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ORIGIN OF THE CORDIERITE-BEARING GNEISSES OF THE GANANOQUE-WESTPORT AREA, ONTARIO (*)

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(5 fig. dans le texte)

RÉSUMÉ

Les gneiss à cordiérite et à grenat de la série de Grenville du sud-est de la province de l'Ontario appartiennent à un faciès intermédiaire entre le f. granulite à hornblende et le f. g. à pyroxène. En vue de reconnaître la nature de la roche originelle, dont les caractères distinctifs ont été effacés par la recristallisation métamorphique, on a soumis 43 analyses de ces gneiss à une série de tests, comprenant des diagrammes de dispersion, de calculs pétrochimiques et une analyse discriminatoire. Ces gneiss proviennent en majeure partie de roches argileuses, en moindre proportions de grauwackes et de subgrauwackes et, accessoirement, de roches ignées de caractère rhyolitique ou dacitique. Il n'y a pas de rapport entre la roche originelle et l'apparition d'associations à grenat et/ou cordiérite.

ABSTRACT

The cordierite- and garnet-bearing gneisses of the Grenville Series of southeastern Ontario, probably representing hornblende granulite to pyroxene granulite metamorphism, are difficult to distinguish as to their protolith due to masking by metamorphic recrystallization. Forty-three analyses of the gneisses were subjected to a series of tests including scatter diagrams, petrochemical calculations, and discriminant analysis to discern the original nature of these rocks. The gneisses are found to be, for the great part sedimentary with a preponderence of shale and minor greywacke and subgraywacke. A small portion of the rocks have a definite igneous character representing probable rhyolitic and dacitic material. No relation between the original lithology and the production of garnet- and/or cordierite-bearing assemblages is noted.

INTRODUCTION

The cordierite-bearing paragneisses of the Grenville Province of Ontario have attracted much interest in recent years. Wynne-Edwards & Hay (1963) described the world-wide distribution of such gneisses produced by regional metamorphism and a thorough investigation of the phase equilibria involved has been carried out by Reinhardt (1968). More recently, investigations of the peculiarities of the garnet-cordierite equilibria were reported by Currie (1971) and Hensen & Green (1973).

Compatible mineral associations in these rocks, including quartz, feldspar and opaque oxides, are cordierite-sillimanite, cordierite-garnet-sillimanite, cordierite-

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garnet-biotite, cordierite-garnet-hypersthene, cordierite-biotite-hypersthene, cordierite-biotite, garnet-biotite, garnet-biotite-hypersthene, and biotite-hypersthene. WYNNE-EDWARDS & HAY (1963) show that the cordierite-bearing assemblages are favored by low rock values of CaO and FeO. Typically, the cordierite-biotite-sillimanite gneisses are low in CaO with no plagioclase evident except that involved in perthite. On the other hand, the garnet-bearing assemblages are typically higher in CaO and FeO, relative to MgO. Further, these latter gneisses characteristically contain free plagioclase.

The cordierite-bearing rocks are part of thick gneissic units which are well exposed over the Frontenac Axis of southeastern Ontario (fig. 1). The Grenville metamorphic sequence, usually considered to be primarily metasedimentary, includes crystalline limestones, quartzites, granulites and amphibolites. It is probable that the sequence includes salic as well as mafic volcanics as these lithologies are common in other areas of Grenville age rocks (SHAW, 1972; CHESWORTH, 1970). The premetamorphic equivalent of these rocks is of interest and, since the grade of metamorphism is high, estimates made on textural features must be conjectural. The garnet and cordierite from units of varying thickness within granitic paragneisses (WYNNE-EDWARDS, 1969). The units commonly extend for long distance and are, thus-probably not sheet intrusions. On this basis, however, a volcanic origin is not precluded.

