, ultramafic rocks and concordant and discordant pegmatites occur as minor constituents in both main lithologies; a few discordant metabasic dykes occur in the group (1) gneisses.

Throughout the area, rocks with suitable bulk chemical compositions (Korstgård, 1979;

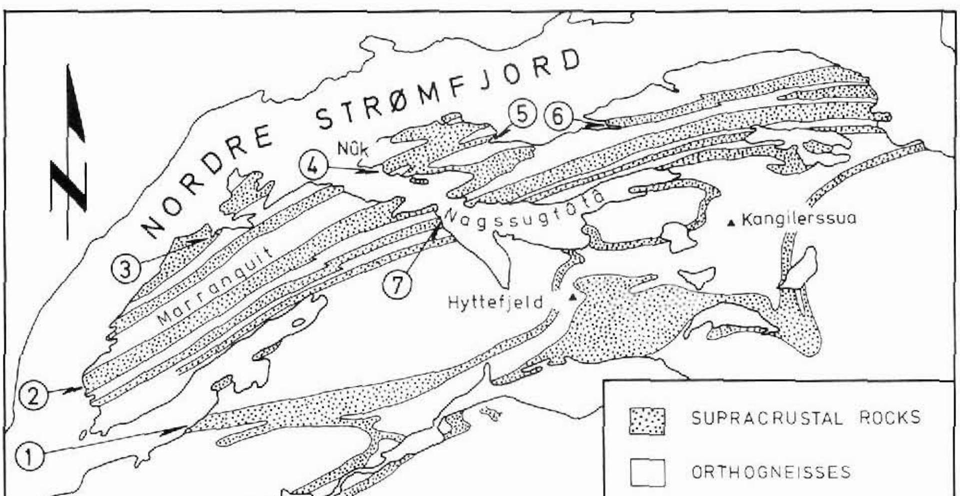


Fig. 2. Simplified geological map of the Marranguit–Kangilerssua area showing sampling sections.

Olsen, 1979) contain orthopyroxene, indicating granulite facies conditions during metamorphism.

Geochemical investigations have shown that the rocks in association (1) are orthogneisses (Korstgård, 1978). The different rock types in (2) are closely related spatially, and the presence of marbles, calc-silicate rocks and quartzitic rocks clearly points to a supracrustal origin of this sequence. Garnet-(sillimanite-)biotite gneisses from the same sequence in the Inugsuk area, south-west of the M–K area, possess geochemical variations typical of sedimentary rocks (Korstgård, 1978).

The general structural pattern in the area is typical for the Nagssugtoqidian mobile belt (Escher *et al.*, 1976) with an alternation between two types of macro-domains: (1) *Linear belts* which are characterised by isoclinal fold structures, well defined linear and planar fabrics and only minor variations in the orientation of all structural elements and (2) *Macroscopic augen areas* which display complex large-scale structures with varying orientations and rather poorly defined linear and planar fabrics. In these structural augen areas, macroscopic closed 'tube-folds' with constant orientation of fold-axes dominate. Detailed mapping and structural analysis (Getreuer & Rehkopff, 1980) have shown that it is possible to correlate most of the supracrustals and interpret them as belonging to a single sequence, intensely folded into the orthogneisses.

Field work in the M–K area was carried out in 1976 and 1977 as part of the Agto 2 project (Korstgård & Olesen, 1978). The supracrustals were sampled in detail in 1977. The aim of this paper is to present the geochemistry of the quartzo-feldspathic component of the M–K supracrustals and to discuss its origin.

SUPRACRUSTAL LITHOLOGIES

Field relations

The supracrustals in the M–K area are dominated by quartzo-feldspathic rocks containing concordant layers or lenses of amphibolitic and ultramafic rocks, with marbles and associated calc-silicate rocks as subordinate constituents. In some areas, such as the Nûk peninsula, it is possible to map the supracrustals in great lithological detail and follow the same sequence for considerable distances along the strike. However, it is not possible to recognize a consistent stratigraphy for the whole area. This may reflect primary variations within the supracrustal sequence or may be caused by deformation, or both. There are, however, some noteworthy features within the sequence (fig. 3): marbles and calc-silicate rocks are often the rock types in contact with the orthogneisses, or close to this contact. When the contact is not defined by marble, it is defined by garnet-sillimanite-biotite gneiss.

With respect to the quartzo-feldspathic supracrustals, the sequence (1) wavy foliated garnet-sillimanite-biotite gneiss, (2) heterogeneous banded garnet-biotite gneiss and (3) leucocratic garnet-biotite gneiss often occurs in this order (or the reverse). The contacts between these rock types are gradational. Quartzitic leuco-gneisses also have gradational contacts with the above mentioned rocks, but do not have a systematic spatial relationship to the other rock types. Quartzitic leuco-gneisses appear locally in the supracrustal sequence as 10–20 m thick concordant layers around Nagssugtûtâ, and as the dominant rock type, probably much thicker, in a tube-fold south-east of Hyttefjeld (fig. 2). Graphite and

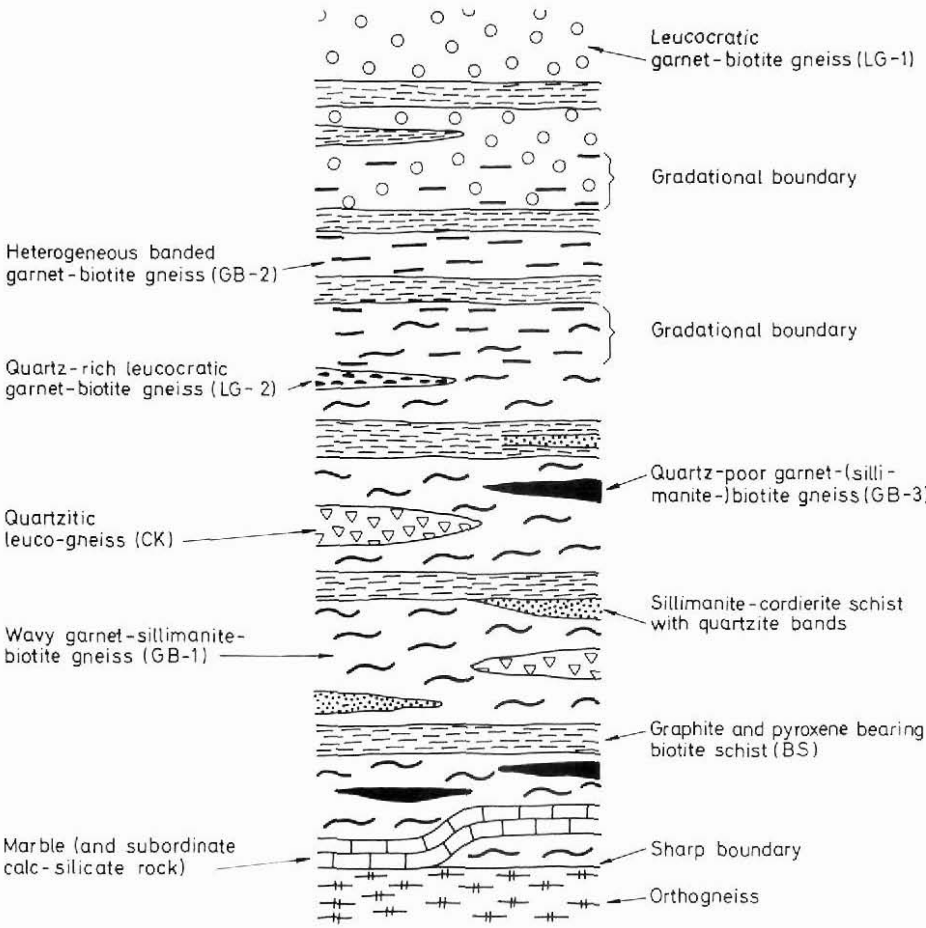


Fig. 3. Schematic representation of (observed and interpreted) field relations in the M–K supracrustals; amphibolites, ultramafic rocks and pegmatites not shown.

pyroxene bearing biotite schists occur within the supracrustal rock types as irregularly distributed 1–100 m thick concordant layers with sharp boundaries. Within the garnet-sillimanite-biotite gneiss, rather quartz-poor and garnet, biotite and sillimanite-rich zones occur (GB-3, see below). Rusty, often very graphite-rich (>50%), sillimanite-cordierite schists containing quartzite bands occur sporadically within the garnet-sillimanite-biotite gneiss and the biotite schist. Although often quartzo-feldspathic, the sillimanite-cordierite schists are not treated in this paper.

