A PRELIMINARY INVESTIGATION OF THE GEOCHEMISTRY OF GREYWACKES FROM SOUTH GEORGIA

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Abstract. 160 greywackes were analysed for ten major and 14 trace elements by X-ray fluorescence spectrometry in order to establish the nature and magnitude of chemical variation within the Cumberland Bay Formation. These data were used as a basis for comparison with the chemistry of the other stratigraphical units on South Georgia, namely, the Sandebugten Formation, the Barff Point Member and the Cooper Bay metasediments.

Geochemically, the rocks of the Cumberland Bay Formation are fairly typical greywackes and, with the exception of Cr and Ni, they show no marked enrichment or impoverishment in the minor elements relative to average crustal abundances. Significant variations in the concentrations of Mg, Cr, Ni, Zr and K between the Prince Olav Harbour and Royal Bay areas may reflect differences in the chemistry of the volcanic centres from which the Cumberland Bay Formation greywackes were derived and not the dispositions of these two areas relative to the source of the turbidites.

The chemical data support petrographic evidence by indicating a relatively basic provenance for the Cumberland Bay Formation and a more acidic provenance for the Sandebugten Formation greywackes. The Cumberland Bay Formation greywackes show trace-element abundances typical of calc-alkaline volcanic rocks; they also define trends on a variety of graphical plots which clearly indicate their calc-alkaline volcanic provenance.

There is no significant chemical difference between the Cumberland Bay Formation and the Barff Point Member. However, the Barff Point Member and the Sandebugten Formation show significant differences in the concentrations of Mn, Mg, Y and Th, thus indicating that rocks from these two stratigraphical units were derived from different source areas. Similarly, there are few significant chemical differences between the Cumberland Bay Formation and the Cooper Bay metasediments, and the two units probably share a common provenance. At 99 per cent confidence, the majority of elements determined indicate that the Sandebugten Formation greywackes and the Cooper Bay greywackes were derived from different source areas.

160 greywackes from South Georgia were analysed by X-ray fluorescence spectrometry for the following elements: Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, P, Cr, Ni, Zn, Rb, Sr, Y, Zr, Ba, La, Ce, Pb, Th and Ga. CO_2 and FeO were determined by wet chemical methods and a representative number of H_2O- and total volatile determinations were made for each rock group. The locations of all analysed samples are shown in Fig. 1.

The main objective of this work was to establish the nature and magnitude of chemical variation within the Cumberland Bay Formation and to examine the chemical relationship between the two main greywacke formations on South Georgia and two much smaller areas of petrographically dissimilar sediments in the Barff Point and Cooper Bay areas.

Chemical Composition of the Cumberland Bay Formation

The Cumberland Bay Formation crops out over most of South Georgia and was estimated by Trendall (1959) to be at least 10 km. thick. The geochemistry of the South Georgia sediments was first investigated by Tyrrell (1930), who analysed a tuffaceous greywacke from Prince Olav [illegible]rbour and a clay-slate and a phyllite from Royal Bay (Table I). He concluded that the general character of the greywacke was "between that of a spilite or albite-dolerite and a keratophyre". Tyrrell also noted that the clay-slate and the phyllite were much richer in alumina and the alkalis than average analyses of shale and slate. However, these rocks from Royal Bay also show much higher concentrations of alumina and the alkalis than both the Cumberland Bay and Sandebugten Formation pelites (Table I).

Petrographic examination of the Cumberland Bay Formation has shown that the detrital components are mainly basic to intermediate volcanic fragments and broken plagioclase phenocrysts. Modal analysis has revealed that in the coarse greywackes, andesitic, trachytic and felsitic volcanic clasts comprise about three-quarters of the rock, quartz is very low and feldspar ranges from 5 to 25 per cent. The pelites consist essentially of clay minerals, finely divided volcanic detritus and occasional small feldspar grains.

In Table II the composition of the Cumberland Bay Formation rocks is compared with published greywacke analyses. Although the Cr and Ni contents of the Cumberland Bay

Br. Antarct. Surv. Bull., No. 51, 1982, p. 89–109.

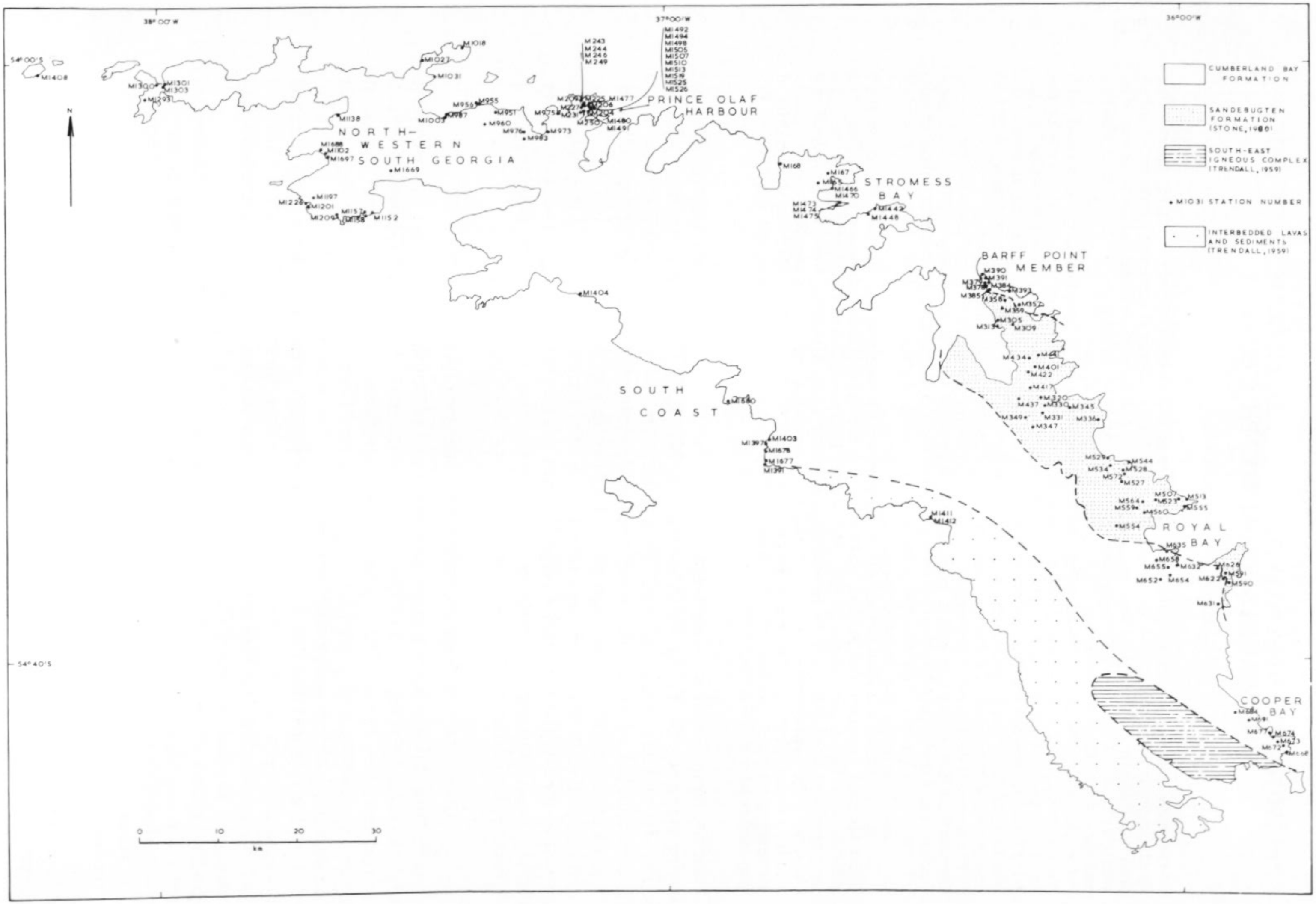


Fig. 1. Sketch map of South Georgia showing the geographical locations of the main rock types and the station numbers of the analysed rocks.