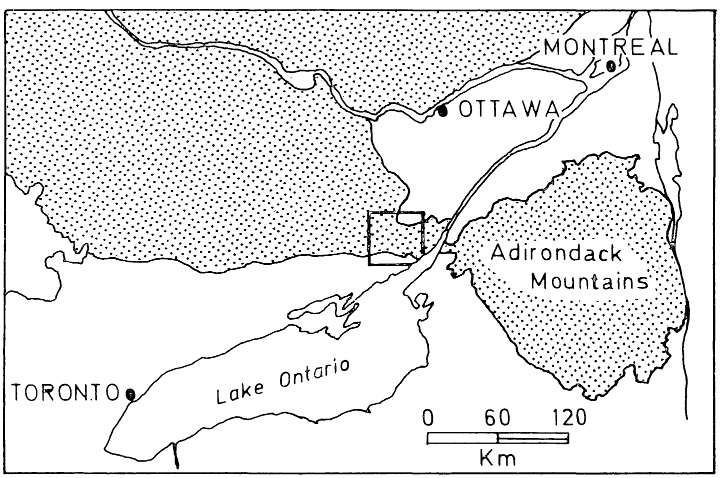

Fig. 1. — Index map showing the collection area within the Precambrian rocks (stippled) of southeastern Ontario.

Typically, the gneisses are medium- to coarse-grained with granoblastic textures. The biotite is typically deep brown and pleochroic and may be associated with sillimanite, garnet or cordierite. Normally, biotite lies in the plane of foliation and is generally, concentrated in layers. Garnet commonly occurs as anhedral crystals often elongate parallel to foliation and lineation (BLACKBURN & DENNEN, 1968). It is always intimately associated with biotite and sillimanite. Cordierite is found usually in dark blue patches or segregations where it is associated with sillimanite. Cordierite may occur in amounts of up to 40 percent and is generally altered to some extent.

Complete petrographic descriptions of these gneisses are given by WYNNE-EDWARDS (1967) and REINHARDT (1968). The assemblages present in the samples used in this study are given in Table I.

TABLE I

Mineral assemblages in the gneisses in addition to quartz, feldspar and opaque oxides

Assemblage	Reference Number (*)
Cordierite-biotite	D-34, D-115, H-60, H-90, H-105, WE-17, G-29
Cordierite-sillimanite	D-121
Cordierite-garnet-biotite	D-28, D-56, D-87, R-114, R-124, D-175, W-53, H-29, H-70, WE-4, WE-10, G-1, G-2A, G-3, G-8, G-12, G-16, G-25, G-26, G-27, G-34, G-35
Cordierite-garnet-sillimanite	D-102
Cordierite-biotite-hypersthene	D-24, D-136
Garnet-biotite	D-141, D-149, D-165, H-66, H-126, G-30
Garnet-hypersthene-biotite	D-139

* Reference number prefixes refer to data taken from the literature (D, R or W from REINHARDT, 1968; H or WE from WYNNE-EDWARDS & HAY, 1963) or new analyses (G).

The metamorphic sequence in the study area contains crystalline limestones and quartzites which are definitely of sedimentary origin and amphibolites which are most likely metabasalts. The thick sequences of quartzo-feldspathic gneisses, of which the cordierite and garnet gneisses are members, are, however, not so easily classified. They may represent metamorphosed salic volcanics or they may be derived from sediments ranging from pelite to psammite. The textural evidence has been obliterated by metamorphism and the present study attempts by chemical means to determine two things. First, an attempt is made to classify the gneisses as meta-volcanic or metasedimentary. Second, the rocks are classified further as to which type of volcanic or sediment.

DATA SOURCES AND TREATMENT

The data used for the discussion of the origin of the cordierite- and garnet-bearing gneisses are taken from WYNNE-EDWARDS & HAY (1963) and from REINHARDT (1968). Further, fifteen new analyses made by the author are presented here. In all, the results are based on 43 whole-rock analyses. A brief description of the techniques used for the new analyses is given below and sample locations are given in Fig. 2.

Following trimming of the sample of any weathered rind, a 1 cm slab was cut from the center of the specimen, perpendicular to the plane of foliation, for thin section preparation. The remaining rock was crushed to pea size in a steel jaw crusher and reduced to — 200 mesh using a tungsten-carbide « shatter-box ».