The boundary between the supracrustal sequence and the orthogneisses is sharp and concordant to the foliation; there are no relics of primary structures indicating whether it is a depositional or a tectonic contact. Likewise, no primary structures have been found in the supracrustals to indicate their environment of formation. The foliation in the rocks is parallel to lithological boundaries, and the microstructures are related to the latest deformational and metamorphic episodes in the area (Getreuer & Rehkopff, 1980).

Petrography

Brief descriptions of the quartzo-feldspathic supracrustals are given below.

The wavy garnet-sillimanite-biotite gneisses (GB-1) are bluish grey and homogeneous with alternating quartzo-feldspathic and biotite-rich layers. A pinch-and-swell structure is often developed, accentuated by biotite-rich layers wrapped around frequent garnet porphyroblasts within the light bands, imparting a characteristically wavy foliation. Sillimanite needles are always present in the biotite-rich bands, and graphite is often visible. Modal variations of this rock type are shown in fig. 4. Biotite and garnet are present in amounts from 1 to 10% and sillimanite from 1 to 5%. Accessory zircon is always present; apatite and opaque minerals are common accessory phases.

The heterogeneous banded garnet-biotite gneisses (GB-2) resemble the wavy garnet-sillimanite-biotite gneisses but have a much more heterogeneous banding or veining, in which rather homogeneous garnet-biotite gneiss alternates with white, pegmatitic bands, veins, lenses or streaks. Sillimanite and graphite are absent; garnet porphyroblasts are always present. The rock contains less quartz than GB-1 and in the QAP-diagram plots in the fields of quartz-poor granite to tonalite (fig. 4). Biotite contents vary from 1 to 20%; garnet from 0 to 5%. Accessory zircon is always present, and apatite and opaque minerals are common accessories.

The quartz-poor garnet-(sillimanite-)biotite gneisses (GB-3), which occur as minor zones in GB-1, have a rather variable mineralogical composition. The rock always has less quartz and more mafics than the other garnet-biotite gneisses. Garnet contents vary from 5 to 25%, biotite from 1 to 25% and sillimanite from 1 to 5%. The feldspar component of GB-3 is either dominantly plagioclase or dominantly alkali-feldspar (fig. 4). Graphite may be present as a minor or accessory phase; zircon, apatite and opaque minerals are common accessories.

The graphite and pyroxene bearing biotite schists (BS) are fine grained rocks, brown on weathered surfaces and khaki brown on fresh fractures, indicating the presence of orthopyroxene. The rock is well foliated, and fresh zones may alternate with more rusty zones on a metre scale. The rock is always

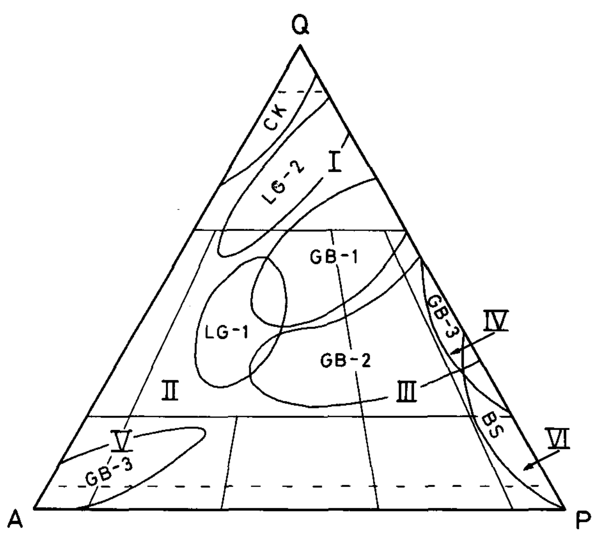


Fig. 4. Modal variations (visual estimates) within the investigated M–K supracrustal rock types shown in the QAP triangular diagram of Streckeisen (1974); abbreviations of rock types as explained in Table 2. Q: quartz, A: alkali-feldspar, P: plagioclase. I: quartz-rich granitoids, II: granites, III: granodiorites, IV: tonalites/trondhjemites, V: syenitic rocks, VI: quartz-diorites.

graphite and pyroxene bearing (orthopyroxene ≫ clinopyroxene), and may locally contain garnet. The felsic composition of the rock is rather constant, and lies within the quartz-dioritic to tonalitic range (fig. 4). Zircon, apatite and opaque minerals are always present as accessory phases.

The leucocratic gneisses are characterised by their low contents of mafic minerals, mainly biotite:

The leucocratic garnet-biotite gneisses (LG-1) are almost white rocks containing various amounts of randomly distributed garnets. Coarse grained isotropic varieties and medium grained foliated varieties are present. LG-1 may grade into a non-leucocratic rock type rich in red alkali-feldspar bands, with a higher content of biotite. On the QAP diagram (fig. 4), the rock plots in the granite field; biotite is present in amounts from 0 to 5% (in the non-leucocratic type 5–10%); garnet from 1 to 10%. Zircon is always present while apatite and opaque minerals are less common. Graphite and sillimanite are sporadic accessory minerals.

The quartz-rich leucocratic garnet-biotite gneisses (LG-2) are light grey, well foliated rocks and have been found in one horizon in the supracrustal sequence at the eastern part of Marranguit (sampling section 7, fig. 2). It is a quartz-rich granitoid rock (fig. 4) with up to 5% garnet and biotite. Graphite and sillimanite may be present as minor or accessory phases; rutile, zircon and opaque minerals are less common accessories.

The quartzitic leuco-gneisses (CK) are dominated by quartz and contain small amounts of plagioclase (2–5%), cordierite (2–5%) and biotite (0–10%); 10–25% alkali-feldspar may be present; minor sillimanite and graphite may occur. Zircon and opaque minerals are common accessories. The rock occurs as fine grained mylonites in the supracrustal sequence within the Nordre Strømfjord shear zone and in a medium to coarse grained variety with less pronounced fabric elements within a tube-fold south-east of Hyttefjeld.

GEOCHEMISTRY

Analytical procedures

The supracrustals have been sampled from 7 sections (fig. 2) and a few single localities; finely banded samples have been chosen to eliminate the variations caused by the banding. Fortynine samples have been analysed for major elements and the trace elements Cr, Co, Ni, Cu, Zn, Rb, Sr, Zr and Ba. Half of the major element analyses were carried out by the Geological Survey of Greenland; Na_2O and MgO were determined by atomic absorption and the other major elements by X-ray fluorescence analysis (XRF); the rest of the major element analyses and all the trace element determinations were carried out at the Department of Geology, Aarhus University, by XRF. These analyses were carried out on a Philips PW 1220/00 XRF spectrometer using powder pellets for the trace elements plus Na_2O, MnO and P_2O_5 (Leake *et al.*, 1969), and glass discs for the other major elements. FeO was determined by titration. The lower limits of detection for the trace elements are: Co: 4 ppm, Ni: 1 ppm, Ba: 5 ppm and Cr, Cu, Zn, Rb, Sr and Zr: 2 ppm (Bertin, 1975, p. 531).

Mean analyses of the 7 rock types studied are shown in Table 1; the abbreviations and symbols are explained in Table 2. A complete list of analyses is available from the author.

