The petrology and geochemistry of the St. David's granophyre and the Cwm Bach rhyolite, Pembrokeshire, Dyfed

T. W. BLOXAM AND M. H. J. DIRK

Department of Geology, University College, Swansea

Abstract

A petrological and geochemical study has been made of the late Precambrian St. David's granophyre (SDG) and the Cwm Bach rhyolites (CBR). The SDG is trondhjemitic, peraluminous, and chemically zoned with lower Na/K ratios in its interior portions. Although the SDG contains only minor amounts of K, the Rb content is relatively high and ratios of immobile versus mobile elements indicate that K has been removed. The CBR are flow-banded and autobrecciated subaerial rhyolite flows which are more K-rich and less altered than the SDG, lying close to the ternary minimum composition of the system Q-Or-Ab-(H$_2$O). K mobility is considered to result from the reaction K-feldspar → K-mica which released excess K ions, imparting peraluminous compositions to the rocks. On the basis of this reaction the original K content of the rocks has been estimated, the values for which are more compatible with immobile element abundances and with normal igneous trends. Similar abundances of the relatively immobile elements Ti, Zr, Sr, Y and Nb, together with K-corrected K/Rb ratios, suggest that the SDG and CBR may be comagmatic volcanic-arc-collision-type granite and rhyolite.

KEYWORDS: St. David's, granophyre, Cwm Bach, rhyolite, Pembrokeshire, Dyfed, Wales.

Introduction

THE Precambrian rocks of South Wales are almost entirely igneous and include granophyre, quartz-diorite, diorite, rhyolite, and minor amounts of basalt and dolerite with associated volcaniclastic material. They occupy three main belts (Fig. 1): a northern belt extending ENE from St. David's; a central strip from Cwm Bach through Roch and Hayscastle, and a southern belt which outcrops around Talbenny extending eastwards through Johnston to Benton. The extrusive volcanic rocks are called Pebidian and the intrusive members Dimetian (Hicks, 1878; Green, 1908). The St. David's granophyre (SDG) constitutes the best exposure of Dimetian and has been described as an alaskite granophyre composed of quartz, orthoclase, oligoclase, and secondary chlorite and epidote (Green, 1908; George and Pringle, 1970). Contacts between the SDG and adjacent rocks are largely obscured but, when exposed, are faults (Fig. 2). The Precambrian age of the SDG was demonstrated by Green (1908) who exhumed an unconformable junction between it and overlying basal Cambrian conglomerate at Porth Clais, although Hicks (1886) had already noted SDG pebbles in the conglomerate. Radioactive dating gave U-Pb zircon ages of 650 and 570 Ma (Patchett and Jocelyn, 1979). There are no radioactive dates for the Pebidian but a magnetization date of 643 +5/−28 Ma has been proposed (Thorpe et al., 1984).

The Cwm Bach rhyolites (CBR) lie about 10 km east of the SDG at the bay of that name and
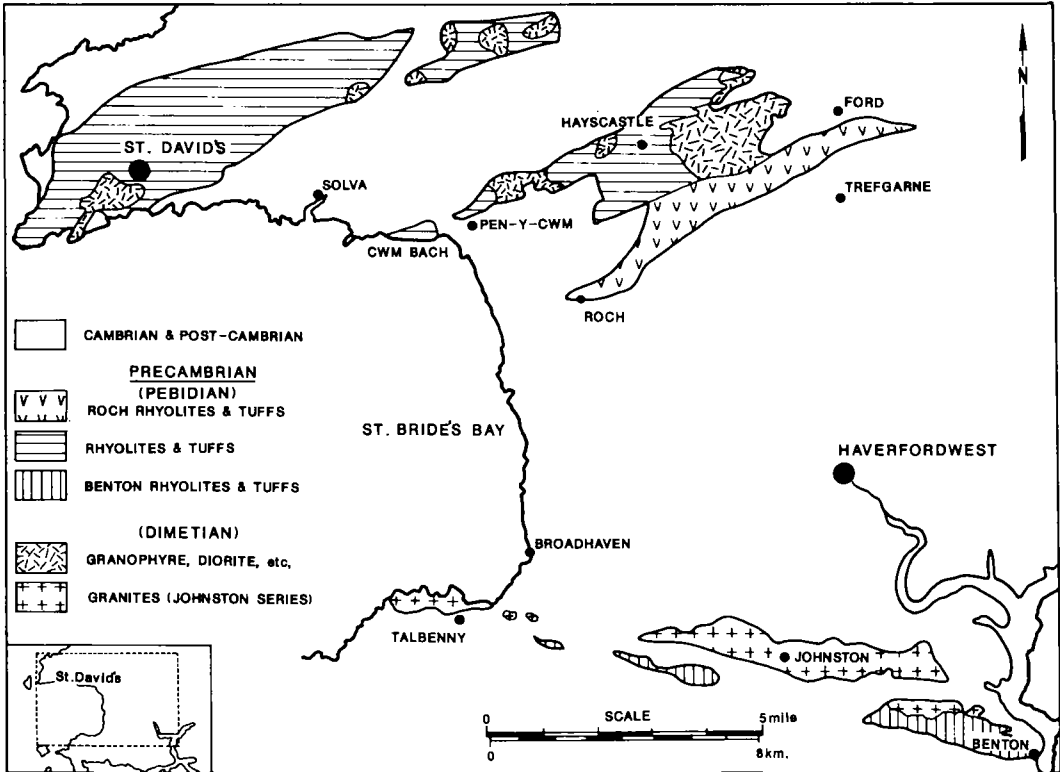
FIG. 1. Geological sketch-map of Precambrian rocks in Pembrokeshire, Dyfed.

appear to be an inlier of Pebidian separated by faults from the main Hayscastle group of Pebidian to the NE (Figs. 1 and 3). Individual exposures are often good but discontinuous, cliff and shore sections being difficult of access. Cambrian strata immediately to the east are faulted against the rhyolites along the line of a gulley containing shattered rhyolite. The ridge of rhyolite (AB in Fig. 3) displays several flows as evidenced by flow-banded units with accompanying upper and lower autobreccias. Considerable variations in the dip of the flow banding indicate the presence of folds although some inclined flow-banding could be an original attitude. The stream (Fig. 3) forms a line separating rhyolites and their flow-breccias to the south from more uniform massive flow-banded and flow-contorted rhyolite to the north. It is not certain whether the stream-line follows a fault; if so it does not alter the general N S strike of the flow banding on either side.