TABLE I. A COMPARISON OF THE CHEMICAL COMPOSITIONS OF THREE SEDIMENTARY ROCKS FROM SOUTH GEORGIA (TYRRELL, 1930) WITH MEAN ANALYSES OF CUMBERLAND BAY FORMATION SANDSTONES AND PELITES AND SANDEBUGTEN FORMATION PELITES

	1	2	3	4	5	6
SiO_2	56·43	32·55	65·13	53·15	61·22	67·54
TiO_2	—	—	0·74	0·6	1·04	0·67
Al_2O_3	23·2	28·07	13·37	18·97	14·06	15·52
Fe_2O_3	0·6	0·64	3·59	1·59	5·72	3·77
FeO	3·44	2·05	3·86	8·09	3·54	1·90
MnO	—	—	0·14	0·21	0·16	0·12
MgO	0·38	1·09	1·68	2·85	2·44	1·66
CaO	4·07	1·72	4·51	3·83	2·79	1·30
Na_2O	2·93	1·52	2·13	4·64	3·45	3·28
K_2O	6·12	7·24	2·40	0·87	1·69	2·55
P_2O_5	—	—	0·24	0·27	0·21	0·11

1. Clay-slate, Whale Valley, Royal Bay, South Georgia (Tyrrell, 1930).
2. Phyllite, northern shore of island in Royal Bay (Tyrrell, 1930).
3. Average of 15 pelites from the Cumberland Bay Formation.
4. Tuffaceous greywacke, Prince Olav Harbour (Tyrrell, 1930).
5. Average of 23 volcanic greywackes from Prince Olav Harbour.
6. Average of eight pelites from the Sandebugten Formation.

TABLE II. A COMPARISON OF THE ABUNDANCE OF CERTAIN ELEMENTS IN CUMBERLAND BAY FORMATION GREYWACKES WITH THOSE IN PUBLISHED GREYWACKE ANALYSES (MODIFIED FROM WEBER AND MIDDLETON (1961))

Formation	Ba	Cr	Ga	Ni	Sr	Zr
Cumberland Bay Formation (80 analyses)	404	29	21	13	224	163
Normanskill Formation New York (64 analyses)	230	120	14	34	240	280
Upper Mississippian, Kulm, Germany	270	130	8	32	140	340
Macigno, Italy	620	130	3	59	270	200
Barmouth Grit, North Wales	570	87	6	37	110	330
Gowganda Formation, Ontario, Canada	500	170	10	55	130	200

All values are in p.p.m.

Formation rocks are strikingly low, the other elements show fairly typical greywacke concentrations. The apparent depletion of Cr and Ni in the Cumberland Bay Formation relative to the "average greywacke" may be a reflection of the predominantly intermediate composition of the provenance of the Cumberland Bay Formation. The Cumberland Bay Formation rocks also show a slight enrichment in Ga relative to mean greywacke compositions (Table II).

In Table III the most reliable available estimates of crustal abundances (Weber and Middleton, 1961) are compared with means for the Cumberland Bay Formation turbidites. With the exception of Cr and Ni, it is apparent that no marked enrichment or impoverishment in the minor elements listed has taken place during the formation of these greywackes from crustal material. Basic igneous rocks contribute by far the greatest quantities of Cr and Ni to the oceans and so the relatively low Cr and Ni concentrations in the Cumberland Bay Formation may be attributed to a provenance low in these elements.

TABLE III. RELIABLE ESTIMATES OF THE CRUSTAL ABUNDANCES OF CERTAIN ELEMENTS COMPARED WITH THOSE IN THE CUMBERLAND BAY AND SANDEBUGTEN FORMATIONS (MODIFIED FROM WEBER AND MIDDLETON (1961))

Element	*Crustal abundance*	*Cumberland Bay Formation*	*Sandebugten Formation*
Ba	250 (Green, 1953)	404	526
Cr	100 (Shaw, 1954)	29	24
Ga	20 (Fleischer, 1955)	21	13
Mg	20,900 (Green, 1953)	33,200	12,200
Mn	1,000 (Green, 1953)	1,700	900
Ni	80 (Rankhama and Sahama, 1950)	13	14
Sr	450 (Turekian and Kulp, 1956)	224	181
Zr	156 (Degenhardt, 1957)	163	224

All values are in p.p.m.

CHEMICAL VARIATION WITHIN THE CUMBERLAND BAY FORMATION

To determine chemical differences between greywackes from several geographical areas within the Cumberland Bay Formation (Fig. 1), the *t*-test has been used to assess the significance of the apparent chemical variation shown by the mean analyses in Table IV. This was done by testing the null hypothesis *Ho*.

$Ho\colon \mu_1 = \mu_2$ (null hypothesis)
Under *Ho*

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sigma\left(\frac{1}{N_1} + \frac{1}{N_2}\right)^{\frac{1}{2}}} \text{ where } \sigma = \left(\frac{N_1S_1^2 + N_2S_2^2}{N_1 + N_2 - 2}\right)^{\frac{1}{2}}.$$

N_1 = size of first sample,
N_2 = size of second sample,
$\overline{X}_1$ = sample mean of first sample,
$\overline{X}_2$ = sample mean of second sample,
S_1 = standard deviation of first sample,
S_2 = standard deviation of second sample,
$N_1 + N_2 - 2$ = degrees of freedom (D.F.).

TABLE IV. MEAN CHEMICAL ANALYSES OF GREYWACKES FROM DIFFERENT GEOGRAPHICAL AREAS WITHIN THE CUMBERLAND BAY FORMATION

	North-western South Georgia	*Prince Olav Harbour*	*Stromness Bay*	*Royal Bay*	*South coast*
SiO_2	61·28	61·22	55·83	55·00	56·46
TiO_2	1·07	1·04	1·21	1·12	1·19
Al_2O_3	13·58	14·06	15·13	14·45	14·88
Fe_2O_3	5·95	5·72	6·53	6·68	7·03
FeO	3·69	3·54	4·19	4·43	5·78
MnO	0·16	0·16	0·18	0·19	0·18
MgO	2·98	2·44	3·65	4·15	3·40
CaO	4·16	2·79	3·25	4·82	3·20
Na_2O	3·16	3·45	3·76	3·33	3·07
K_2O	1·29	1·69	1·72	0·95	1·63
P_2O_5	0·14	0·21	0·17	0·15	0·17
CO_2	2·52	1·63	1·72	2·54	1·64
TOTAL	99·98	97·95	97·34	97·81	98·63
Trace elements (p.p.m.)					
Cr	25	19	29	37	35
Ni	10	11	12	16	15
Zn	112	121	116	115	117
Rb	33	51	44	30	47
Sr	212	237	224	211	237
Y	26	32	34	24	35
Zr	150	189	176	130	170
Nb	5	7	6	5	6
Ba	350	450	569	248	403
La	19	23	23	20	23
Ce	32	42	40	31	45
Pb	9	13	10	10	12
Th	6	6	4	5	6
Ga	19	20	23	21	21
Number of analyses	25	23	10	11	14