Table 1. Mean analyses of the 7 M–K supracrustal rock types

	GB-1 (N=9)			GB-2 (N=9)			GB-3 (N=5)		
	Mean	Range	s.d.	Mean	Range	s.d.	Mean	Range	s.d.
SiO_2	75.48	72.20-78.71	2.37	72.14	70.07-73.16	1.01	55.71	52.06-58.67	2.54
TiO_2	0.51	0.42- 0.61	0.06	0.31	0.17- 0.51	0.09	1.01	0.62- 1.36	0.30
Al_2O_3	11.40	9.36-13.04	1.42	14.55	14.07-15.49	0.43	20.37	16.40-24.89	3.07
Fe_2O_3	0.36	0.02- 0.94	0.30	0.24	0.02- 0.79	0.25	1.43	0.62- 2.39	0.81
FeO	3.48	2.93- 4.16	0.42	1.83	0.95- 3.43	0.73	6.88	3.69- 8.94	2.01
FeO^{tot}	3.80	3.24- 4.44	0.50	2.05	1.05- 3.75	0.80	8.16	4.56- 9.80	2.08
MnO	0.06	0.03- 0.08	0.02	0.04	0.00- 0.09	0.03(8)	0.31	0.10- 0.74	0.26
MgO	1.62	1.31- 2.04	0.29	0.84	0.51- 1.74	0.37	3.60	2.19- 5.56	1.35
CaO	1.40	0.87- 1.95	0.30	2.27	0.79- 3.47	0.88	2.45	1.38- 3.81	0.91
Na_2O	2.36	1.74- 2.93	0.34	3.95	3.12- 4.74	0.55	2.47	1.62- 3.09	0.65
K_2O	2.40	1.46- 3.53	0.57	2.92	1.35- 6.05	1.57	3.50	1.13- 6.16	2.11
P_2O_5	0.07	0.04- 0.10	0.02	0.09	0.07- 0.13	0.03	0.11	0.04- 0.21	0.07
Vol.	0.62	0.42- 0.84	0.15	0.50	0.37- 0.86	0.16	1.30	0.27- 2.42	0.82
Cr	80	66- 107	13	7	2- 17	5	210	139- 386	100
Co	7	0- 17	6(7)	4	0- 11	5(4)	24	10- 31	9
Ni	21	13- 28	4	8	3- 20	5	62	27- 98	33
Cu	10	5- 20	5	9	3- 36	10	30	7- 54	20
Zn	73	54- 108	18	52	26- 67	13	127	92- 168	30
Rb	109	75- 204	38	110	65- 217	49	134	30- 277	101
Sr	191	120- 260	47	202	129- 338	80	246	159- 327	76
Zr	221	175- 308	40	143	97- 222	37	178	125- 233	49
Ba	498	210- 739	136	435	134- 661	186	825	319-1517	437

	BS (N=8)			LG-1 (N=11)		
	Mean	Range	s.d.	Mean	Range	s.d.
SiO_2	62.98	56.85-69.40	5.41	74.48	71.50-77.54	1.82
TiO_2	0.55	0.37- 0.71	0.11	0.15	0.02- 0.27	0.08
Al_2O_3	15.50	13.61-17.59	1.60	13.68	11.23-14.56	0.90
Fe_2O_3	1.40	0.23- 3.62	1.25	0.07	0.00- 0.41	0.12(5)
FeO	3.37	1.60- 4.58	1.09	1.02	0.66- 1.82	0.37
FeO^{tot}	4.63	1.89- 5.85	1.28	1.08	0.66- 1.92	0.44
MnO	0.08	0.02- 0.11	0.03	0.03	0.01- 0.06	0.02
MgO	3.28	1.76- 5.06	1.11	0.41	0.22- 0.80	0.17
CaO	4.19	3.17- 5.38	0.74	1.24	0.71- 2.76	0.59
Na_2O	3.25	2.57- 3.95	0.50	3.71	2.89- 4.41	0.49
K_2O	2.79	1.74- 4.40	0.84	4.67	1.25- 6.24	1.38
P_2O_5	0.25	0.12- 0.31	0.08	0.08	0.04- 0.14	0.03
Vol.	1.77	0.42- 3.22	1.00	0.34	0.20- 0.43	0.07
Cr	246	63- 403	101	3	0- 14	4(7)
Co	19	5- 33	10	0	0- 5	2(1)
Ni	80	24- 137	48	4	2- 11	3
Cu	69	10- 130	44	6	3- 20	5
Zn	202	65- 458	135	28	10- 56	14
Rb	97	67- 140	23	168	24- 223	55
Sr	578	395- 891	184	142	48- 230	62
Zr	114	84- 138	19	100	44- 223	56
Ba	857	485-1099	218	424	173- 794	193

Table 1 cont.

	LG-2 (N=4)			CK (N=3)		
	Mean	Range	s.d.	Mean	Range	s.d.
SiO_2	84.50	83.23-85.72	1.08	90.05	88.71-90.78	1.16
TiO_2	0.22	0.10- 0.41	0.14	0.14	0.07- 0.26	0.10
Al_2O_3	8.39	7.46- 9.05	0.67	5.10	4.35- 6.27	1.03
Fe_2O_3	0.11	0.00- 0.21	0.09(3)	0.01	0.00- 0.03	0.02(1)
FeO	1.92	1.04- 3.50	1.14	0.78	0.38- 1.41	0.55
FeO^{tot}	2.02	1.17- 3.69	1.18	0.79	0.38- 1.44	0.57
MnO	0.04	0.00- 0.08	0.03(3)	0.01	0.00- 0.03	0.02(1)
MgO	1.07	0.78- 1.39	0.27	1.11	0.88- 1.44	0.29
CaO	0.71	0.09- 1.53	0.62	0.47	0.04- 0.70	0.37
Na_2O	1.37	0.78- 1.68	0.41	0.40	0.17- 0.54	0.20
K_2O	2.50	1.15- 3.27	1.01	1.73	1.04- 2.14	0.60
P_2O_5	0.04	0.02- 0.05	0.01	0.03	0.01- 0.04	0.02
Vol.	0.44	0.34- 0.55	0.09	1.01	0.52- 1.67	0.59
Cr	23	16- 32	7	17	9- 22	7
Co	1	0- 5	3(1)	0		0
Ni	7	4- 10	3	10	3- 17	7
Cu	7	5- 8	2	6	4- 7	2
Zn	29	23- 35	6	30	17- 49	17
Rb	82	46- 137	41	57	32- 89	29
Sr	93	70- 112	18	59	41- 79	19
Zr	156	134- 197	28	145	108- 182	37
Ba	587	398- 730	145	598	480- 824	196

s.d. = standard deviation; N = number of samples; oxides in wt.% and trace elements in ppm.
For elements, where the mean contains samples with the value 0 (not detected), the number of samples containing significant amounts of the element is given in brackets.

Major elements

In fig. 5 all analyses are plotted in AFM and normative Qz – Or – Ab+An triangular diagrams. From this figure and Table 1 the most characteristic major element relations can be deduced. In general, the rocks show a rather constant FeO^{total}/MgO ratio, falling within the calc-alkaline trend in the AFM diagram. Relatively spoken, LG-1 is richest in Na_2O+K_2O, succeeded by GB-2, LG-2, GB-1 and then GB-3. There is an overlap between LG-1 and GB-2 in the AFM diagram, but since GB-2 has higher CaO and lower K_2O

Table 2. The M–K supracrustal rock types with indication of their respective abbreviations and symbols used in the diagrams

ROCK TYPE	Abbr.	SYMBOL	N
Wavy garnet-sillimanite-biotite gneiss	GB-1	⊕	9
Heterogeneous banded garnet-biotite gneiss	GB-2	○	9
Quartz-poor garnet-(sillimanite)-biotite gneiss	GB-3	●	5
Leucocratic garnet-biotite gneiss	LG-1	△	11
Quartz-rich leucocratic garnet-biotite gneiss	LG-2	▲	4
Quartzitic leuco-gneiss	CK	▽	3
Graphite-pyroxene-bearing biotite schist	BS	+	8

N is the number of samples investigated.