Geotectonic setting

The Precambrian rocks of South Wales form a complex basement to the main lower Palaeozoic trough of Wales and England (Jones, 1938). However, Rast and Crimes (1969) concluded that much of the Welsh Precambrian sequence has to be included within the Caledonian of Britain on the basis of several 'Precambrian' dates in the range 600 570 Ma coupled with stratigraphical evidence of a Caledonian orogenic episode accompanied by intrusion of granite at about this time. Wright (1969) and Rast et al. (1976) place most Precambrian igneous rocks of Wales and Central England within one calc–alkali magmatic episode between 650–550 Ma. Thorpe (1972) linked the SDG with the Johnston igneous complex to the south, considering them to be calc–alkali subduction-related intrusions. An initial $^{87}Sr/^{86}Sr$ isotopic ratio of 0.7037–0.7053 for the SDG (Thorpe et al., 1984) indicates derivation from melts of mantle origin.

The St. David's granophyre (SDG)

Petrology. Although well exposed in coastal sections, inland outcrops are poor and discontinuous, so that fixed grid sampling was precluded, while extensive fracturing requires careful collecting. All the samples are leucocratic with coarse,
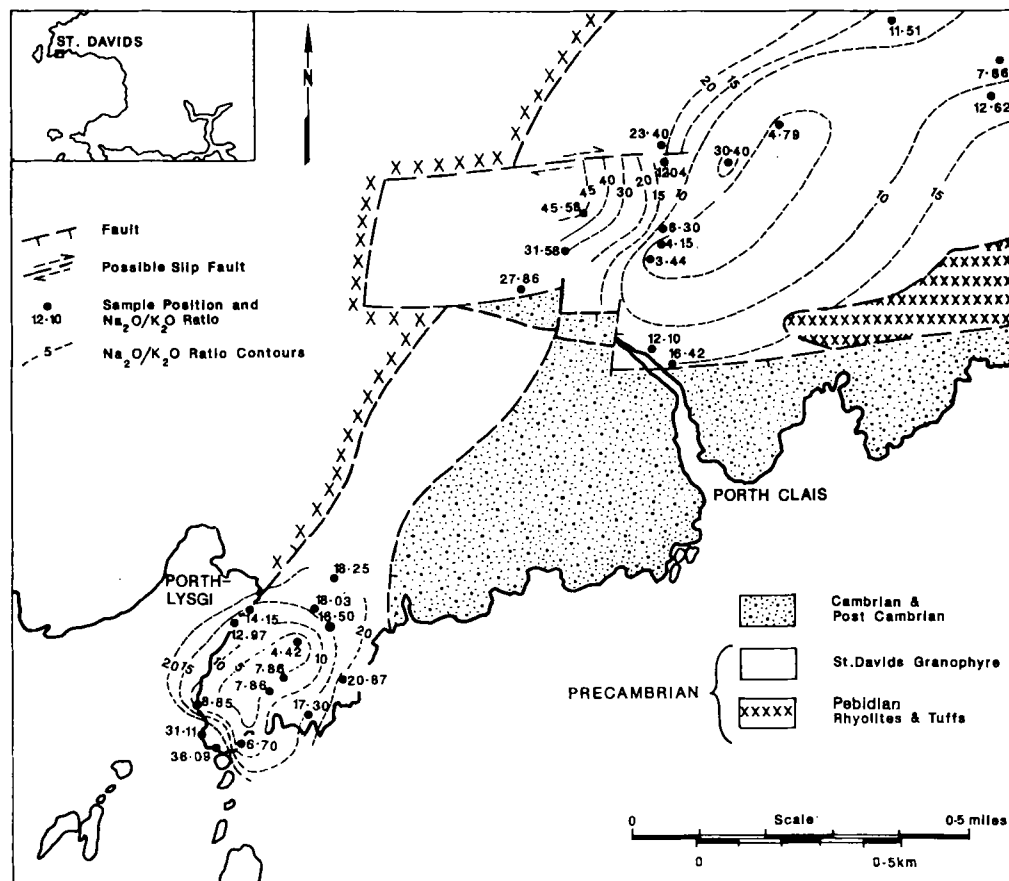
FIG. 2. Geological map and alkali ratios of the St. David's granophyre. Modified from Green, 1908.

medium and finer grained (aplitic) varieties occurring. Coarse-grained rocks are the most abundant; the medium-grained types are confined mainly to the western edge of the intrusion and may represent a chilled marginal zone. The fine-grained granites appear as thin dykes or irregularly developed segregations and veins within the main body of coarse or medium-grained granophyre.

All rocks have a granophyric texture although many samples show that granophyric-symplectic textures have also developed along microfractures. Quartz is frequently cracked, 'dusty' in thin section and often displays undulatory extinction. The feldspar is almost exclusively albite with variable albite twin lamellae combined with pericline twinning, often showing marginal reverse zoning and a chessboard structure, characteristic of late magmatic crystallization. Very rare anhedral orthoclase, microcline and microcline-perthite is interstitial to the quartz and plagioclase. The low

abundance of K-feldspar is confirmed by the low K-content of the rocks (Table 1) and by thin section staining which produced no reaction for K-feldspar. Patches of sericitic mica and granular quartz represent the remains of K-feldspar, but albite is unaltered. X-ray diffraction of the rock powder produces strong peaks for mica but none for paragonite or kaolinite.

Veins containing epidote, chlorite, quartz and calcite are common throughout the granophyre and suggest a propylitic type of alteration like that described by Allen *et al.* (1985) from Llandeloy to the east. The modal composition of five coarse grained samples plotted on the Q–A–P diagram (Streckeisen, 1973) straddles the alkali (soda) granite and granite fields (Fig. 4).