The *t*-test is used to reveal chemical differences between different rock groups at certain pre-determined levels of significance (5 per cent and less, 1 per cent and less or 0·1 per cent and less). *t*-values for all the potentially significant differences (see Table IV) between rock-unit means in the Cumberland Bay Formation are given in Table V. The *t*-test assumes the presence of a normal distribution and that both populations possess standard deviations of a similar magnitude. However, some of the distributions are not normal and in a few cases the standard deviations are of a different magnitude. These limitations have been allowed for by lowering the level of significance for *Ho* rejection. The highest conventional level (5 per cent and less) has generally been ignored and only the intermediate (1 per cent and less) and lowest (0·1 per cent and less) levels for *Ho* rejection are considered. These are denoted by two and three asterisks respectively in Table V. Although the *t*-test has been used as a preliminary method of statistical analysis, it is recognized that more sophisticated techniques are available.

TABLE V. *t*-VALUES OBTAINED FROM A COMPARISON OF THE MEAN CHEMICAL ANALYSES OF CUMBERLAND BAY FORMATION GREYWACKES FROM THE PRINCE OLAV HARBOUR (PH) AREA WITH THOSE FROM ROYAL BAY (RB) AND THE SOUTH COAST (SC) OF SOUTH GEORGIA

D.F.	PH : RB 34	PH : SC 37
Si	+2·09*	+0·93
Ti	−0·19	−0·21
Al	−0·18	+0·43
Fe	−0·87	−0·82
Mg	−2·99**	−1·02
Mn		
Na	+0·63	+1·77
K	+2·74**	+0·68
Cr	−3·50***	−2·47*
Ni	−2·74**	−1·48
Zr	+4·71***	+1·71

* *Ho* is rejected with 95–99 per cent confidence.
** *Ho* is rejected with 99–99·9 per cent confidence.
*** *Ho* is rejected with more than 99·9 per cent confidence.
D.F. Degrees of freedom.

The mean analyses in Table IV indicate that elements such as Si, Na, K and Al, which go into the lighter quartz, feldspar and clay minerals, show higher concentrations at the north-western end of South Georgia. Conversely, the elements such as Cr, Ni, Ti, Fe, and Mg, which constitute the heavy minerals, appear to decrease in concentration towards the north-west (Table IV). The *t*-values of Table V show that the higher concentrations of K and lower concentrations of Mg, Cr and Ni in rocks from the Prince Olav Harbour area relative to rocks from the Royal Bay area are significant at the 99 per cent confidence level.

Trendall (1959) and Dalziel and others (1975) suggested that the predominant sediment-dispersal pattern within the Cumberland Bay Formation was towards the north-west. Elements which go into the heavy minerals such as Mg, Cr and Ni might therefore be expected to show higher concentrations at the south-eastern end of the island. However, recent work (personal communication from D. I. M. McDonald) has shown that the sediment dispersal pattern is much more complex and so, although differences in the concentrations of certain elements may be due to the sorting effect of turbidity current transport, it is possible that much of this chemical variation is due to other factors. Evidence against chemical variation within the Cumberland Bay Formation being produced mainly by the sorting effect of turbidity current transport comes from the absence of significant chemical differences between greywackes from the south coast of South Georgia and those from the Prince Olav Harbour area, 50 km. to the north-west. In addition, the element Zr, which in most rocks goes into the heavy mineral zircon, shows a higher concentration (at the 99·9 per cent confidence level) in greywackes from the Prince Olav Harbour area, relative to those from the Royal Bay area (Table V). This difference could only be attributed to turbidity current sorting if most of the Zr in the Cumberland Bay Formation was present as an incompatible phase and free to substitute for elements such as Mg in montmorillonite (Krauskopf, 1967). Concentration of Zr in clay minerals would probably lead to a higher concentration of this element in distal rather than proximal turbidites. However, zircon may be present in the Cumberland Bay Formation (Skidmore, 1972) and so the variation in concentration shown by Zr between different geographical areas is unlikely to be due mainly to turbidity current action.

Although the concentrations of certain elements have probably been influenced by the sorting effect of turbidity current transport, most of the highly significant chemical variation within the Cumberland Bay Formation (Table V) is probably due to differences in provenance of the volcaniclastic greywackes. Variations in the concentrations of Mg, Cr, Ni, Zr and K between the Prince Olav Harbour and Royal Bay areas may reflect differences in the chemistry of the parent volcanic centres from which these sediments were derived.

EFFECT OF PROVENANCE ON THE CHEMICAL COMPOSITION OF THE CUMBERLAND BAY AND SANDEBUGTEN FORMATIONS

The Sandebugten Formation crops out along the north-east coast of South Georgia (Fig. 1). The Cumberland Bay and Sandebugten Formations are probably facies variants of the same age which were deposited by turbidity flows from opposite sides of a depositional basin (Trendall, 1959; Dalziel and others, 1975). Mean analysis (Table VI) and *t*-values (Table VII) show marked variations in the concentrations of both major and trace elements between these two formations. Petrographic examination of the South Georgia greywackes suggests that the Cumberland Bay Formation derived the bulk of its sediment from an active volcanic arc, whereas the greywackes of the Sandebugten Formation were supplied from a more acidic provenance comprising sedimentary, metamorphic and igneous rocks (Trendall, 1959; Stone, 1980).

Table VIII compares the distribution pattern of elements in acidic and basic rocks given by Rankhama and Sahama (1950) and Nockolds and Allen (1953) with those of the Cumberland Bay and Sandebugten Formations. Ti, Mg and Mn are more concentrated in basic rocks and have higher values at the 99·9 per cent confidence level in the Cumberland Bay Formation rocks, whereas Zr and Ba are typically found in acid rocks and are higher in concentration in the Sandebugten Formation at the 99 per cent confidence level (Table VII). Th, Rb and Na, which are also characteristically more concentrated in acidic rocks, show higher concentrations at 99 per cent confidence in the Sandebugten Formation than in the Cumberland Bay Formation. The element which does not follow this pattern is Ga, which is generally highly concentrated in acidic rocks, but at the 99 per cent significance level it appears to be more highly concentrated in the more basic Cumberland Bay Formation (Table VII). Geochemical evidence therefore supports petrographic data in indicating a relatively basic provenance for the

Table VI. Mean chemical analyses of greywackes from the Cumberland Bay Formation, Barff Point Member, Cooper Bay metasediments and Sandebugten Formation