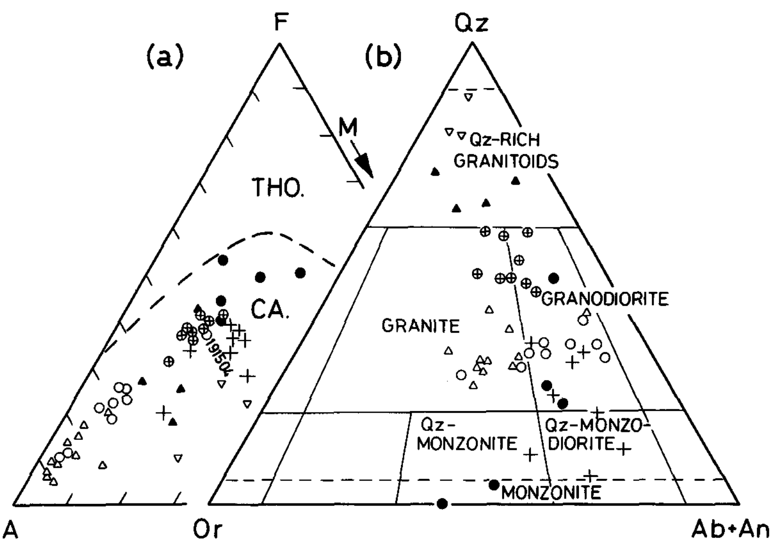


Fig. 5. The principal geochemical relations within the M–K supracrustals; symbols as explained in Table 2. (a) AFM diagram divided in tholeiitic (THO) and calc-alkaline (CA) fields (Irvine & Baragar, 1971). (b) CIPW normative Qz – Or – Ab+An triangular diagram divided in composition fields similar to the QAP triangle of Streckeisen (1974).

contents than LG-1, the two rock types are clearly separated in fig. 5b, where LG-1 and GB-2 plot in the normative granitic and granodioritic fields, respectively. Compared with GB-2 (and LG-1), GB-1 has higher SiO_2, FeO^{total} and MgO and lower alkali contents and plots in the normative quartz-rich granitic-granodioritic fields (fig. 5b). One of the GB-2 samples (GGU no. 191504) shows affinities to GB-1 (fig. 5a). This is the only GB-2 sample from section 1 (fig. 2), and is intermediate between GB-1 and GB-2. LG-2 and CK are SiO_2-rich and lower in Al_2O_3, CaO, Na_2O and K_2O than the other rock types. The very high SiO_2 content and correspondingly lower contents of all other oxides in CK compared to LG-2 separate the two rock types geochemically; the FeO^{total}/MgO ratio in CK is lower than in the other rock types. GB-3 and BS are the rock types lowest in SiO_2 and highest in TiO_2, Al_2O_3, FeO^{total} and MgO. Between the two, GB-3 is lowest in SiO_2 and has a higher FeO^{total}/MgO ratio than BS; BS has the highest CaO contents (mean 4.19%) of the supracrustals.

Trace elements

The trace element relations are shown in fig. 6. Apart from Rb and Zr, the SiO_2-poor BS samples possess the highest trace element contents. For the other supracrustals, Cr, Co, Ni, Cu and Zn in general show a negative correlation with SiO_2, this trend being rather smooth in the succession GB-3, GB-1, LG-2 and CK. LG-1 and GB-2, which have almost the same SiO_2 content as GB-1, are lower in these elements than GB-1, lying below the trend defined by the other supracrustals. Zr and Rb do not show any correlation with SiO_2, GB-1 being highest and LG-1 lowest in Zr, while LG-1 and two GB-3 samples have notably high Rb contents. Likewise, Ba does not show any correlation with SiO_2, and some scatter is seen within each rock type. BS and GB-3 have higher mean Ba levels than the other rock types. Apart from BS which is highest in Sr among the supracrustals, there is a general decrease in Sr with increasing SiO_2.

Metasomatism

It has been convincingly demonstrated that granulite facies metamorphism may lead to depletion of 'granitophile' elements (e.g. Lambert & Heier, 1968; Sighinolfi, 1971; Holland & Lambert, 1972) and give rise to magmatic-like trends in the depleted, more basic granulite facies residuum (Sighinolfi & Gorgoni, 1978). Likewise, the formation of meso- and macroscopic shear zones may change the chemistry of the deformed rocks and increase the correlation among certain elements within these rocks (Beach, 1973, 1976). The possibility of serious metasomatic changes of the original compositions of the M–K supracrustals cannot therefore be neglected. However, no unambiguous field, petrographic or geochemical evidence indicate such changes (Rehkopff, 1981): K–Rb–Sr data are inconclusive, and investigation of Barth's (1948) 'unit-cell' in the manner of Beech & Chadwick (1980) does not show any samples as clearly metasomatized. The formation of the the fine banding in the garnet-(sillimanite-)biotite gneisses is attributed to a combination of both primary variations, anatexis and metamorphic segregation (Yardley, 1978), but as this banding is in a much smaller scale than sample size, these variations are eliminated. It thus seems reasonable to assume that the supracrustals have not undergone any severe metasomatic changes

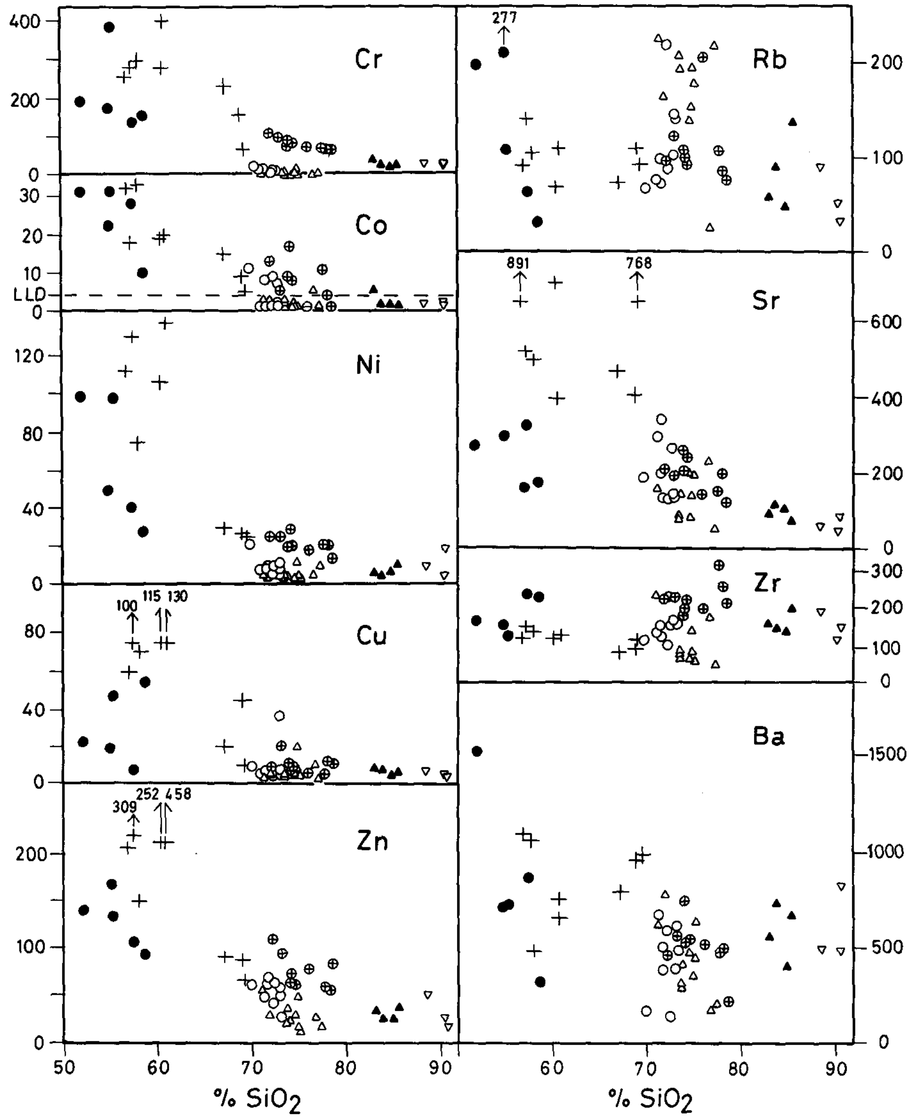


Fig. 6. Trace elements (ppm) plottet against SiO_2 (wt.%) for the M–K supracrustals; symbols as explained in Table 2.

although minor changes, especially involving the alkalies, cannot be excluded. An exception is the Fe_2O_3/FeO ratio, which probably reflects the oxygen-fugacity during metamorphism. The fairly low Fe_2O_3/FeO ratio (mean 0.12, excluding two anomalous samples) is in agreement with the presence of graphite in some of the supracrustals (Winkler, 1974, p. 22).