Chemical composition and affinities. Of the 62 samples of SDG collected, 29 were analysed for Na and K. Of these 29, 12 were selected for analyses of the remaining major elements (Table 1).
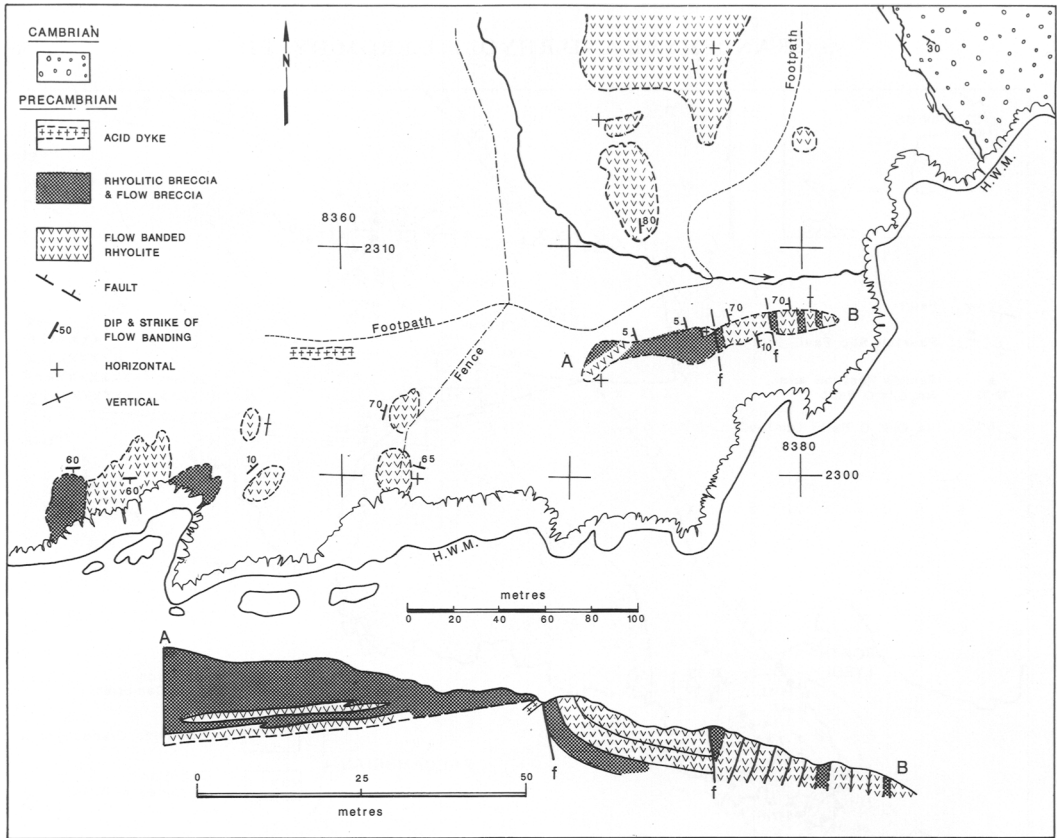
FIG. 3. Geological map of the Cwm Bach rhyolites, Pembrokeshire. Topography on the cross-section (AB) is not exactly to scale.
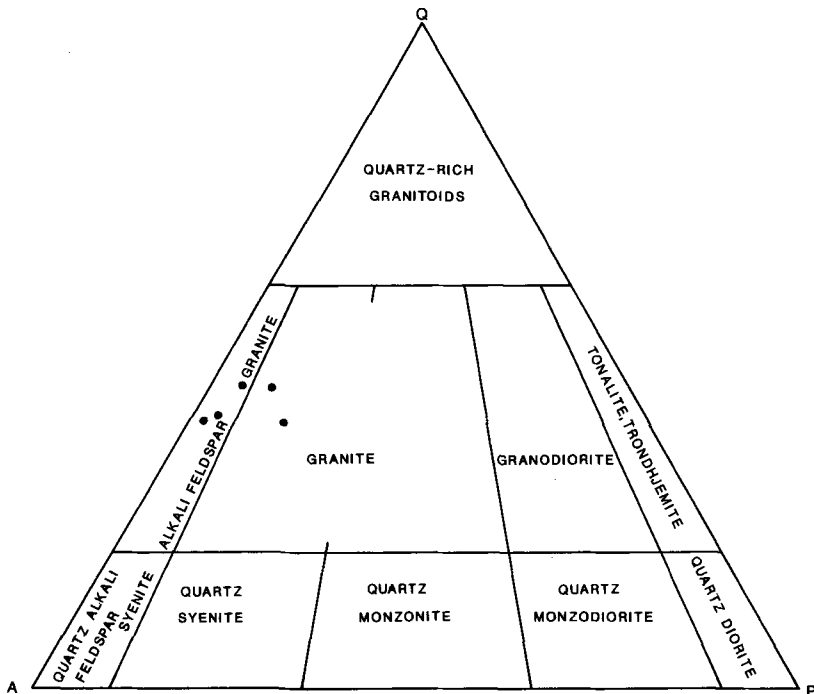

FIG. 4. Modal analyses of the St. David's granophyre on the Q–A–P diagram of Streckeisen, 1973.

Table 1. Chemical analyses of the St. David's granophyre

Wt. %	001	003	009	013	016	021	023	024	025	027	038	046	Average
SiO_2	74.92	78.13	74.92	79.23	72.02	77.56	74.08	75.25	73.18	71.24	76.15	76.22	75.07
Al_2O_3	14.15	14.32	13.12	12.45	16.30	13.22	12.49	13.92	15.65	15.04	14.97	15.36	14.25
Fe_2O_3	2.08	1.87	1.92	2.32	2.55	2.26	1.98	2.01	2.46	2.55	1.97	1.64	2.13
FeO	0.44	0.12	0.28	0.36	0.64	0.72	0.80	0.44	0.20	0.72	0.48	0.32	0.46
MnO	0.03	0.01	0.01	0.02	0.03	0.02	0.02	0.01	0.02	0.03	0.03	0.04	0.02
MgO	0.50	0.36	0.30	0.27	0.57	0.71	0.57	0.36	0.81	0.44	0.47	0.30	0.47
CaO	1.63	0.06	0.80	0.17	0.53	0.18	0.08	0.08	0.87	0.88	0.16	1.54	0.58
Na_2O	4.86	5.81	5.00	5.13	4.93	5.20	5.67	4.93	5.26	5.47	5.53	5.00	5.23
K_2O	0.13	0.18	1.13	0.16	0.41	0.82	0.18	1.03	0.45	0.43	0.33	0.38	0.47
H_2O+	0.67	0.39	0.78	0.75	0.90	1.11	0.68	0.65	0.78	0.73	0.86	0.61	0.74
P_2O_5	0.09	0.03	0.05	0.04	0.08	0.06	0.06	0.05	0.09	0.09	0.06	0.12	0.06
TOTAL	99.50	101.28	98.31	100.90	98.96	101.86	96.61	98.63	99.77	97.62	101.01	101.53	99.48
% Norm													
qtz	41.52	44.34	40.38	48.90	36.24	44.10	40.02	42.18	40.20	34.46	41.34	41.94	41.13
cor	2.96	4.79	2.45	3.77	5.71	3.77	2.96	4.59	5.92	3.67	5.10	3.67	4.11
or	0.56	1.11	5.56	1.11	2.22	5.00	1.11	5.56	2.78	2.78	2.22	2.22	2.69
ab	41.92	47.16	41.92	41.92	47.16	41.92	47.16	41.92	47.16	47.16	47.16	41.92	44.54
an	8.34	0.28	3.89	0.83	2.50	0.83	0.28	0.28	2.78	4.45	0.83	8.34	2.80
hy	1.20	0.90	0.70	0.70	1.40	1.80	1.40	0.90	2.00	1.10	1.10	0.70	1.16
mt	1.39	0.46	0.93	1.16	2.09	2.32	2.55	1.39	0.70	2.32	1.62	0.93	1.49
hm	1.12	1.60	1.28	1.44	1.12	0.64	0.16	0.96	1.92	0.96	0.80	0.96	1.08
ppm													
Ti	2940		1980		3240				3900	3600		1980	2940
Rb	151		146		153				149	147		304	175
Sr	113		62		42				83	85		83	78
Y	8		7		8				45	38		37	23
Zr	209		198		212				217	221		232	214
Nb	1		3		2				2	10		2	3

In addition, 6 of the 12 were analysed for Zr, Nb, Y, Rb and Sr (Table 1). Si, Al, Fe^{3+}, Ti, Zr, Y, Sr, Rb and Nb were determined using XRF; Fe^{2+} titrimetrically; Na and K by flame photometry; Ca and Mg by AAS; Mn and P by spectrophotometry and H_2O gravimetrically. International rock standards were used for calibration.