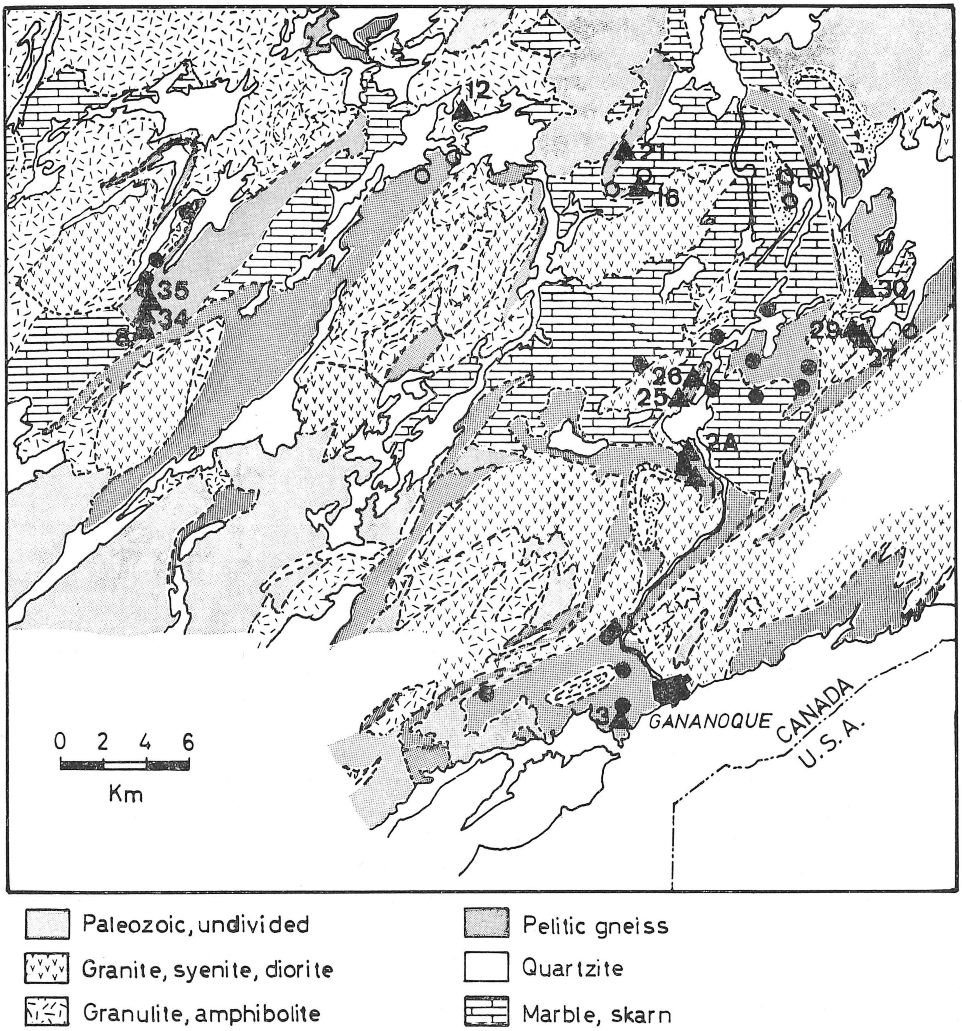

Fig. 2. — Geologic map showing localities of specimens used in this study. Sample localities from REINHARDT (1968) are shown as black dots; those from WYNNE-EDWARDS & HAY (1963) are shown as open circles. Localities for the new analyses presented here are given as black triangles with sample numbers. Geology is generalized from WYNNE-EDWARDS (1962, 1967).

The X-ray fluorescence technique of ROSE et al. (1963) was used for the determination of SiO_2, Al_2O_3, total Fe, TiO_2, MnO, CaO and K_2O. MgO and Na_2O were determined by atomic absorption spectrophotometry and FeO determinations were after the method of REICHEN & FAHEY (1962). Results are presented in Table II. It should be noticed that the totals average about 98 percent. This is deemed reasonable since P_2O_5, H_2O and CO_2 were not determined.