ORIGIN OF THE SUPRACRUSTALS

In the absence of any diagnostic field or petrographic evidence as to the original nature of the M–K supracrustals, geochemical criteria will be considered. In view of the fact that the composition fields of sedimentary and igneous rocks are, in general, very similar, comparisons of average analyses have mostly been avoided. Discrimination diagrams based on few elements or computed parameters have been used.

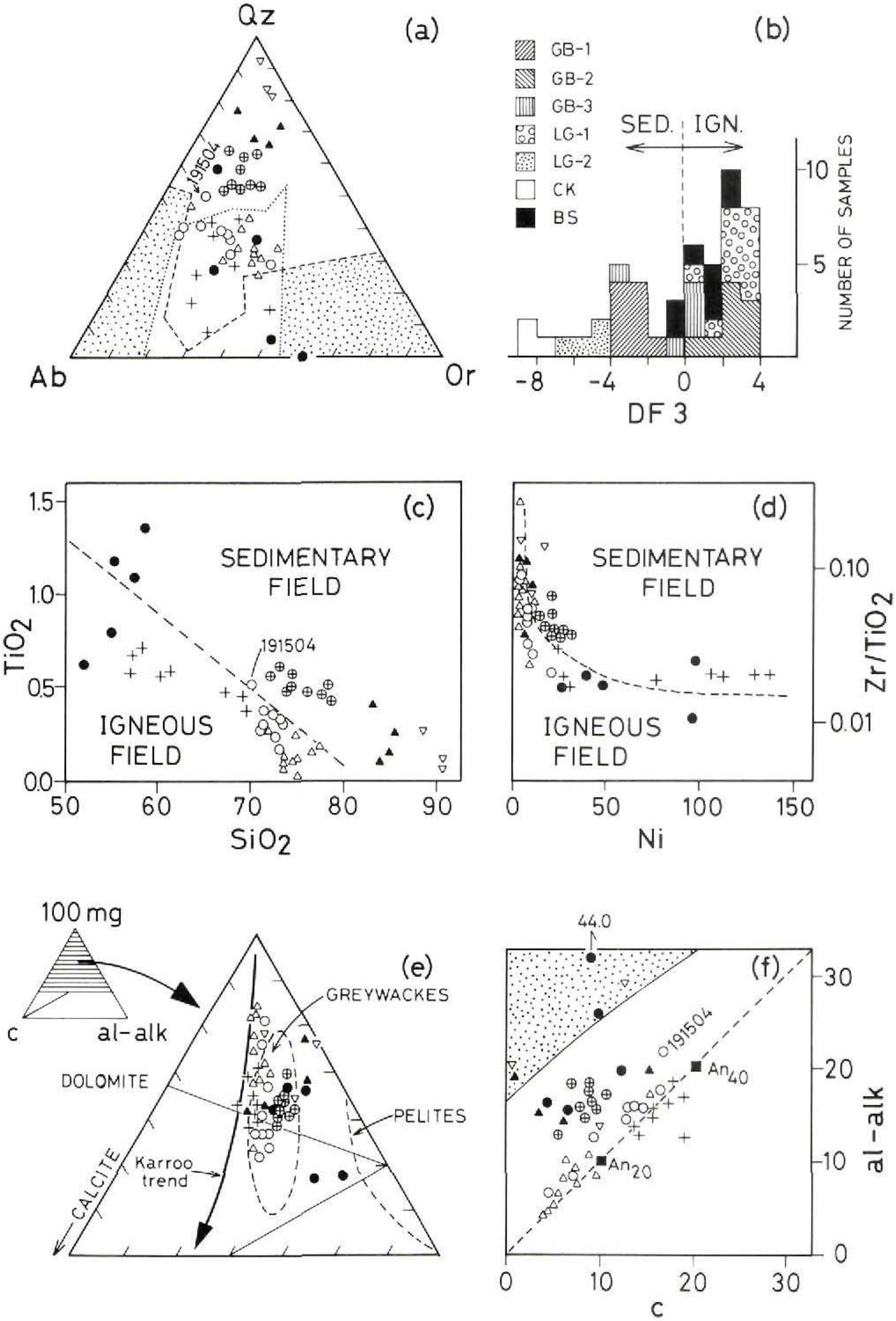
Using analyses of rhyolites, dacites and arkoses, Davoine (1969) was able to identify para-leptynites as having CaO <2.5%, in combination with $Na_2O + K_2O$ <7%. The discriminator only works one way; the field outside the para-leptynite field is inconclusive. According to this criterion, all of the GB-1, LG-2 and CK samples are metasedimentary.

Blackburn (1974) suggested that normative corundum >5% indicated sedimentary parentage; using this criterion only 3 GB-3 samples are deemed metasedimentary. Furthermore, Blackburn (1974) found that a MgO/CaO ratio >1, combined with a K_2O/Na_2O ratio >1, was characteristic of many sedimentary rocks, especially pelites rich in illite or montmorillonite. All CK samples, and most of the LG-2 and GB-3 samples are of metasedimentary origin according to this discriminator. Only 3 out of the 9 GB-1 samples are indicated as being of sedimentary origin; this may suggest a sediment poor in pelitic material. The test is inconclusive for the other rock types.

Shaw (1972) presented a normative Qz–Ab–Or triangular diagram in which the composition fields of sedimentary and igneous rocks are outlined (fig. 7a); in this diagram there is a large area of overlap. However, a clear sedimentary origin is inferred for the most quartz-rich supracrustals, GB-1, LG-2 and CK. In addition, Shaw (1972) found that the function DF 3 = $10.44 - 0.21\,SiO_2 - 0.32\,Fe_2O_3^{total} - 0.98\,MgO + 0.55\,CaO + 1.46\,Na_2O + 0.54\,K_2O$ represented the most successful discriminator; positive values of DF 3 indicate igneous parentage and negative values sedimentary parentage. Using this method (fig. 7b) GB-1, LG-2 and CK are deemed metasedimentary, while LG-1 and GB-2 are considered as having igneous protoliths. BS and GB-3 give ambiguous results, although most of these samples show igneous affinities. The same results are obtained in the SiO_2 versus TiO_2 discrimination diagram (fig. 7c) proposed by Tarney (1977). While this method clearly indicates an igneous parentage for all the BS samples, the results for GB-3 are ambiguous, and one GB-2 sample (191504) shows sedimentary affinity.

Winchester *et al.* (1980) suggested that the SiO_2-TiO_2 diagram should be supplemented by a Zr/TiO_2 versus Ni discrimination diagram (fig. 7d) because Zr, Ti and Ni are thought to be relatively immobile during metamorphism. This discriminator is of limited value for the M–K supracrustals since most of the rock types plot on or near the line separating igneous and sedimentary fields. However, GB-1 has clear sedimentary affinities, while LG-1 and GB-2 show unambiguous igneous Zr-TiO_2-Ni relations.

Discrimination diagrams based on Niggli numbers have been widely used to investigate the origin of especially amphibolites (e.g. Evans & Leake, 1960; Leake, 1964; Van de Kamp, 1969; Rivalenti & Sighinolfi, 1969; Kalsbeek & Leake, 1970; Satyanarayana *et al.*, 1974), but have also proved to be useful for other rock types (e.g. Van de Kamp, 1968, 1970; Leake, 1969; Wilson & Leake, 1972; Senior & Leake, 1978; Leake, 1980). In a Niggli *c* versus Niggli *mg* plot BS shows an igneous trend (fig. not shown). However, the diagram is inconclusive for the other supracrustals, which may partly be due to Niggli *mg* being an inefficient



Qz
(a)
191504
Ab
Or
(b)
GB-1
GB-2
GB-3
LG-1
LG-2
CK
BS
SED.
IGN.
NUMBER OF SAMPLES
DF 3
(c)
SEDIMENTARY FIELD
IGNEOUS FIELD
191504
TiO2
SiO2
(d)
SEDIMENTARY FIELD
IGNEOUS FIELD
Zr/TiO2
Ni
100 mg
c
al-alk
(e)
GREYWACKES
DOLOMITE
PELITES
Karroo trend
CALCITE
(f)
44.0
191504
An40
An20
al-alk
c

Table 3. Summary of the results of the discriminators used to establish the origin of the M–K supracrustals