	Cumberland Bay Formation	*Barff Point Member*	*Cooper Bay metasediments*	*Sandebugten Formation*
SiO_2	58·04	59·03	55·91	69·58
TiO_2	1·13	1·00	1·13	0·61
Al_2O_3	14·42	14·58	14·45	13·25
Fe_2O_3	6·38	5·37	6·74	3·09
FeO	3·60	3·99	4·52	1·80
MnO	0·17	0·17	0·19	0·09
MgO	3·32	2·66	5·54	1·22
CaO	3·64	3·28	5·15	1·48
Na_2O	3·35	3·95	2·41	4·16
K_2O	4·15	1·78	0·65	1·86
P_2O_5	0·17	0·16	0·15	0·18
CO_2	2·01	2·71	1·28	1·75
TOTAL	100·38	98·68	98·12	99·07
Trace elements (p.p.m.)				
Cr	29	23	94	24
Ni	13	11	27	14
Zn	116	111	108	96
Rb	41	46	28	59
Sr	224	226	266	181
Y	30	34	27	21
Zr	163	199	132	224
Nb	6	7	6	9
Ba	404	489	215	526
La	22	22	19	27
Ce	38	42	31	49
Pb	11	12	10	14
Th	5	7	6	11
Ga	21	20	20	13
Number of analyses	78	7	9	29

TABLE VII. *t*-VALUES OBTAINED FROM A COMPARISON OF THE MEAN CHEMICAL ANALYSES OF ROCKS FROM THE CUMBERLAND BAY FORMATION (CF), SANDEBUGTEN FORMATION (SF) AND COOPER BAY METASEDIMENTS (CB)

	CF : SF	CF : CB	SF : CB
D.F.	55	35	40
Si	−2·04*	+1·18	+2·93**
Ti	+3·74***	+0·19	−3·69***
Al	+0·33	+1·80	−0·15
Fe	+2·68**	−1·53	−3·31**
Mn	+4·11***	−0·67	−5·0***
Mg	+4·20***	−2·46*	−6·68***
Ca	+1·36	−0·87	−5·46***
Na	−6·13***	+0·97	+3·78***
K	−1·75	+2·52*	+4·36***
Cr	+0·54	−1·80	−2·16*
Ni	−1·41	−4·86***	−3·70***
Rb	−2·93**	+0·48	+4·24***
Sr	+0·72	−0·86	−3·37**
Y	+1·24	−0·52	−3·23**
Zr	−3·88***	+0·25	+3·15**
Ba	−3·08**	+1·59	+4·37***
Th	−4·35***	−0·34	+2·95**
Ga	+3·39**	−0·79	−4·87***

* *Ho* is rejected with 95–99 per cent confidence.
** *Ho* is rejected with 99–99·9 per cent confidence.
*** *Ho* is rejected with more than 99·9 per cent confidence.
D.F. Degrees of freedom.

Cumberland Bay Formation and a more acidic provenance for the Sandebugten Formation [illegible]eywackes.

COMPARISON OF THE CHEMICAL COMPOSITION OF SANDSTONES AND PELITES FROM THE CUMBERLAND BAY AND SANDEBUGTEN FORMATIONS

The nature and magnitude of chemical variation within turbidite beds are governed by a number of factors: provenance, rates of erosion, transport and deposition, and depositional environment are all important and often interrelated variables which together determine primary concentration. The chemistry of sandstones and pelites from the Sandebugten and Cumberland Bay Formations are compared using mean analyses (Table IX) and *t*-values (Table X), and an attempt is made to explain significant chemical variation in terms of the above parameters.

The *t*-values of Table X show that, at the 95 per cent confidence level, Ti and Mg are more highly concentrated in the sandstones of the Cumberland Bay Formation relative to the pelites.

TABLE VIII. A COMPARISON OF THE DISTRIBUTION PATTERN OF CERTAIN ELEMENTS IN ACIDIC AND BASIC ROCKS GIVEN BY RANKHAMA AND SAHAMA (1950) AND NOCKOLDS AND ALLEN (1953) WITH THOSE OF THE CUMBERLAND BAY AND SANDEBUGTEN FORMATIONS

Element	*Rankhama and Sahama (1950)*		*Nockolds and Allen (1953)*		*Cumberland Bay Formation*	*Sandebugten Formation*
	Acid	Basic	Acid	Basic		
Ba	High		High			High
Cr		High	High		High	
Ga	High		Little difference		High	
Mn		High			High	
Mg		High		High	High	
Ni		High	High		Little difference	
Sr	High		Little difference		Little difference	
Ti		High			High	
Zr	High		High			High

These elements are characteristically associated with heavy minerals which settle out of a turbidity current first, leaving the lighter feldspar grains, clay particles and finely divided volcanic material to settle out higher in the turbidite bed. Mn also shows a higher concentration in the Cumberland Bay Formation sandstones at this level of confidence. Such a concentration of Mn is perhaps anomalous because Ronov and Ermishkina (1959) found that platform sediments have lower Mn values than deep-water geosynclinal deposits. Conversely, the Sandebugten Formation pelites show higher Mn concentrations than the sandstones at the 99 per cent confidence level. It is suggested that the high concentration of Mn in the Cumberland Bay Formation sandstones may reflect the high Mn content of their basic to intermediate volcanic provenance. The Mn contents of the rocks of the Sandebugten and Cumberland Bay Formations could also have been influenced by the oxidation state of the depositional environment, strong oxidizing conditions favouring Mn precipitation as oxide.

K, Rb and Ba show higher concentrations in the pelites of the Cumberland Bay Formation at more than 99·9 per cent confidence (Table X). The chemistry of Ba is closely related to that of K, an important constituent of clay minerals, as they have a similar ionic radius. Rb also follows the distribution of K in clay minerals and generally goes into illite. Th also follows the distribution of K and is therefore more highly concentrated in the Cumberland Bay Formation pelites (Table X). Pliler and Adams (1962) noted that the Th/K ratio of shales is generally constant, a clear indication of the close chemical relationship between these two elements.

At the 99 per cent confidence level, Pb shows a higher concentration in the pelites of the Cumberland Bay Formation (Table X). Pb is most probably concentrated under reducing conditions and thus occurs in black muds; it may also be present in clay minerals. Ni is similarly concentrated in black shales (Peltola, 1968). Wakeel and Riley (1961) suggested that Ni is also associated with clay minerals, thus explaining its higher concentration in the Cumberland Bay Formation pelites (Table X).

Geochemical data indicate that there is no apparent heavy mineral concentration in the sandstones of the Sandebugten Formation (Table X). All the highly significant concentrations of elements have occurred in the pelites relative to the sandstones. Elements which characteristically go into clay minerals, such as Al, Rb, Sr, Y and Ga, show higher concentrations in the Sandebugten Formation pelites (Table X). K does not show such a significant concentration but

TABLE IX. A comparison of the chemistry of sandstones and pelites from the Cumberland Bay and Sandebugten Formations using mean analyses

	Cumberland Bay Formation		*Sandebugten Formation*	
	Sandstone	*Pelite*	*Sandstone*	*Pelite*
SiO_2	58·04	65·13	69·58	67·54
TiO_2	1·13	0·74	0·61	0·67
Al_2O_3	14·42	13·37	13·25	15·52
Fe_2O_3	6·38	3·59	3·09	3·77
FeO	3·60	3·86	1·80	1·90
MnO	0·17	0·14	0·09	0·12
MgO	3·32	1·68	1·22	1·66
CaO	3·64	4·51	1·48	1·30
Na_2O	3·35	2·13	4·16	3·28
K_2O	1·45	2·40	1·86	2·55
P_2O_5	0·17	0·24	0·18	0·11
H_2O-	1·16	1·21	0·40	0·30
CO_2	2·01	2·22	1·75	2·23
Trace elements (p.p.m.)				
Cr	29	31	24	24
Ni	13	17	14	18
Zn	116	119	96	117
Rb	41	84	59	89
Sr	224	207	181	33
Y	30	26	21	33
Zr	163	166	224	196
Nb	6	9	9	10
Ba	404	575	526	642
La	22	26	27	27
Ce	38	47	49	52
Pb	11	17	14	17
Th	5	9	11	11
Ga	21	18	13	18
Number of analyses	78	15	29	8