TABLE II

Chemical Analyses of gneisses

	1	2A	3	8	12A	12B	16	21	25	26	27	29	30	34	35
SiO_2	62.8	66.0	54.2	60.3	65.1	67.1	68.6	70.4	64.0	57.0	59.2	65.1	78.4	60.9	58.1
TiO_2	0.99	1.38	1.64	1.03	0.81	0.82	1.84	1.49	1.40	1.34	1.71	0.91	1.02	1.40	1.83
Al_2O_3	16.8	15.4	20.7	18.1	13.4	13.0	9.62	11.3	17.1	16.1	17.0	17.6	8.08	17.2	18.2
Fe_2O_3	2.23	2.16	3.61	2.35	2.22	2.05	3.63	0.78	2.43	2.07	3.17	2.53	0.36	1.73	2.05
FeO	3.72	4.13	6.57	5.41	3.85	3.72	7.27	5.11	4.07	4.54	6.07	4.23	4.29	3.45	4.30
MnO	0.11	0.06	0.09	0.06	0.11	0.13	0.18	0.15	0.03	0.10	0.12	0.05	0.04	0.03	0.06
MgO	2.51	2.33	3.59	2.43	4.25	3.41	5.85	3.17	2.02	1.49	4.16	2.65	1.49	2.70	2.80
CaO	2.89	0.66	2.24	0.71	3.40	3.10	0.62	0.85	0·40	5.28	2.94	0.56	1.05	2.00	0.68
Na_2O	2.42	1.20	2.11	3.57	2.69	2.74	0.13	0.21	1.64	2.89	1.21	1.42	1.01	2.39	1.88
K_2O	4.12	5.65	3.18	3.80	2.44	2.57	1.87	5.10	5.32	6.81	2.71	3.33	1.73	6.61	8.67
Total	98.59	98.97	97.93	97.79	98.27	98.64	99.61	98.56	98.41	97.62	98.29	98.38	97.47	98.41	98.75

PETROCHEMICAL STUDIES

The use of chemical parameters to investigate the nature of pre-metamorphic lithologic equivalents has received much attention in recent years. The approach is reasonable as pure mineralogic or petrographic studies are often hampered by the masking effects of metamorphic reactions. It should be emphasized, however, that any geochemical study of this sort should be used in conjunction with other investigations.

The recognition of metamorphic precursors using chemical criteria has been recently reviewed by SHAW (1972). Any such study involves several assumptions, including : (a) the rocks have not been altered radically by metasomatism, and (b) large scale metamorphic differentiation has not taken place. When these assumptions are valid or if the changes involved are known then the use of whole-rock chemistry as an indicator of metamorphic protolith may then be used.

Chemical mobility during metamorphism, in the absence of a significant fluid phase, is known to be limited. Measured volumes of chemical communication range from a few cubic millimeters in greenschist facies rocks to a few cubic centimeters in granulites (BLACKBURN, 1968; SMITH & BLACKBURN, 1969). Thus, during sub-anatectic metamorphism, the bulk composition of original lithologies should change only slightly.

Several chemical criteria have been proposed to distinguish metasediments from metaigneous material. For example, it is unlikely to find igneous rocks which exceed 80 percent SiO_2 (or 50 % normative quartz), or 8 percent K_2O, or 15 percent total Fe as Fe_2O_3 (QUESADA et al., 1968). In addition, other criteria which may be used to establish a *sedimentary* origin are : (a) an excess of alumina according to the molar ratio $(Al_2O_3)/(Na_2O + K_2O + CaO)$; (b) an excess of K_2O over Na_2O coupled with an excess of MgO over CaO. This latter test is particularly diagnostic of argillaceous rocks with appreciable amounts of illite and montmorillinite (MASON, 1966). The peraluminous nature of many salic igneous rocks precludes the use of the ratio $(Al_2O_3)/(Na_2O + K_2O + CaO)$ as a definition of pelitic chemistry. However, it is obvious from fig. 3 that few igneous rocks exceed 5 percent normative corundum. This may be a better criterion.

SHAW (1972) makes a comprehensive review of the chemical test applied by various authors to determine the origin of metamorphic quartz-feldspathic rocks. In his analysis of the premetamorphic nature of the Apsley Gneiss of Ontario, SHAW (1972) finds that the use of the scatter diagrams proposed by KÖHLER & RAAZ (1951), WEISBROD (1969), and MOINE & DE LA ROCHE (1968) give ambiguous results for the bulk of his samples. He finds that discriminant analysis is most useful in discerning protoliths and, through the use of discriminant functions, is able to conclude that the Apsley Gneiss is most likely a series of silicic volcanicsi nterspersed with sandstones.