DISCRIMINATOR	GB-1	GB-2	GB-3	LG-1	LG-2	CK	BS
$CaO - Na_2O + K_2O$	S	–	–	–	S	S	–
Normative Corundum	–	–	(S)	–	–	–	–
$MgO/CaO - K_2O/Na_2O$	(S)	–	S	–	S	S	–
Normative Qz-Ab-Or	S	–	–	–	S	S	–
DF 3	S	I	(I)	I	S	S	(I)
$TiO_2 - SiO_2$	S	I	–	I	S	S	I
$Zr/TiO_2 - Ni$	S	I	–	I	–	–	–
Niggli mg - c	–	–	–	–	–	–	I
Niggli c - (al - alk)	S	I	S	I	S	S	I
Niggli c - 100mg - (al - alk)	S	I	S	I	S	S	I
SCORE	-7	+5	-3	+5	-7	-7	+4

S, sedimentary parentage; I, igneous parentage; (), uncertain result; –, inconclusive test. For each rock type the combined result of all discriminators is quantitatively expressed in 'score', where S = −1, I = +1, () = 0 and – = 0.

differentiation indicator in the intermediate-acid range occupied by most M–K supracrustals. A Niggli *al–alk* versus Niggli *c* plot (fig. 7f) is more successful: while most samples plot inside the field of overlap between sedimentary and igneous compositions, LG-1, GB-2 and BS define clearly igneous trends of variation, parallel to the feldspar line. The other rock types lie in the field of *al–alk* poor greywackes. The same features are seen in the triangular diagram combining Niggli *c, mg* and *al–alk* (fig. 7e): BS, LG-1 and GB-2 both separately and together create an igneous trend. GB-1, LG-2, GB-3 and CK do not follow this igneous trend and are mainly clustered in the field of greywackes. A sedimentary origin is therefore

Fig. 7. The M–K supracrustals plotted in various diagrams for the distinction between metasedimentary and metaigneous rocks. Symbols as explained in Table 2. (a) CIPW normative Qz–Ab–Or triangular diagram. Dotted line encloses field of igneous rocks, dashed line sedimentary rocks. Vacant fields stippled. After Shaw (1972). (b) Histogram of DF 3 values (Shaw, 1972). Positive values indicate igneous parentage and negative values sedimentary parentage. (c) TiO_2 versus SiO_2 discrimination diagram (Tarney, 1977); dashed line separates sedimentary from igneous rocks. Oxides in wt.%. (d) Zr/TiO_2 versus Ni discrimination diagram (Winchester *et al.*, 1980). Zr and Ni in ppm and TiO_2 in wt.% × 10^4; dashed line separates igneous and sedimentary rocks. (e) Niggli *c* – 100 *mg* – (*al–alk*) triangular diagram. Variation trends of the Karroo dolerites, dolomite-pelite and calcite-pelite mixtures and the composition field of typical pelites drawn from Kalsbeek & Leake (1970); the composition field of greywackes is from Satyanarayana *et al.* (1974). (f) Niggli *al–alk* versus Niggli *c* variation diagram (Leake, 1969). The feldspar line (dashed) with the position of plagioclases with different compositions shown (filled boxes). The full line separates field of overlap between sedimentary and igneous compositions from field of sedimentary compositions (stippled).

inferred for these rocks, and it is also noted that (perhaps apart from two GB-3 samples) there is no indication of significant amounts of dolomite-pelite-calcite components in the original sediments.

The results of the discrimination methods used are summarized in Table 3. It is noted that while many of the tests are inconclusive, there are no conflicting results. It is therefore

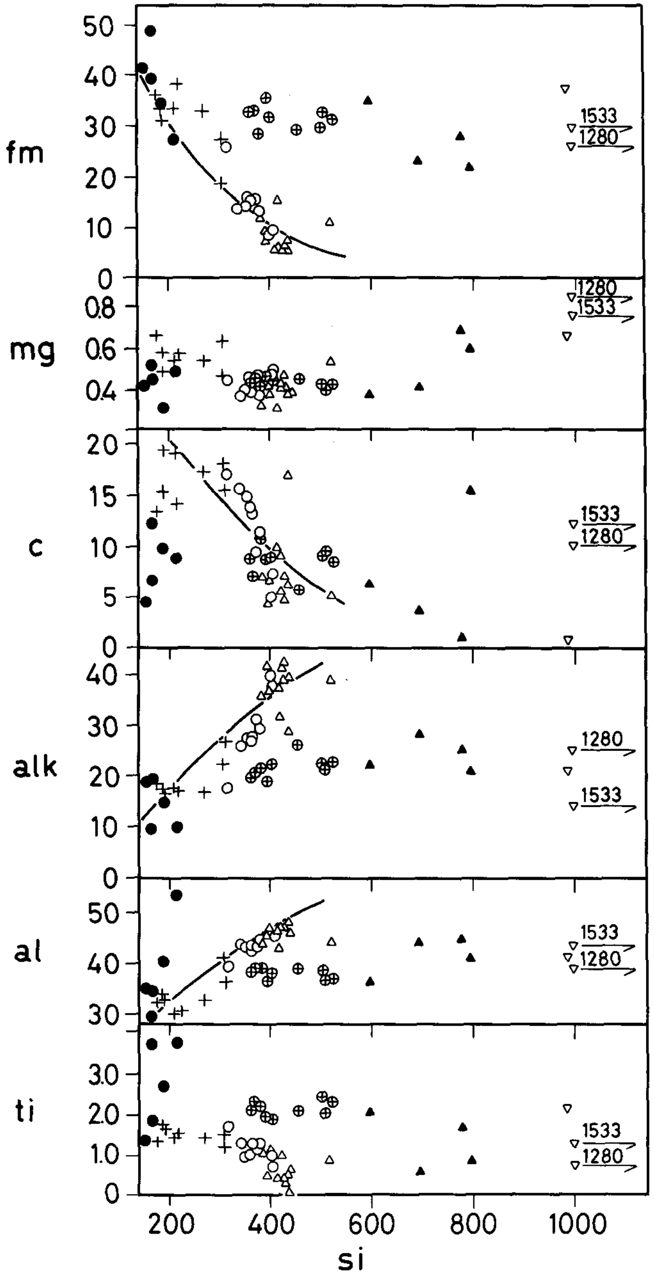


Fig. 8. Niggli *fm, mg, c, alk, al* and *ti* versus Niggli *si* for the M–K supracrustals. Calc-alkaline igneous trends (Zeil & Pichler, 1967) are shown. Symbols as explained in Table 2.

suggested that GB-1, GB-3, LG-2 and CK have sedimentary protoliths while GB-2, LG-1 and BS are of igneous parentage. These results are substantiated by the Niggli variation diagrams (fig. 8) in which LG-1, GB-2 and BS collectively and partly also individually have well defined igneous trends. Niggli *c, ti, fm* (and to a lesser extent *mg*) show negative, and *al* and *alk* positive correlations with Niggli *si,* variations which are typical of intermediate to acid igneous rocks (e.g. Barth, 1962, p. 164; Zeil & Pichler, 1967). GB-1, GB-3, LG-2 and CK show no correlation between Niggli *si* and the other Niggli values and there is a slight indication of a positive correlation between Niggli *si* and *mg,* a relation not expected in igneous rocks but which may be found in sedimentary rocks (Van de Kamp *et al.,* 1976).

It is, therefore, concluded that the M–K supracrustals consist of alternating layers of metamorphosed sedimentary and igneous rocks. Since rather consistent lithological successions can be recognized over large areas and metaigneous rock types (GB-2 and LG-1) exhibit gradational boundaries towards the metasediments, the metaigneous rocks must originally have been extrusives and are most easily explained as reflecting pyroclastic deposits; the transitional boundaries would then be mixing zones of sedimentary and pyroclastic material. Sample 191504 (e.g. figs 5a, 7a, c, f) is thought to reflect such a mixing zone between GB-1 and GB-2.

THE PREMETAMORPHIC NATURE OF THE METASEDIMENTS

In specifying the original nature of the M–K metasediments, it is first noted that no pelite-dolomite-calcite trends are seen on the Niggli diagrams (figs 7e-f). GB-1 shows affinities to greywackes, and the high SiO_2 content of LG-2 and CK indicates that they may also represent terrigeneous sandstones. The high contents of FeO^{total}, MgO and Al_2O_3, and corresponding low SiO_2 in GB-3 may indicate a more pelitic precursor for this rock type.