TABLE X. *t*-VALUES OBTAINED FROM A COMPARISON OF THE MEAN CHEMICAL ANALYSES OF SANDSTONES (SST) AND PELITES (PEL) FROM THE CUMBERLAND BAY AND SANDEBUGTEN FORMATIONS

	Cumberland Bay Formation SST : PEL	*Sandebugten Formation* SST : PEL
D.F.	38	39
Si	−1·63	−0·09
Ti	+2·07*	−0·93
Al	−0·43	−2·34*
Fe	+1·66	−1·38
Mn	−2·13*	−3·00**
Mg	+2·57*	−1·38
Ca	+1·85	+0·32
Na	+2·28*	+1·46
K	−4·10***	−2·0
Cr	−1·50	−0·2
Ni	−2·92*	−0·75
Rb	−4·71***	−3·36**
Sr	+0·05	−2·76**
Y	−0·55	−3·04**
Zr	−1·53	+0·62
Ba	−3·84***	−1·77
Th	−2·65*	−0·22
Ga	−0·07	−3·12**
Pb	−3·37**	−2·65*

* *Ho* is rejected with 95–99 per cent confidence.
** *Ho* is rejected with 99–99·9 per cent confidence.
*** *Ho* is rejected with more than 99·9 per cent confidence.
D.F. Degrees of freedom.

the mean analyses in Table IX suggest that this may reflect high variance rather than an actual absence of K concentration. Ga substitutes for Al and thus follows it in showing a significantly higher concentration in the pelites of the Sandebugten Formation and *not* the Cumberland Bay Formation. Hirst (1962) found the Ga : Al ratio was constant through widely differing sedimentary facies. Concentration of Pb in the Sandebugten Formation pelites, relative to the sandstones, is attributed to the association of this element with black shales and clay minerals (Table X).

Chemical variations between the sandstones and pelites of both the Sandebugten and Cumberland Bay Formations appear to be controlled mainly by the effect of turbidity current transport on mineralogical differences. Elements, which are constituents of the clay minerals, are concentrated in the pelites, whereas those which go into the heavy minerals occur more abundantly in the sandstones. Differences in the concentration of elements between the pelites and sandstones from the Sandebugten Formation and the Cumberland Bay Formation are probably due to differences in the provenance of these two rock types.

THE RELATIONSHIP BETWEEN THE BARFF POINT MEMBER AND GREYWACKES OF THE SANDEBUGTEN AND CUMBERLAND BAY FORMATIONS

Stone (1980) suggested that rocks from the Barff Point area (Fig. 1) represent a mixed lithology ranging in composition from volcanic greywacke to quartzose greywacke. He considered that the Barff Point Member was petrographically intermediate in composition between the Cumberland Bay and Sandebugten Formations. The rocks of the Barff Point Member plot on the Sandebugten Formation side of the Cumberland Bay Formation field on the QFM diagram (Fig. 2) but, as evidence for an intermediate composition, these petrographic data are inconclusive.

The mean analyses in Table VI suggest that the Barff Point Member rocks are geochemically more similar to the greywackes of the Cumberland Bay Formation than those of the Sandebugten Formation. The *t*-values in Table XI show that, at the 99 per cent significance level, there is no chemical variation between the Barff Point Member and the Cumberland Bay Formation. However, at the same significance level, Mn, Mg and Y are higher and Th is lower in concentration in the Barff Point Member than in the Sandebugten Formation, clearly indicating that the Barff Point Member and Sandebugten Formation greywackes were derived from different source areas (Table XI). In spite of the apparent petrographic differences (Stone, 1980; Fig. 2) between the Cumberland Bay Formation and the Barff Point Member, there is insufficient chemical variation between these two groups to suggest that the rocks of the Barff

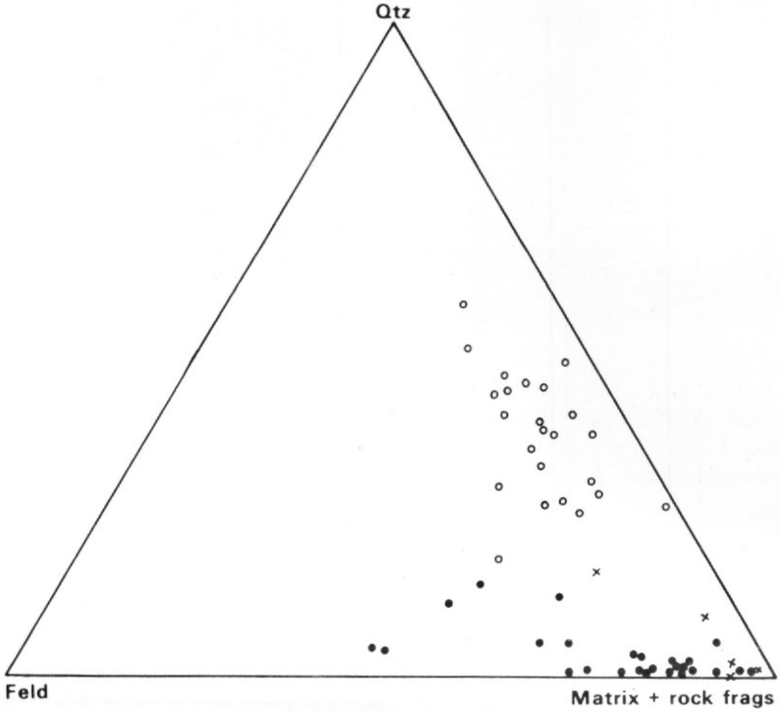


Fig. 2. QFM diagram for the South Georgia sediments. Solid circles, Cumberland Bay Formation greywackes; open circles, Sandebugten Formation greywackes; crosses, Barff Point Member greywackes.

TABLE XI. *t*-VALUES OBTAINED FROM A COMPARISON OF THE MEAN CHEMICAL ANALYSES OF THE CUMBERLAND BAY FORMATION (CF) AND THE BARFF POINT MEMBER (BM), AND THE SANDEBUGTEN FORMATION (SF) AND THE BARFF POINT MEMBER (BM)

D.F.	CF : BM 33	SF : BM 38
Si	+0·88	+2·37*
Ti	+0·84	−2·59*
Al	+0·18	+0·03
Fe	+0·46	−2·21*
Mn	+0·33	−5·0***
Mg	+0·79	−3·83***
Ca	−0·98	−2·04*
Na	−0·85	+1·08
K	−0·66	+0·60
Cr	+0·83	+0·87
Ni	+0·59	+1·33
Rb	−0·45	+1·45
Sr	+0·06	−0·78
Y	−0·88	−2·79**
Zr	−1·0	+1·31
Ba	−0·88	+0·99
Th	+0·16	+3·10**
Ga	+0·92	−2·17*

* *Ho* is rejected with 95–99 per cent confidence.
** *Ho* is rejected with 99–99·9 per cent confidence.
*** *Ho* is rejected with more than 99·9 per cent confidence.
D.F. Degrees of freedom.