In the present study, use was made of certain scatter diagrams which proved diagnostic for sedimentary rocks. The procedure was as follows. 175 igneous rock analyses were selected at random from a laboratory file over 5000 such samples. Following calculation of the needed parameters, the data was plotted and the field of igneous rocks outlined to include all samples. Identical parameters for the Grenville gneisses were then calculated and plotted on the diagrams. If the sample did not fall within the igneous field, it was deemed sedimentary. In agreement with SHAW (1972), it was found that the plots proposed by KÖHLER & RAAZ (1951), MOINE & DE LA ROCHE (1968), and LEAKE (1964) were not of much use for these

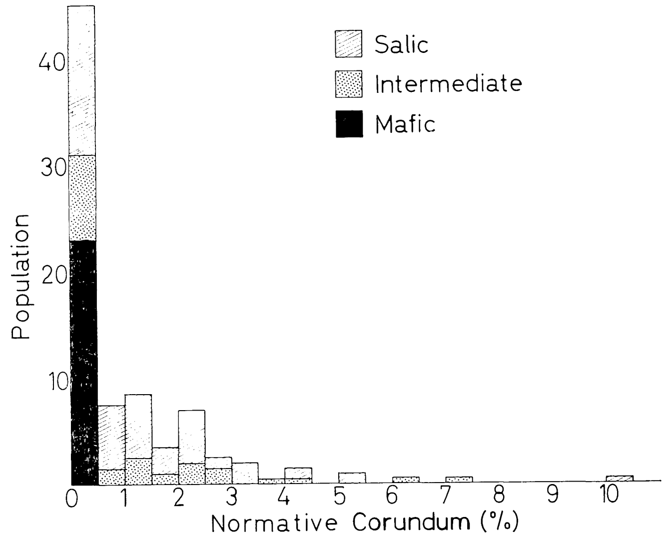

Fig. 3. — Frequency diagram of percentage normative corundum in a sampling of 175 igneous rocks.

particular rocks. However, that proposed by WEISBROD (1969), the Al-Ca-(Na + K) diagram of OSANN (JOHANSSEN, 1939), and the ACF diagram proved quite diagnostic. These diagrams are presented in figure 4. In addition, the gneisses were subjected to further tests.

1. If the MgO content is greater than CaO while K_2O is greater than Na_2O, the rock is deemed sedimentary.

2. If normative corundum is greater than 5 percent, the rock is sedimentary.

3. DAVOINE (1969) showed that paraleptynites have usually less than 2.5 percent CaO while (Na_2O + K_2O) is less than 7 percent. Ortholeptynites of igneous origin have a CaO content of more than 2.5 percent. This test is also applied to the present samples.

4. Samples were plotted on the Ab-Or-Q diagram given by SHAW (1972) on which he has outlined the fields of 278 igneous rocks and 506 sediments. If a gneiss fell outside the igneous field it was deemed sedimentary.

5. SHAW (1972) has derived several discriminent functions based upon sizeable populations of igneous and sedimentary rocks. One of these, DF3, was judged of most use in the present study. This function (wt. %) is :

$$DF3 = -0.21\ SiO_2 - 0.32\ Fe_2O\ \text{(total Fe)} - 0.98\ MgO$$

$$+ 0.55\ CaO + 1.46\ Na_2O + 0.54\ K_2O + 10.44.$$

This expression permits assignment of quartzo-feldspathic gneisses to an igneous (DF3 > 0) group or to a sedimentary group (DF3 < 0) with a probality of misclassification equal to 0.29.