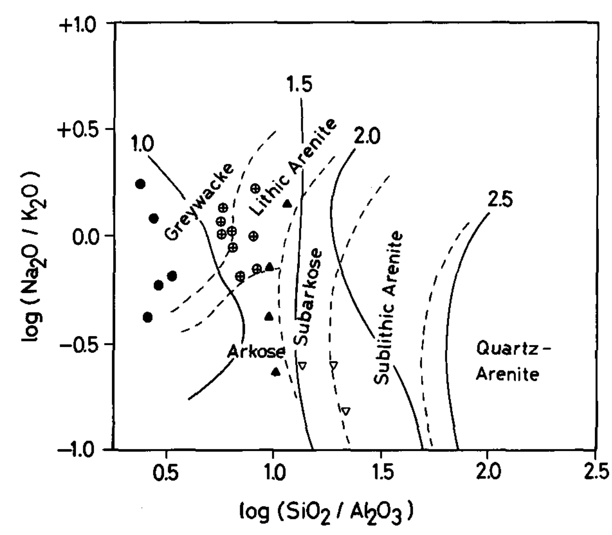


Fig. 9. Log (Na_2O/K_2O) versus log (SiO_2/Al_2O_3) plot of the M–K metasediments; oxides in wt.%. Dashed lines separate fields of different sandstones and full lines represent different values of log (($SiO_2+Al_2O_3$)/(Na_2O+K_2O)). From Pettijohn *et al.* (1973). Symbols as explained in Table 2.

In a log (Na_2O/K_2O) versus log (SiO_2/Al_2O_3) diagram (fig. 9), GB-3 and 4 GB-1 samples plot in the greywacke field, whereas the rest of the GB-1 samples are classified as lithic arenites. The variable Na_2O/K_2O ratio of LG-2 classifies the samples as either arkoses or lithic arenites, approaching subarkosic compositions. The CK samples plot as subarkoses or sublithic arenites. As the expression log $((SiO_2+Al_2O_3)/(Na_2O+K_2O))$ is a measure of the degree of compositional maturity of the sandstones (Pettijohn *et al.*, 1973, p. 61), increasing maturity is seen in the succession GB-3, GB-1, LG-2 and CK.

Similar results are obtained by comparing average analyses with published analyses of sandstones (e.g. Pettijohn, 1975, p. 216–274). However, apart from the Na_2O/K_2O ratio, GB-1 may just as well correspond to a Fe-Mg rich arkose, whereas GB-3 is pelitic and compares well with analyses of shales and slates (mudstones).

THE PREMETAMORPHIC NATURE OF THE METAVOLCANICS

According to their chemical compositions, the volcanic precursors of LG-1, GB-2 and BS were slightly peraluminous (corundum normative) and intermediate to acid (quartz normative) rocks. From the diagrams of Irvine & Baragar (1971) the rocks are subalkaline (fig. 10a) mostly with calc-alkaline Al_2O_3 – normative An % relations (fig. 10b) and show a typical calc-alkaline iron-depletion trend in the AFM diagram (fig. 5a). For such rocks a classification, based on normative Colour Index (C.I.) and normative An %, is appropriate and classifies BS as andesites, GB-2 mainly as dacites and LG-1 as dacites to rhyolites (fig. 10c). The andesites are partly K-rich, while most of the other volcanics lie in the normal composition field in a normative feldspar triangular diagram (fig. 10d).

Comparison of the compositions of the M–K metavolcanics with published averages of the Andesite-Dacite-Rhyolite association (Zeil & Pichler, 1967; Ewart *et al.*, 1968; El-Hinnawi *et al.*, 1969; Irvine & Baragar, 1971; Carmichael *et al.*, 1974, p. 35; Ewart, 1979) indicates that LG-1 has rhyolitic chemistry, whereas GB-2 has both rhyolitic (SiO_2) and dacitic (Na_2O, K_2O and CaO) affinities, comparing quite well with analyses of rhyodacites. The SiO_2-rich schists (BS, 3 samples) have dacitic chemistry and the SiO_2-poor schists (BS, 5 samples) are quartz-andesitic. Classification methods based on elements believed to be immobile during metamorphism and deformation provide the same results (Winchester & Floyd, 1976; Floyd & Winchester, 1978) (fig. 10e-f).

The geochemical variations of the metavolcanics substantiate their calc-alkaline character (El Hinnawi *et al.*, 1969; Jensen, 1973; Bailey, 1979, p. 186–218; Ewart, 1979), and in most cases systematic and well defined variations are exhibited against the Thornton-Tuttle Differentiation Index (D.I.) (fig. 11). The smooth trends in figs 8 & 11 and the gradational field and geochemical relations imply that these rocks are comagmatic. The observed variations thus express a calc-alkaline differentiation from quartz-andesite to rhyolite within the M–K metavolcanics. As argued elsewhere, at least the rhyodacites and the rhyolites must originally have formed as pyroclastic rocks.