Plotting the normative compositions of the SDG (Table 1) on an Or–Ab–An diagram (O'Connor, 1965) places the granophyres in the field of trondhjemite (Fig. 5) and in the low-K field of keratophyre and quartz-keratophyre (Donnelly, 1966). Due to its variable K-content the SDG produces a scatter on the discriminative diagram of Coleman and Peterman (1975), the average lying within the field for continental trondhjemite (Fig. 6; Bloxam, 1981).

In the granite system Qtz–Or–Ab (H_2O) they lie close to the low-pressure, high-temperature Qtz–Ab eutectic (Fig. 7; Tuttle and Bowen, 1958; James and Hamilton, 1969).

Alkali zoning. Na_2O/K_2O ratio contours plotted on an outcrop map of the SDG brings out definite patterns (Fig. 2). The Na_2O (average 5.14%) has a standard deviation of 0.41, K_2O (average 0.48%) a value of 0.33. Since the concentration range of
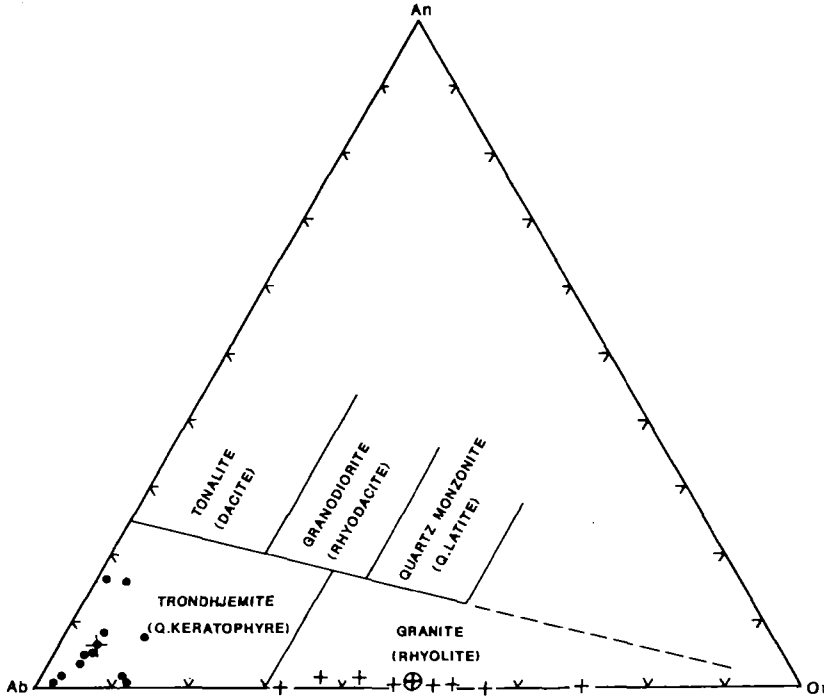
FIG. 5. Normative (CIPW) plots of the St. David's granophyre and Cwm Bach rhyolites on the Or-Ab An diagram of O'Connor, 1965. Dots are SDG and average; crosses CBR and average.

K_2O relative to the mean is nearly ten times that of Na_2O, variation in the Na_2O/K_2O ratios is almost exclusively the result of K variability. Low ratios appear at the SW end of the intrusion and a similar but broader 'low' is present to the NE. The displacement of the contours along the line of a possible fault is also evident, but paucity of outcrops in this area limits precise definition. The form and structural attitude of the SDG has not been established. However, if it is regarded provisionally as a sill or sheet-like body which now has a steep or vertical dip comparable to adjacent Precambrian strata, then the low Na_2O/K_2O ratios lie towards the centre of the intrusion. There is some confirmation of this from the fact that the western margin around Porthlysgi is finer grained (chilled) where the Na_2O/K_2O ratios are also highest. The low ratios to the NE are more widely spaced, suggesting that either the sheet is thicker in this direction or that a different level is exposed. Indeed, the closure of contours in the SW and NE parts could be due to separate intrusions or cupolas.

Alkali and other forms of primary chemical zoning are a common feature of granitic intrusive complexes, zones being arranged concentrically and parallel to contacts with the enclosing rocks. Vance (1961) reviewing the evidence, favours *in situ* solid–liquid fractionation of an initial magma crystallizing inwards from the margins to produce continuous compositional changes with silica and alkali enrichment towards the interior (Brown *et al.*, 1979). Volatiles concentrate towards the centre and promote the transport of elements such as K which is readily exchanged between melt and vapour phases (Tuttle and Bowen, 1958).

Although decreasing Na/K ratios towards the interior of the SDG conform with primary magmatic patterns, evidence of late K-mobility (to be considered presently) suggest that, although some primary zoning may have survived, it has been overprinted by subsolidus metasomatic alteration involving the removal of K.

Cwm Bach rhyolites (CBR)