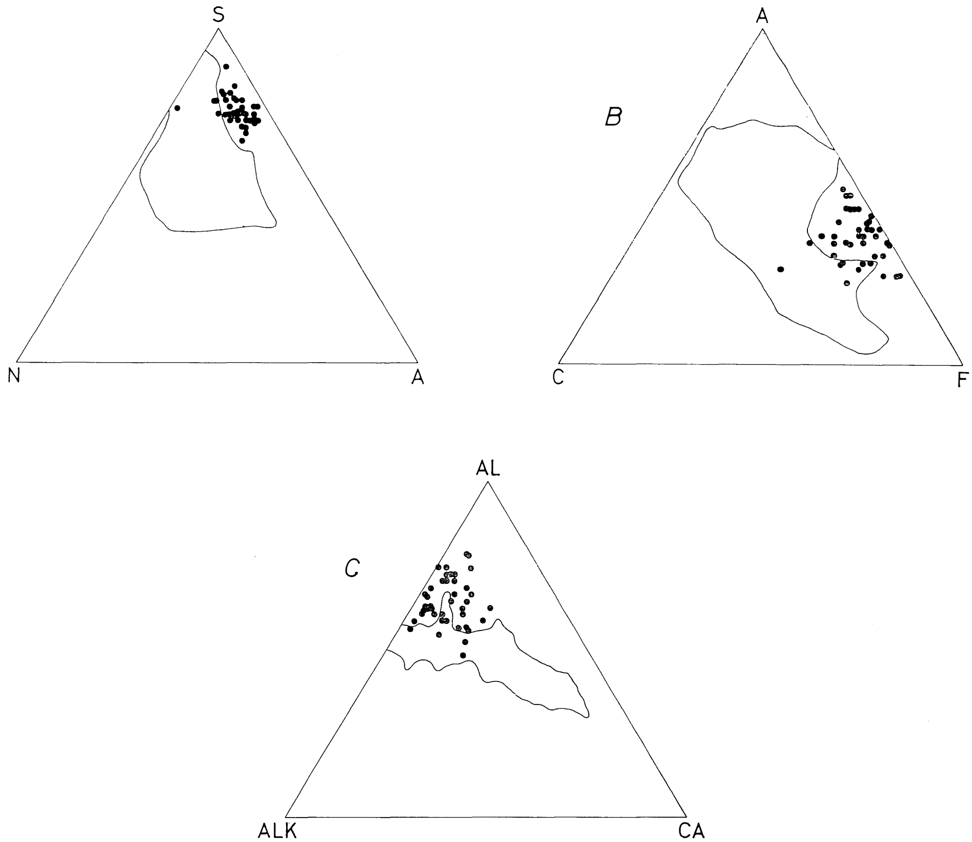

Fig. 4. — Scatter diagrams showing the field of 175 igneous rocks (continuous line) and points representing the 43 analyses of the study gneisses. (A) WEISBROD (1969) plot. (B) ACF. (C) Osann Al-(Na + K)-Ca diagram (JOHANNSEN, 1939).

TABLE III

Primary classification of the gneiss precursors as igneous (I) *or sedimentary* (S) *by various tests*

	DIAGRAMS			OTHER TESTS (*)					SCORE	PROTOLITH
Sample Number	SNA	AL-ALK-Ca	ACF	I	II	III	IV	V	S=1, I=—1, I or S=0	
H 28	S	S	S	S	S	S	S	I	6	S
H 60	S	S	S	S	S	I	S	S	6	S
H 66	S	I	S	S	S	S	S	S	6	S
H 70	S	S	S	S	S	S	S	S	8	S
H 90	S	S	S	S	S	I	S	S	6	S

TABLE III (*continued*)

H 105	S	S	S	S	S	S	S	S	8	S
H 126	S	S	S	S	S	S	S	I or S	7	S
WE 4	S	S	S	S	S	S	S	S	8	S
WE 10	S	I	S	S	I	I	S	I	0	I or S
WE 17	I	I	S	S	I	I	I	S	—2	I
D 141	S	S	S	S	S	I	S	S	6	S
D 149	S	S	S	S	S	I	S	S	6	S
D 165	S	S	I	S	S	S	S	S	6	S
D 28	S	S	S	S	S	S	S	S	8	S
D 56	S	S	S	S	S	S	S	I	6	S
D 87	S	I	S	S	S	S	S	S	6	S
D 102	S	S	S	S	S	S	S	S	8	S
D 175	S	S	S	S	S	S	S	S	8	S
R 114	S	S	S	S	S	S	S	S	8	S
R 124	S	S	S	S	S	S	S	S	8	S
W 53	S	S	S	S	S	I	S	S	6	S
D 24	S	S	I	S	I	I	S	S	2	S
D 136	S	I or S	S	S	S	I	S	S	5	S
D 34	S	S	S	S	S	I	S	S	6	S
D 115	S	S	S	S	S	S	S	S	8	S
D 121	S	S	S	S	S	S	S	S	8	S
D 174	S	S	S	S	S	S	S	S	8	S
D 139	I	I	I	S	I	IorS	S	S	—1	I
G 1	I	S	I	I	I	I	I	I	—6	I
G 2A	S	S	S	S	S	S	S	S	8	S
G 3	S	S	S	S	S	S	S	I	6	S
G 8	S	S	S	S	S	I	I	I	2	S
G 12A	S	S	I	I	I	S	S	I	0	I or S
G 12B	S	S	I	I	I	S	S	I	0	I or S
G 16	S	S	S	S	S	S	S	S	8	S
G 21	S	S	S	S	I	S	S	S	6	S
G 25	S	S	S	S	S	S	S	S	8	S
G 26	I	I	I	I	I	IorS	I	S	—5	I
G 27	S	S	S	S	S	I	S	S	6	S
G 29	S	S	S	S	S	S	S	S	8	S
G 30	S	S	I	S	I	S	S	S	4	S
G 34	I	I	I	S	I	I	I	S	—4	I
G 35	S	S	S	S	I	I	I	S	2	S
Apsley Ave. (**)	I	I	I	I	I	S	I	I	—6	I