Point Member were formed by intermixing of Cumberland Bay Formation and Sandebug[illegible] Formation turbidites. The minor chemical differences that exist between greywackes from the Cumberland Bay Formation and the Barff Point Member may be attributed to facies variation within the Cumberland Bay Formation.

THE RELATIONSHIP BETWEEN THE COOPER BAY METASEDIMENTS AND THE SANDEBUGTEN AND CUMBERLAND BAY FORMATIONS

At the south-eastern end of South Georgia in the Cooper Bay–Wirik Bay area, original sandstones and shales have suffered low-grade regional metamorphism to form schists, phyllites and slates (Stone, 1980). The grade of metamorphism and intensity of folding in this area are higher than at any other locality on the north-east coast of South Georgia. Stone (1980) recognized that there is a marked compositional difference between the Cooper Bay metasediments and rocks of both the Cumberland Bay and Sandebugten Formations. However, on the basis of the quartz content, the greater similarity is with the rocks of the Sandebugten Formation.

Chemical variation between the Cooper Bay metasediments and the greywackes of the Sandebugten and Cumberland Bay Formations was investigated using mean analyses (Table VI) and *t*-values (Table VII). Table VII shows that at the 99 per cent confidence level, the elements Si, Ti, Fe, Mn, Mg, Ca, Na, K, Ni, Rb, Sr, Y, Zr, Ba, Th and Ga indicate that the Cooper Bay metasediments and the Sandebugten Formation greywackes were derived from different source areas. A comparison of the Cooper Bay metasediments with the Cumberland Bay Formation greywackes shows far fewer significant differences in chemical composition between the two rock types (Table VII). Ni appears to be more highly concentrated in the Cooper Bay metasediments at 99·9 per cent confidence but Cr, which shows very high variance in the Cooper Bay metasediments, does not. Mg follows Ni in showing a significantly higher concentration in the Cooper Bay metasediments (Table VII). At the 95 per cent significance level, K is more highly concentrated in the Cumberland Bay Formation greywackes than the Cooper Bay metasediments. Clearly, the Cooper Bay metasediments are not a highly metamorphosed equivalent of the Sandebugten Formation but they may be related in some way to the chemically similar Cumberland Bay Formation greywackes.

Stone (1980) suggested that the Cooper Bay metasediments could be a metamorphosed equivalent of the Cumberland Bay Formation. However, no detectable changes in rare-element content are produced by low-grade metamorphism unless the rocks have been permeated by solutions during metamorphism (Krauskopf, 1967). At higher grades of metamorphism, the minor elements re-distribute themselves locally but, unless movement of solutions has occurred, overall concentrations do not change. Chemical differences between the Cooper Bay metasediments and the Cumberland Bay Formation greywackes are therefore perhaps too striking to be a product of high-grade metamorphism.

TABLE XII. A COMPARISON OF THE TRACE-ELEMENT ABUNDANCES IN ISLAND-ARC THOLEIITIC AND CALC-ALKALINE LAVAS WITH THOSE OF THE CUMBERLAND BAY FORMATION VOLCANICLASTIC GREYWACKES

Element	*Andesitic lavas*		*Cumberland Bay Formation greywackes*
	Island-arc tholeiite (Gill, 1970)	*Island-arc calc-alkaline (Gill, 1970)*	
Cr	5	34	29
Ni	n.d.	9	13
Rb	4	20	21
Sr	201	489	224
Y	30	18	30
Zr	71	107	163
Ba	93	354	404
La	4	9	22
Ce	10	17	38
Pb	4	3	11
Th	0	2	5

All values are in p.p.m.
n.d. Not determined.

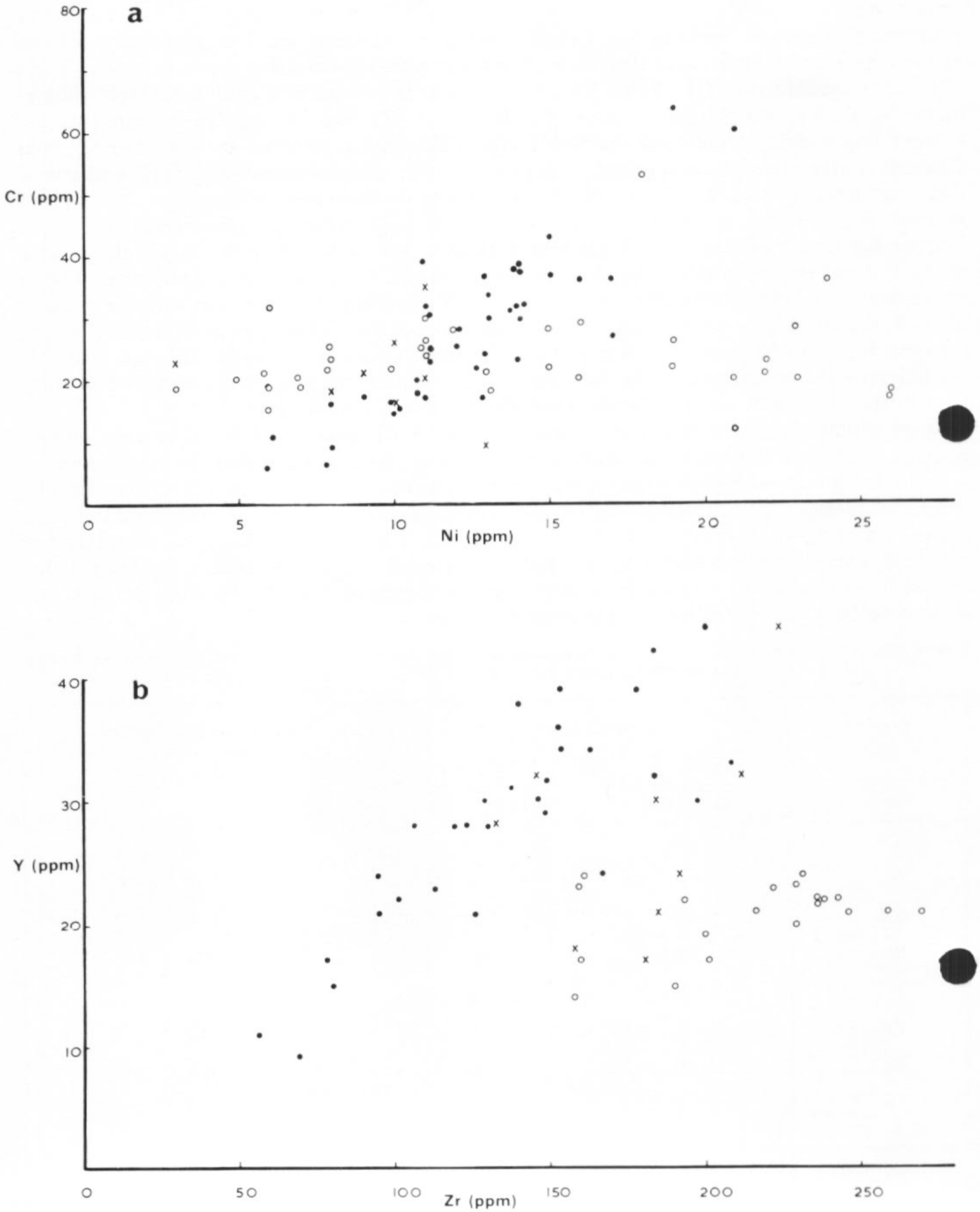


Fig. 3. Plots of Cr against Ni (a) and Y against Zr (b) for the South Georgia sediments. Solid circles, Cumberland Bay Formation greywackes; open circles, Sandebugten Formation greywackes; crosses, Barff Point Member greywackes.