Petrology. The flow-banded rhyolites comprise flow-aligned phenocrysts of euhedral to subhedral albite and sanidine, often grouped in glomeropor-
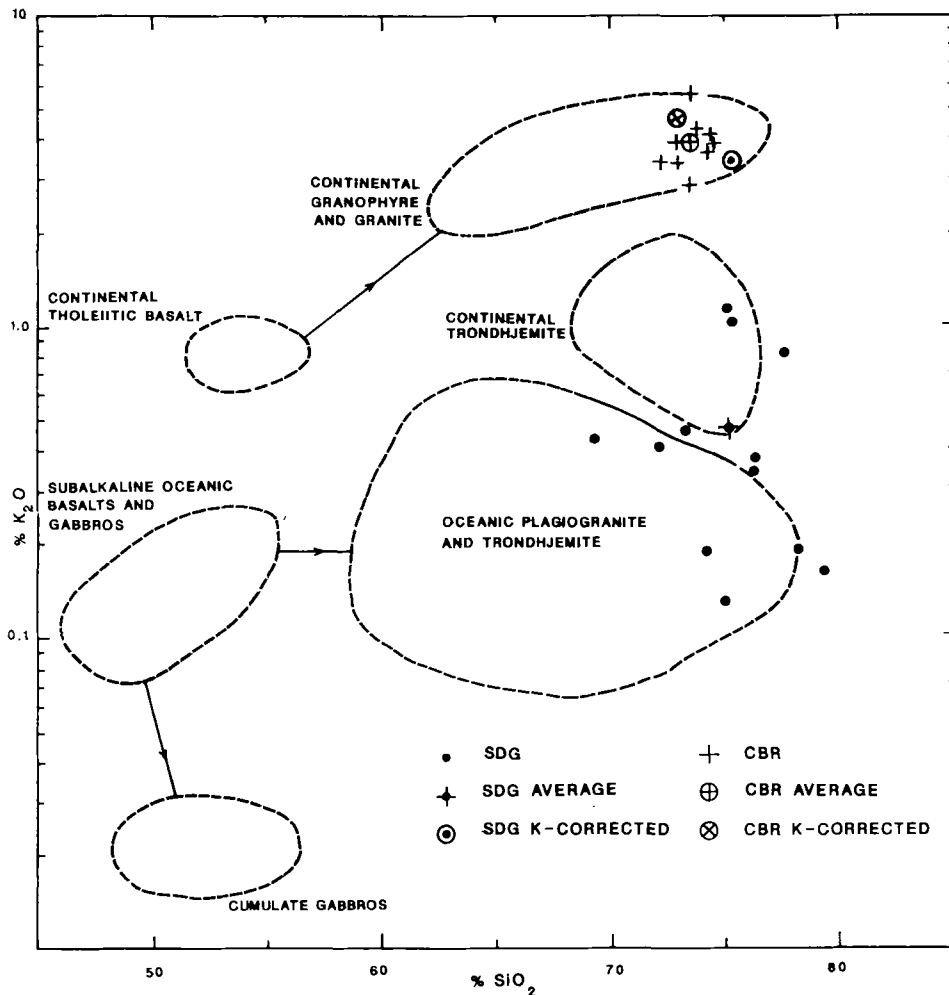
FIG. 6. K_2O vs. SiO_2 showing positions of St. David's granophyre and Cwm Bach rhyolites in relation to assemblages defined by Coleman and Peterman, 1975; Coleman and Donato, 1979.

phyritic patches. The groundmass is birefringent but either cryptocrystalline (felsitic) and/or micro-crystalline, consisting of quartz, feldspar and seri-citic mica. Much of the groundmass probably represents an originally glassy mesostasis. Sub-rounded aggregates of mosaic quartz appear to be amygdales. X-ray diffraction of rock powder gives peaks for mica, weaker for chlorite, and none for paragonite or kaolinite.

Chemical composition and affinities. The chemi-cal and normative compositions of 9 samples are given in Table 2. Plotted on the Or Ab–An diagram (Fig. 5) all samples lie within the field for rhyolite. Compared with the SDG, the CBR

contain much more K and plot within the field for continental rhyolite (Fig. 6). In the Qtz–Or Ab system several samples approach the ternary minimum composition (Fig. 7).

Alkalies and alumina in SDG and CBR

A feature of the SDG and CBR is their strongly peraluminous nature (normative $Al_2O_3 > Na_2O + K_2O + CaO$). Optical and XRD examination showed that the aluminous minerals are albite, K-feldspar and K-mica. No paragonite or kaolinite was detected and chlorite is only a very minor constituent. Peraluminous characters, evidenced

Table 2. Chemical analyses of Cwm Bach rhyolite

Wt. %	010	020	030	040	050	060	070	080	090	Average
SiO_2	72.23	73.13	73.49	74.42	74.46	72.84	74.31	73.79	73.50	73.57
Al_2O_3	15.05	14.02	14.28	14.67	13.82	14.63	13.40	14.42	14.02	14.25
Fe_2O_3	2.16	2.48	2.56	1.87	2.16	2.49	2.02	1.86	2.31	2.21
FeO	0.40	0.56	0.20	0.24	0.56	0.88	0.24	0.12	0.52	0.41
MnO	0.03	0.05	0.03	0.02	0.04	0.06	0.03	0.01	0.05	0.03
MgO	0.56	0.76	0.58	0.34	0.61	0.88	0.48	0.29	0.77	0.58
CaO	0.17	0.19	0.02	0.04	0.01	0.06	0.04	0.06	0.03	0.07
Na_2O	3.37	4.18	1.62	2.02	2.30	2.30	2.51	3.37	4.38	2.89
K_2O	3.37	3.37	5.54	4.10	3.85	3.86	3.61	4.33	2.88	3.87
H_2O+	0.99	1.39	1.47	1.01	1.12	1.44	0.81	0.85	0.78	1.09
P_2O_5	0.07	0.09	0.02	0.10	0.05	0.06	0.03	0.05	0.12	0.06
TOTAL	98.40	100.22	99.81	98.83	98.98	99.50	97.48	99.15	99.36	99.03
% Norm										
qtz	38.64	34.56	42.00	46.08	45.48	43.32	45.36	37.26	35.58	40.92
cor	5.51	3.16	5.61	6.73	5.81	6.53	5.30	4.08	3.47	5.13
or	20.02	20.02	32.80	24.46	22.80	22.80	21.13	25.58	17.24	22.98
ab	28.30	35.11	13.62	17.29	19.39	19.39	20.96	28.30	37.20	24.38
an	0.83	0.83	0.68	0.28	0.06	0.28	0.28	0.28	0.14	0.34
hy	1.40	1.90	1.40	0.80	1.50	2.20	1.20	0.70	1.90	1.44
mt	1.39	1.86	0.70	0.70	1.86	2.78	0.70	0.46	1.62	1.34
hm	1.12	1.12	2.08	1.44	0.80	0.64	1.60	1.60	1.12	1.28
ppm										
Ti	2820		2340	2400		2400			2460	2484
Rb	254		264	229		250			178	235
Sr	47		27	23		31			20	29
Y	77		28	44		23			18	38
Zr	178		163	128		175			117	152
Nb	2		4	6		2			1	3

by normative corundum, are likely to occur in acid rocks containing mica since the Al/K ratio in this mineral is $3:1$ compared to $1:1$ in alkali feldspar.