* The other tests include : I. If K_2O/Na_2O and MgO/CaO the rock is sedimentary II. If normative corundum > 5 %, the rock is sedimentary, III. The test given by DAVOINE (1969), IV. The discriminant function DF3 given by SHAW (1972), V. Normative Ab-Or-Q based on SHAW's (1972) diagram.

** Average Apsley Gneiss of SHAW (1972).

The results of the various classification tests are summarized in Table III. These data were scored as follows. A mark of + 1 is given for a positive sedimentary test and — 1 for an igneous result. For those tests where no decision could be reached for a particular sample, a grade of 0 was given. The scores are added and a final result given. In summary, out of 43 specimens, 5 may be definitely accepted as having an igneous proto-lith, 35 appear sedimentary in origin, and no decision is reached for 3 samples. For these last three, a tentative sedimentary origin is given as all give a sedimentary result from SHAW's discriminatory analysis which may be the most powerful test used.

Table III also gives the results calculated for the average Apsley gneiss of SHAW (1972) which gives a strong igneous classification. This is in good agreement with SHAW's conclusion.

TABLE IV

Classification of gneisses by precursor rock type

I. IGNEOUS	Rhyolite	G-34, G-26, D-139, WE-17
	Dacite	G-1
II. SEDIMENTARY	Shale	H-29, H-60, H-66, H-70, H-90, H-105, H-126, WE-4, D-141, D-149, D-165, D-28, D-56, D-87, D-102, D-175, R-114, R-124, W-53, D-24, D-136, D-34, D-115, D-121, D-174, G-3, G-8, G-2A, G-25, G-27, G-29, G-35
	Greywacke	WE-10, G-12A, G-12B, G-21
	Subgraywacke	G-30

PROTO-LITH SUBCLASSIFICATION

The Igneous Rocks

In his paper on the classification of para- and ortholeptynites, DAVOINE (1969) shows that ortho-leptynites can be further classified on the basis of their total alkali content. In this light, rhyolitic rocks average greater than 7 percent ($Na_2O + K_2O$) while dacitic rocks have less than 7 percent total alkalis. Using this criterion, of the five igneous rocks in the gneiss suite, G34, W17-57, D139 and G26 are probably derived from rhyolites. G1 gives a result typical of dacites.

The Sedimentary Rocks

The bulk of the gneiss analyses give a strongly sedimentary test. It is then desirous to further subdivide these metasediments into more specific lithologies. Again, textural and mineralogic observations offer little help with these high-grade metamorphic rocks and a chemical test is preferable. There are few chemical classifications of sedimentary rocks in the literature. However, the test proposed by MOORE & DENNEN (1970) and revised somewhat in DENNEN & MOORE (1971) shows great promise and has been used to advantage by NAVARRO & BLACKBURN (1974) in studying a metasedimentary sequence in Colorado. MOORE & DENNEN (1970) show that the ratio Al/Fe is regularly between 1.5 and 2.4 for common clastic sediments. These rocks then show a chemical sequence based on variable $Si = 100 - (Fe + Al)$.