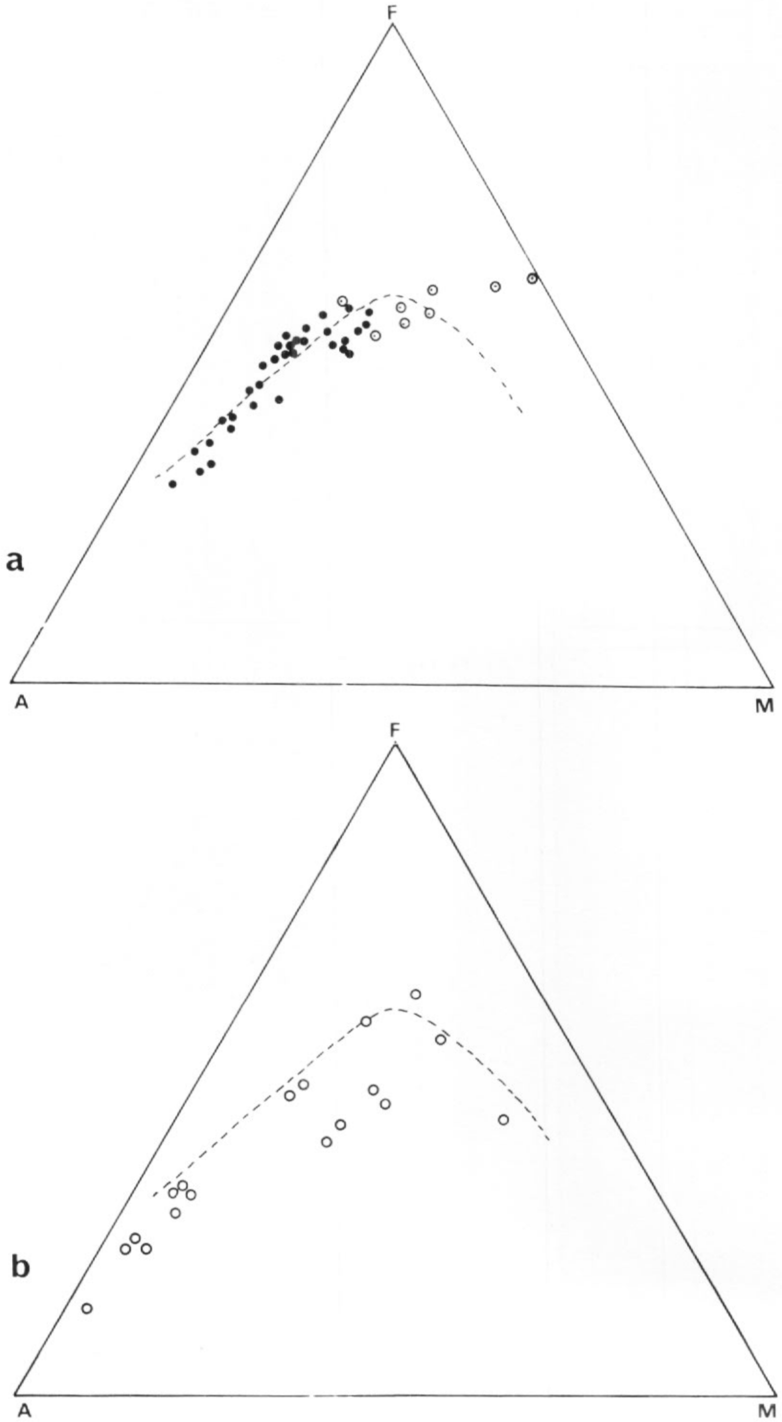
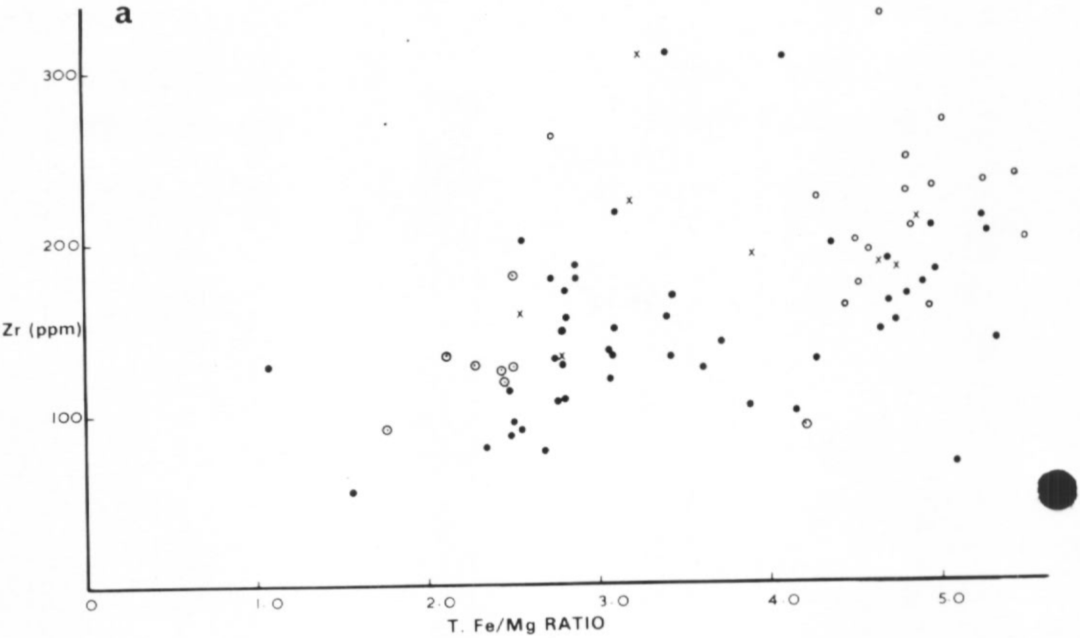


Fig. 4. a. AFM diagram showing the relationship between the Cumberland Bay Formation greywackes and the Cooper Bay metasediments. Solid circles, Cumberland Bay Formation greywackes; circled dots, Cooper Bay metasediments.

b. AFM diagram for the calc-alkaline Danco Coast lavas (West, 1974). The pecked line divides the tholeiitic rocks (above) from the calc-alkaline rocks (below).