Primary muscovite in granites crystallizes at 700 °C at about 2 kbar water pressure (Yoder and Eugster, 1955; Tuttle and Bowen, 1958) and has also been reported in some rhyolites (Schleicher and Lippolt, 1981). However, later deuteric/ hydrothermal alteration processes in granites (e.g. Pitcher and Berger, 1972) also produce K-mica from the breakdown of feldspar. Acid melts cooling in the subsolidus region with water present

will eventually enter the stability field for muscovite (Fig. 8) which can form from feldspar according to the reaction

$$3(KAlSi_3O_8) + 2H^+ \rightarrow$$
(feldspar)
$$KAl_3Si_3O_{10}(OH)_2 + 6SiO_2 + 2K^+$$
(muscovite)
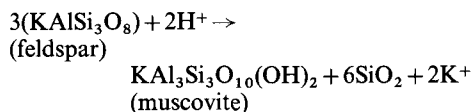
This reaction involves no change in total Al but releases excess K ions increasing the Al/K ratio of the rock. The abundant sericitic mica in the present rocks is considered to be a product of such a reaction as is some of the extensive quartz veining.
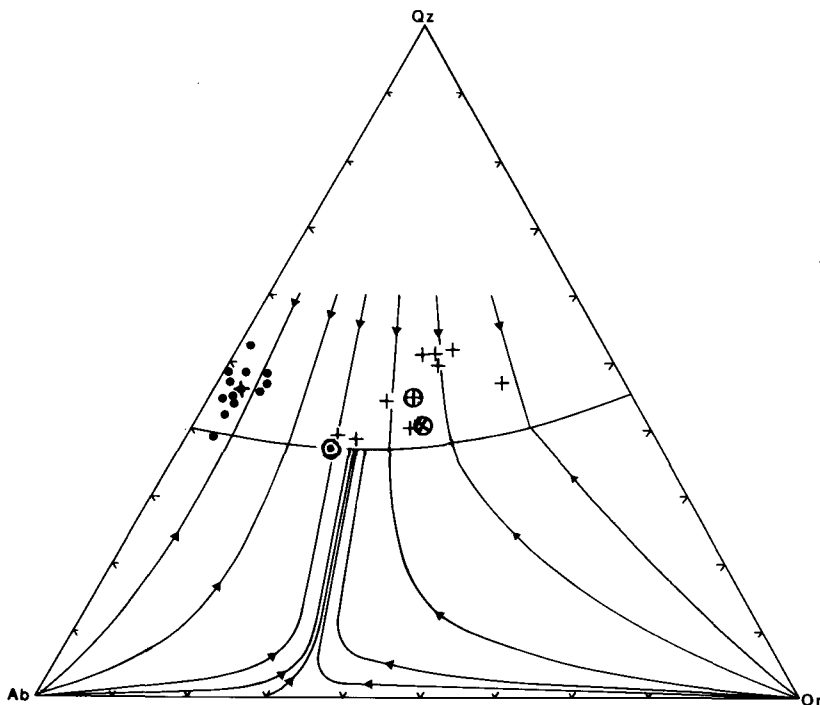
FIG. 7. Normative Q-Or-Ab of St. David's granophyre and Cwm Bach rhyolites (1 kbar H_2O). Data from Tuttle and Bowen, 1958; James and Hamilton, 1969. CIPW norms from Tables 1 and 2 with additional norms calculated from alkali analyses. See Fig. 6 for symbol key.

Alkali mobility in SDG and CBR

Although K is very variable in the SDG, Rb contents remain relatively constant at an average 175 ppm. One high Rb value from the western (faulted) margin of the granophyre may be anomalous. The Rb is much higher than would be expected in rocks with such low K. Other work on the relative mobilities of K and Rb in rocks provides conflicting evidence (e.g. Ambrust and Gannicott, 1980; Olade and Fletcher, 1975, 1976; Davies, 1980), from which it is concluded that these elements can vary independently in systems with active fluid and vapour phases.

In the SDG K has been removed relative to Rb, the latter probably fixed in secondary K-mica, the lattice of which is a preferred site for Rb (Heier and Adams, 1964). The resulting K/Rb ratios in the SDG (Fig. 9) are very low and well removed from the main igneous trend of Shaw (1968) and that of other igneous series (Jakes and White, 1972). Compared with the SDG, the average K/Rb ratio of the CBR lies within the igneous spectrum.
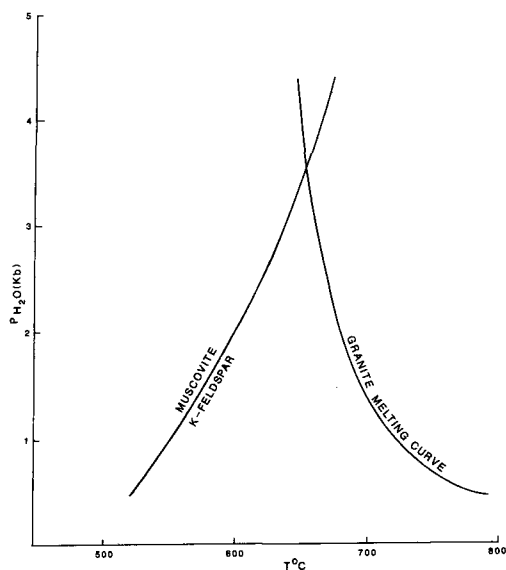
Metasomatism in rocks can be assessed by