The Si, Al and Fe data of those samples, judged by previous criteria to be sedimentary, were treated in the manner proposed by Dennen & Moore (1971). The bulk of these samples have Al/Fe ratios lying between 1.5 and 2.4 as expected for normal clastic sediments and the variation in Si is fairly limited, ranging from 67 to 73 (fig. 5). A definite trend to lower Al/Fe ratios at lower Si values is noted also. This trend is noted by Dennen & Moore (1971) who propose that a departure from the normal trend at low Si values represent supermature sediments produced by recycling of argillaceous lithologies. The field boundaries of the major clastic lithologies are shown on fig. 5 and it seems obvious that the great bulk of sediments derived from shales. Only six samples fall outside the shale field and three of these, WE10, 12A, 12B seem to be definitely graywacke derived. Three samples, G16, G21 and G30 lie well off the main trend having low Al/Fe ratios for their Si values. These samples typically have lower Al_2O_3 coupled with above average total iron, CaO and SiO_2. It is possible that they represent graywackes and subgraywackes which are iron enriched by a greater portion of mafic lithic fragments.

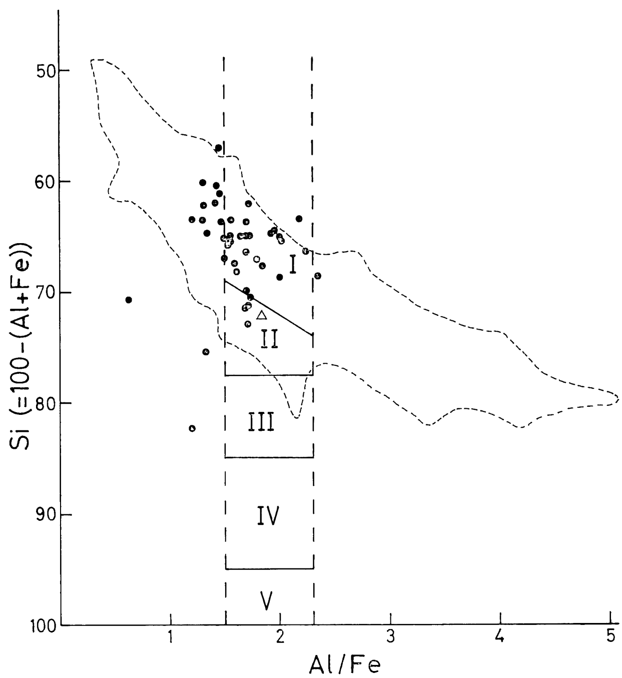

Fig. 5. — The Si-Al/Fe diagram of Dennen & Moore (1971) showing the field for igneous rocks (dotted line) and points representing the gneisses studied. The open triangle is the average Apsley gneiss of Shaw (1972). Clastic rock fields are, after Dennen & Moore (1971) : I. Shale, II. Graywacke, III. Subgraywacke, IV. Sandstone, V. Quartzose sandstone.

CONCLUSIONS

The use of whole-rock analyses for the determination of precursor lithologies of metamorphic rocks has proved useful on application to high-grade gneisses.

Using a combination of scatter diagrams, petrochemical calculations, and a discriminant function, the granulite facies gneisses of southeastern Ontario have been show to be the metamorphic product of shales with minor graywacke, subgraywacke and salic volcanic material. The application of a set of eight tests gave clear cut results as to the igneous or sedimentary origin of 40 out of 43 samples processed. The three remaining samples for which no initial decision be reached were assigned to the sedimentary group on the basis of a sedimentary result from the discrimination function presented by SHAW (1972). Further classification of these rocks into sedimentary or igneous rock species was successful using the test of DAVOINE (1969) for salic igneous rocks and that of MOORE & DENNEN (1970) for clastic sediments.

The precusor lithology plays little or no part in the final metamorphic mineralogy of these gneisses. The various assemblages noted in Table I may be found in rocks of igneous as well as sedimentary origin. It then seems more likely that the occurence of cordierite and/or garnet in these rocks is more dependent on other chemical factors such as the FeO/MgO ratio of the rock coupled with its calcium content as proposed by WYNNE-EDWARDS & HAY (1963). The P-T position and width of the diavariant field in which cordierite and garnet coexist is a function of the Mg/Mg + Fe ratio (HENSEN & GREEN, 1973). Further, the value of this ratio in the garnet and the cordierite is dependent upon interdependent f_{O_2} and f_{H_2O} (REINHARDT, 1968) and temperature (CURRIE, 1971). Thus, the metamorphic production of garnet and for cordierite is probably more dependent on the iron and magnesium contents of these rocks rather than on the chemical factors which discriminate igneous from sedimentary lithologies.

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