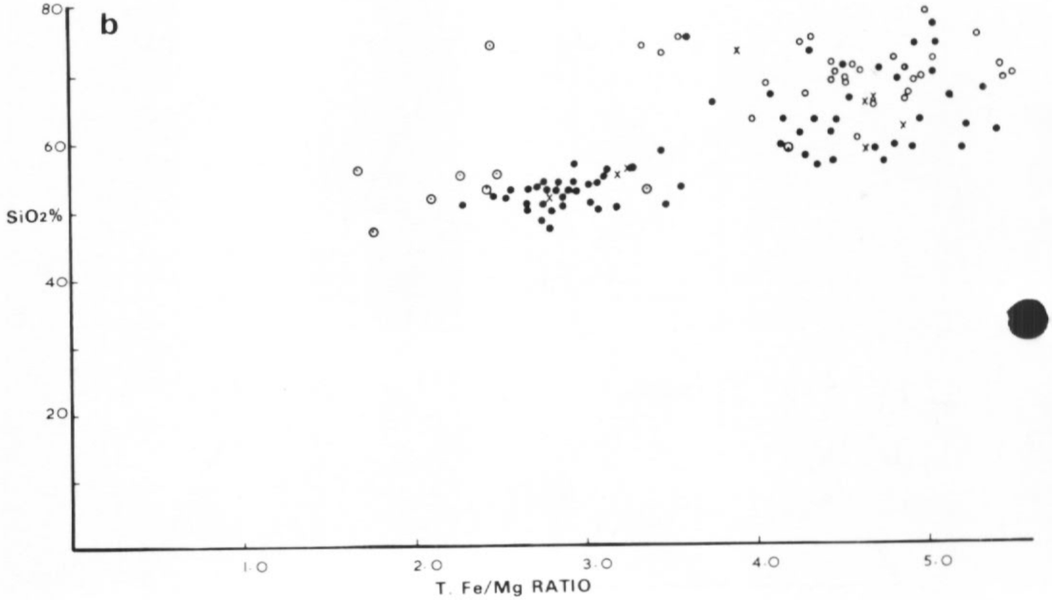


Fig. 5. Plots of total Fe/Mg ratio against Zr (a) and SiO_2 (b) for the South Georgia sediments. Solid circles, Cumberland Bay Formation greywackes; open circles, Sandebugten Formation greywackes; crosses, Barff Point Member greywackes; circled dots, Cooper Bay metasediments.

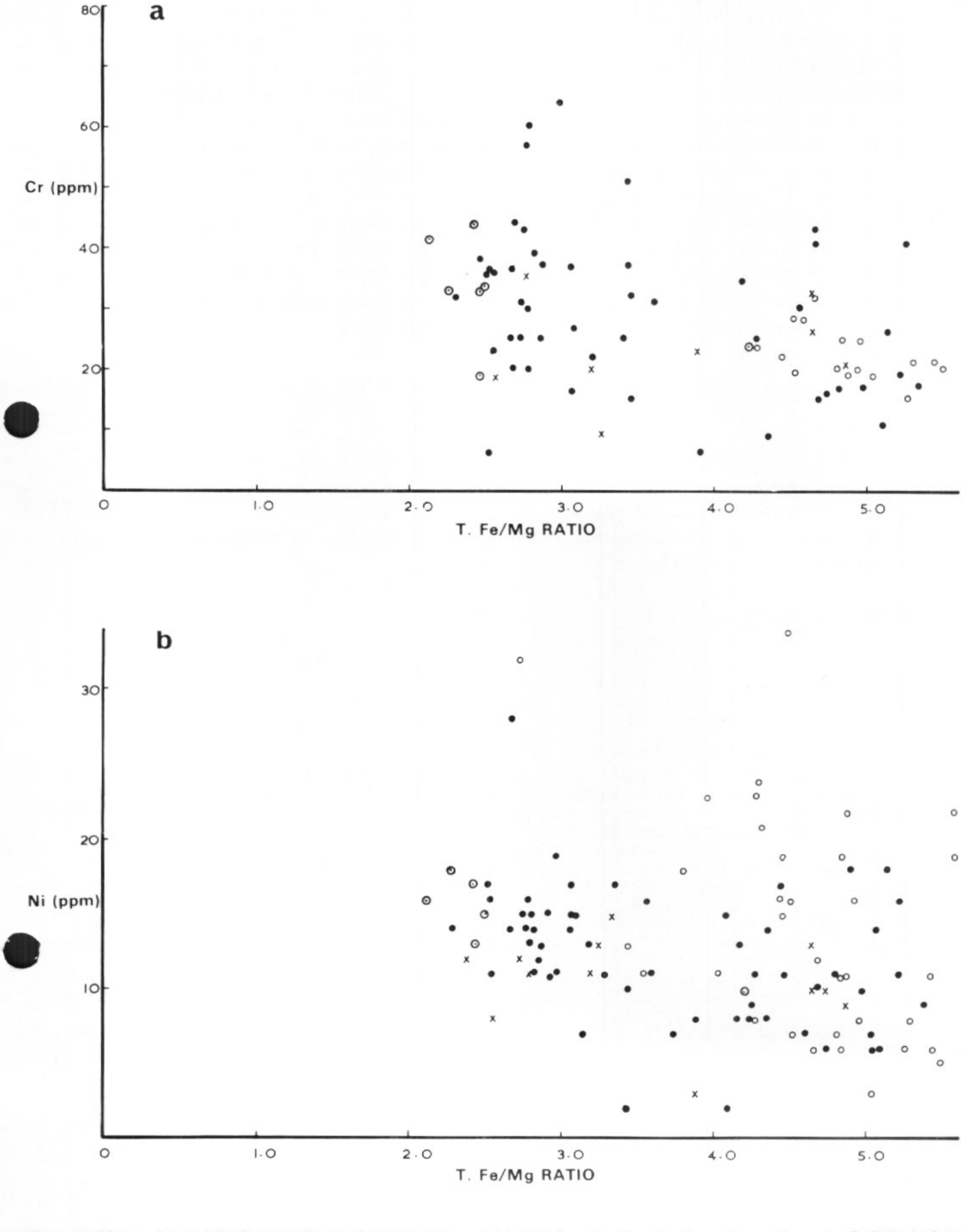


FIG. 6. Plots of total Fe/Mg ratio against Cr (a) and Ni (b) for the South Georgia sediments. Solid circles, Cumberland Bay Formation greywackes; open circles, Sandebugten Formation greywackes; crosses, Barff Point Member greywackes; circled dots, Cooper Bay metasediments.

The graphical plots in Fig. 3 show a crude fractionation trend for the provenance of the Cumberland Bay Formation. A much more distinct and easily recognizable petrogenetic trend is defined on the AFM diagram (Fig. 4a). A comparison with the calc-alkaline Danco Coast lavas (Fig. 4b) of the Upper Jurassic Volcanic Group (West, 1974) suggests that the Cumberland Bay Formation greywackes had a generally calc-alkaline provenance. This is supported by a comparison of the trace-element abundances in island-arc tholeiitic and calc-alkaline andesitic lavas with the Cumberland Bay Formation volcaniclastic greywackes (Table XII). Although trace-element abundances in island-arc tholeiites and calc-alkaline rocks are often similar, the concentrations of all the elements except Sr and Y suggest that the Cumberland Bay Formation rocks were derived from a predominantly calc-alkaline volcanic provenance. The Cooper Bay metasediments plot at the basic end of this calc-alkaline trend (Figs. 3–6), suggesting that they could have been derived from a more basic source than the Cumberland Bay Formation greywackes. However, this difference might also be attributed to the more argillaceous nature of the Cooper Bay metasediments.

ACKNOWLEDGEMENTS

Much helpful criticism and advice was received from my colleagues in the Department of Geological Sciences, University of Birmingham. Professor A. Williams kindly provided facilities in the Department of Geological Sciences, University of Birmingham. Dr. P. W. G. Tanner read the manuscript and made a number of valuable comments. Dr. R. J. Adie gave considerable editorial assistance.

MS. received 3 July 1976

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