FIG. 8. Equilibrium curve for muscovite → K-feldspar (H_2O). See Schleicher and Lippolt (1981) for summary of data.
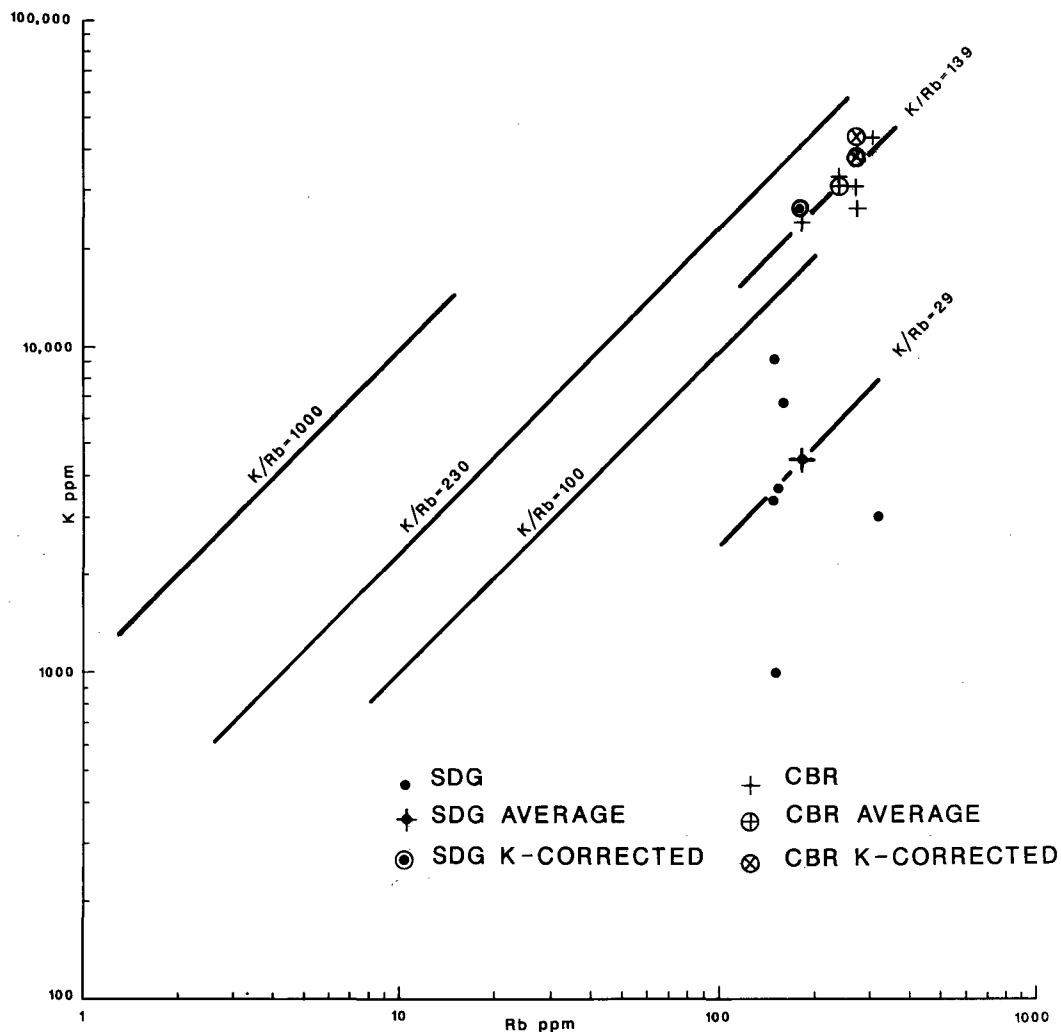
FIG. 9. K–Rb and K/Rb ratios in the St. David's granophyre and Cwm Bach rhyolites (Shaw, 1968). See Fig. 6 for symbol key.

comparing the ratios of relatively immobile elements such as Al, Zr and, in the present case Rb, with the ratios of likely mobile elements such as K (Beswick and Soucie, 1978; Davies *et al.*, 1979). Except for one sample, Rb/K_2O *vs.* Al_2O_3/K_2O in the SDG generates a line resulting from K-mobility (Fig. 10). The same relationship is displayed in plots using Zr/K_2O.

Chemical reconstruction of the SDG and CBR

The mobility of K and to a lesser extent Na, indicates that these elements do not provide a

satisfactory basis for elucidating original compositions in such altered rocks. Assuming that all the excess Al_2O_3 is a result of the reaction 3(K-feldspar) → K-mica, the original K-content has been calculated on the basis of constant Al_2O_3 in the system. After allocating Al_2O_3, Na_2O and K_2O to normative albite and orthoclase, the excess Al_2O_3 is combined with K_2O in the proportions $3Al_2O_3 : 1K_2O$ to form K-mica from which the K_2O 'lost' in the reaction can be determined. The average K_2O correction for the SDG is +2.6% and +0.7% for the CBR, giving an original average K_2O of 3.0 and 4.5% respectively. If these values
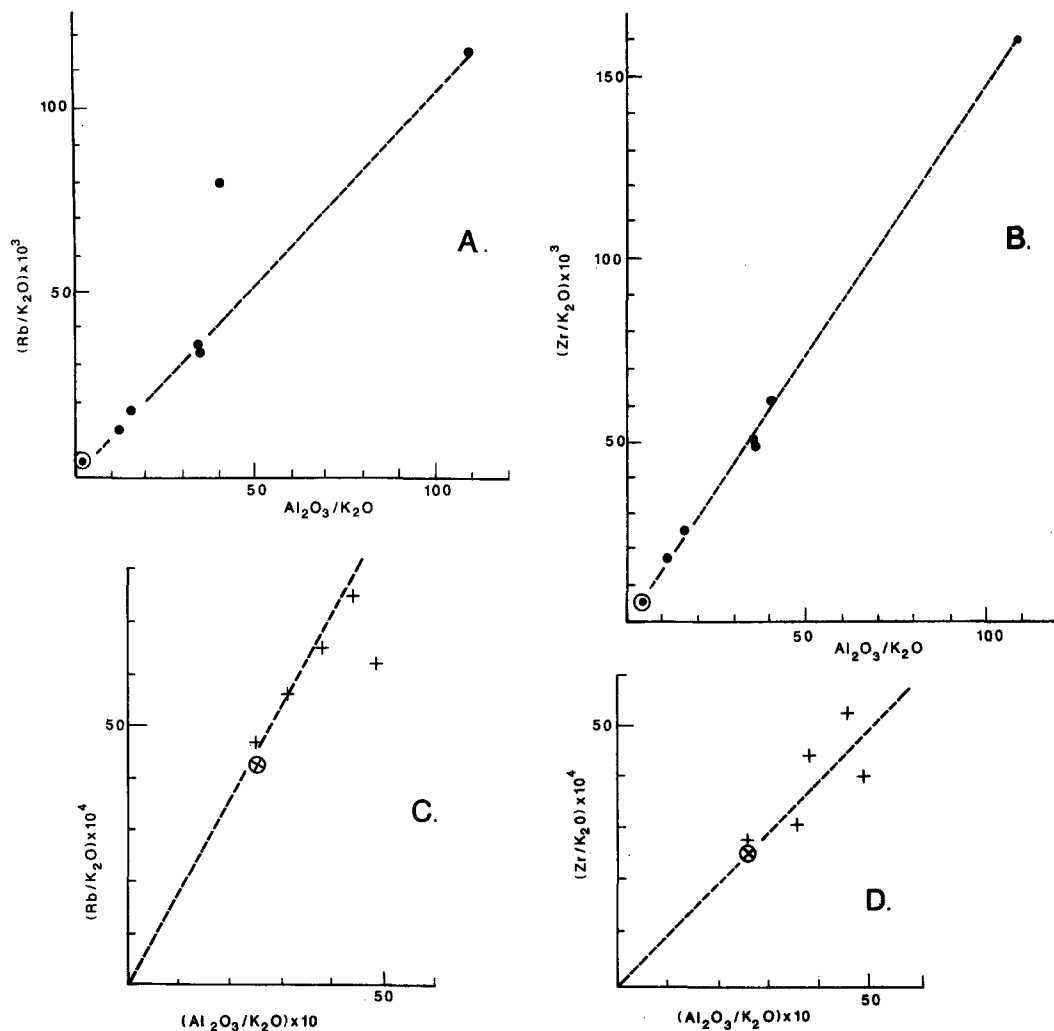
FIG. 10. Immobile element (Al, Zr, Rb) to mobile K ratios in the St. David's granophyre (A, B) and Cwm Bach rhyolite (C, D). See Fig. 6 for symbol key.

are employed, the SDG falls into the field for continental granophyres along with the CBR (Fig. 6). Corrected SDG values also plot close to the ternary minimum in the Qtz–Or–Ab system (Fig. 7).