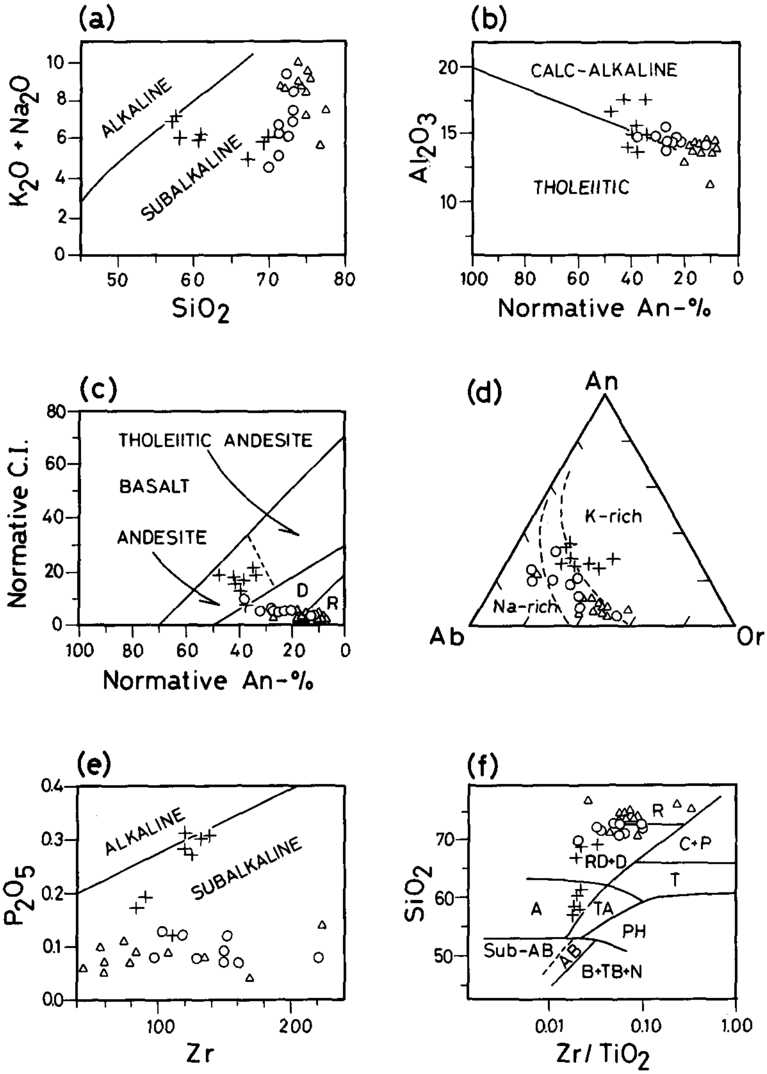
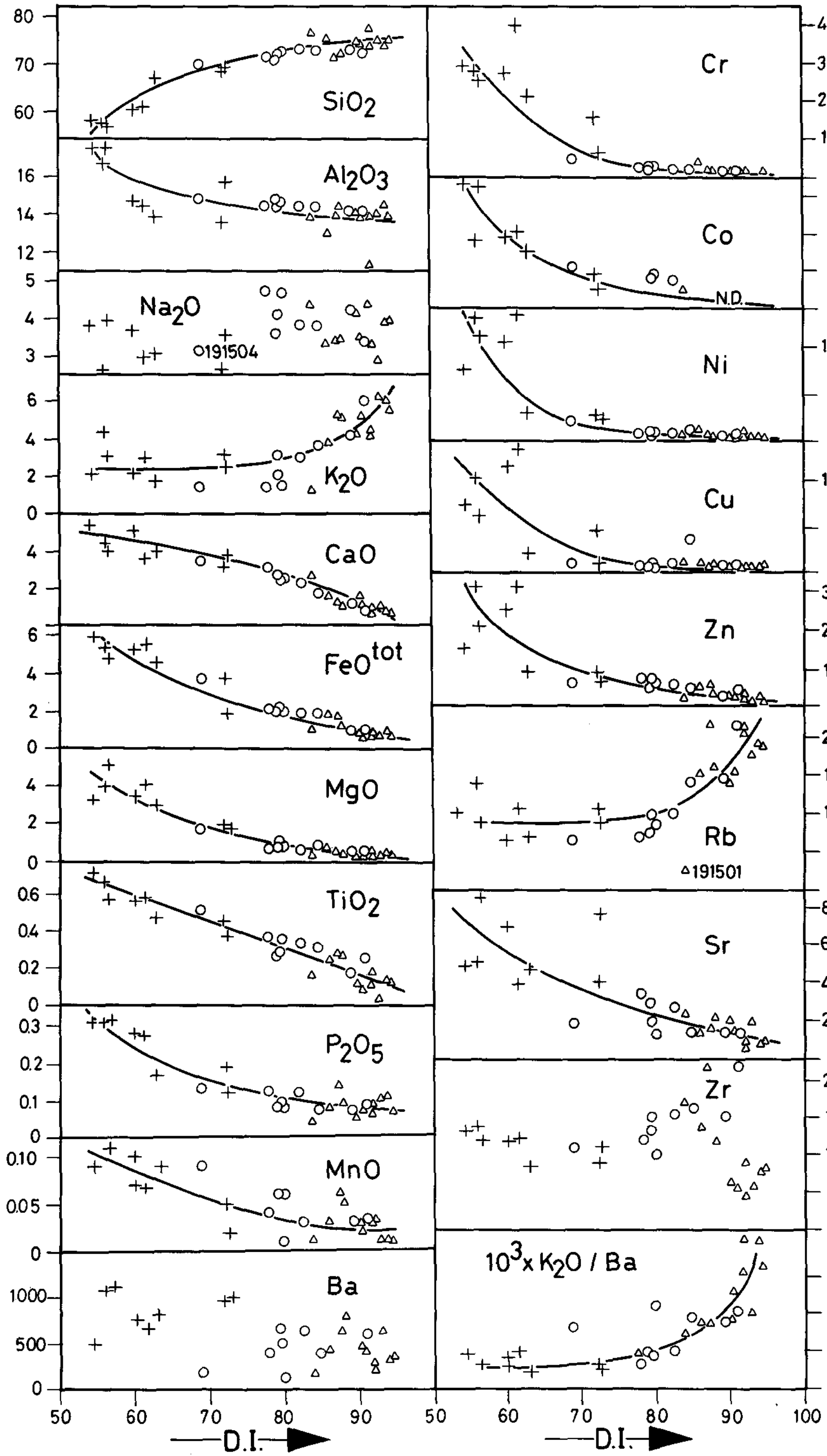


Fig. 10. The M–K metavolcanics plotted in different variation diagrams for the classification of volcanic rocks, mainly according to the procedure of Irvine & Baragar (1971) (a – d). Symbols as explained in Table 2. (a) K_2O+Na_2O versus SiO_2 (wt.%). (b) Al_2O_3(wt.%) versus CIPW normative An % = 100 An/(An+Ab). (c) CIPW normative An % versus normative Colour Index (C.I.) = Ol + Hy + Di + Mt + Il + Hm. D = dacite and R = rhyolite. (d) CIPW normative Ab–An–Or triangular diagram. Dashed lines separate the field of average rocks from Na and K-rich rocks respectively. (e) P_2O_5 (wt.%) versus Zr (ppm) plot with alkaline and subalkaline fields from Winchester & Floyd (1976). (f) SiO_2 (wt.%) versus Zr (ppm)/TiO_2(wt.% × 10^4) diagram with composition fields of different volcanic rocks according to Floyd & Winchester (1978). AB = alkali basalts, hawaiites, mugearites and trachybasalts; Sub-AB = subalkaline basalts; B+TB+N = basanites, trachybasanites and nephelinites; A = andesites; RD+D = rhyodacites and dacites; R = rhyolites; TA = trachyandesites; T = trachytes; PH = phonolites and C+P = comendites and pantellerites.


SiO2
Al2O3
Na2O
o191504
K2O
CaO
FeO tot
MgO
TiO2
P2O5
MnO
Ba
Cr
Co
N.D.
Ni
Cu
Zn
Rb
△191501
Sr
Zr
10³x K2O / Ba
D.I.
D.I.

SUMMARY AND DISCUSSION

The geochemistry of the M–K supracrustals indicates that both sedimentary and volcanic material are present. There is no direct evidence that the supracrustals have undergone major metasomatic modifications during deformation and granulite facies metamorphism, but metasomatic processes cannot be excluded. The alkalies, which are usually reported as being most mobile, play an important role in the sedimentary/igneous discriminators used. However, unrealistic high degrees of element migration are required to affect the results obtained to establish the origin of the M–K supracrustals (Rehkopff, 1981).

The graphite in some of the supracrustals may have formed inorganically or be biogenic, and its presence has not been given significance in this context.

From structural analysis (Getreuer & Rehkopff, 1980) the supracrustals are interpreted as belonging to a single sequence. Well defined successions occur over large areas, but consistent stratigraphic relations are absent. Such features are also reported from Archaean supracrustals in West Greenland, and the relation between the individual supracrustal units is usually only given tectonic significance (Bridgwater *et al.*, 1976). However , the gradational boundaries within the M–K supracrustals are interpreted as an original feature, reflecting the pyroclastic nature of parts of the metavolcanic material. It is thus suggested that the original M–K supracrustals were dominated by greywackes/lithic arenites (GB-1) with intercalations of mudstone (GB-3). Within this sequence, single layers or lensoid bodies of subarkose (LG-2) and sublithic arenite (CK) were developed. The greywackes/lithic arenites graded into calc-alkaline pyroclastics of rhyodacitic (GB-2) and rhyolitic (LG-1) compositions. Associated thinner layers of quartz-andesitic and dacitic extrusives occurred throughout the sequence (BS). In addition to these quartzo-feldspathic rocks, layers of limestone, basic and ultrabasic rocks occur sporadically.

Recent calc-alkaline andesitic to rhyolitic rocks are found in island-arcs or active continental margins (Andean type), formed in connection with subduction zones. Dominated by acid pyroclastic rocks, a modern analogy to the M–K metavolcanics may well be found in the calc-alkaline, continental Andean volcanism. The M–K metasediments are chemically similar to various coarse clastics, but no unambiguous interpretations of the original sedimentary environment can be made. However, the nature of these metasediments does not disagree with the continent-near environment implied by the M–K metavolcanics, and the tonalitic to granitic composition of the surrounding orthogneisses points towards a continental rather than an oceanic geotectonic setting. There is, however, no evidence that these orthogneisses acted as basement for the deposition of the supracrustals, and attaching geotectonic significance of modern extrusives to Precambrian problems may be unwise, since plate tectonics may not have been active in Precambrian times (e.g. Gill & Bridgwater, 1976).
1976).

No relations between the M–K supracrustals and other Precambrian supracrustals of West

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Fig. 11. All major and trace elements plus K_2O/Ba plotted against the Thornton-Tuttle Differentiation Index (D.I.) (=Qz+Ab+Or) for the M–K metavolcanics; oxides in wt.%, trace elements in ppm. N.D. = not detected. Symbols as explained in Table 2.

Greenland can be pointed out; the M–K supracrustals may thus be either Archaean or Proterozoic in age.

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