Discriminative elements

Relatively immobile elements are useful for determining the tectonic setting of igneous rocks, particularly when they have been extensively altered. The Zr/TiO_2 ratios of the SDG and CBR each average 0.046 which places them in the

rhyolite field proposed by Winchester and Floyd (1977, p. 333) and on the acid volcanic line of Peterson (1983). Both existing and K-corrected K/Rb ratios of the CBR lie within the igneous spectrum (Fig. 9) and correspond with those for the alkali shoshonite series which occur on the continental side of volcanic arcs (Jakes and White, 1972). The extremely low K/Rb ratios in the SDG are outside the igneous spectrum but the K-corrected ratio is almost the same as that of the CBR (Fig. 9). Rb, Y and Nb have been variously combined (Pearce *et al.*, 1984) to discriminate between the tectonic environments of granitic
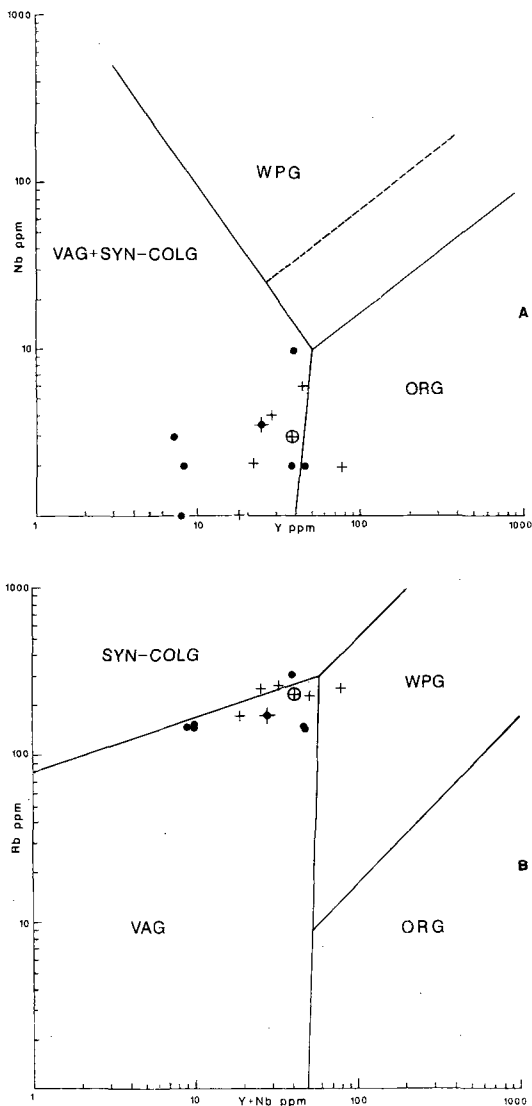
FIG. 11. Rb, Nb, Y discrimination diagrams. (A) Nb vs. Y; (B) Rb vs. Y+Nb (Pearce et al., 1984). Ocean ridge granites (ORG); volcanic arc granites (VAG); within plate granites (WPG); syn-collision granites (SYN-COLEG).

rocks. The SDG and CBR occupy essentially the same fields on the Nb vs. Y and Rb vs. (Nb+Y) diagrams (Fig. 11), placing them within the rather broad group of volcanic arc and collision granites.

Conclusions

The SDG is a chemically zoned low-K intrusion of trondhjemitic composition. In contrast, the CBR is less altered, more K-rich, and within the normal igneous compositional spectrum. Both are peraluminous as the result of K-loss during late-stage sericitization of K-feldspar and calculation of the original K-content of the rocks is based upon constant Al during this reaction. The K-corrected values produce K/Rb ratios in the SDG which fall within the igneous spectrum and are similar to that for the CBR. The K-corrected data also place the rocks close to the ternary minimum melting point of the granite system. Similar abundances of the relatively immobile elements Ti, Zr, Sr, Y and Nb in the SDG and CBR, together with the corrected K/Rb ratios, suggest that they may be comagmatic volcanic arc/collision granite and rhyolite.

References

Allen, P. M. et al. (1985) British Geol. Surv. Mineral Reconnaissance Report No. 78.

Ambrust, G. A. and Gannicott, D. A. (1980) Econ. Geol. 75, 466-77.

Beswick, A. E. and Soucie, G. (1978) Precambrian Res. 6, 235-48.

Bloxam, T. W. (1981) J. Geol. 89, 754-64.

Brown, G. C., Cassidy, J., Tindle, A. G., and Hughes, D. J. (1979) J. Geol. Soc. London, 136, 745-53.

Coleman, R. B. and Donato, M. M. (1979) In Trondhjemites, dacites and related rocks (Barker, F., ed.), Amsterdam, Elsevier Press.

——and Peterman, Z. E. (1975) J. Geophys. Res., 80, 1099-108.

Davies, J. F. (1980) Econ. Geol. 75, 760-70.

——Grant, R. W. E., and Whitehead, R. E. S. (1979) Can. J. Earth Sci. 16, 305-11.

Donnelly, T. W. (1966) Mem. Geol. Soc. Am. 98, 85-176.

George, T. N. and Pringle, J. (1970) British Regional Geology, South Wales (HMSO).

Green, J. F. N. (1908) Q. J. Geol. Soc. London, 64, 363-83.

Heier, K. S. and Adams, J. A. S. (1964) Phys. Chem. Earth, 5, 253-381 (Pergamon Press).

Hicks, H. (1878) Q. J. Geol. Soc. London, 34, 147-69.

——(1886) Ibid. 42, 351-6.

Jakes, P. and White, A. J. R. (1972) Geol. Soc. Am. Bull., 83, 29-40.

James, R. and Hamilton, D. L. (1969) Contrib. Mineral. Petrol. 21, 111-41.

Jones, O. T. (1938) *Q. J. Geol. Soc. London*, **94**, 60–110.

O'Connor, J. T. (1965) *U.S. Geol. Surv. Prof. Paper* 525B, 79–84.

Olade, M. A. and Fletcher, W. K. (1975) *Econ. Geol.* **70**, 15–21.

—————(1976) Ibid. **71**, 733–48.

Patchett, P. J. and Jocelyn, J. (1979) *J. Geol. Soc. London*, **136**, 13–19.

Pearce, J. A., Harris, N. B. W., and Tindle, A. G. (1984) *J. Petrol.* **25**, 956–83.

Peterson, M. D. (1983) *J. Geochem. Explor.* **19**, 615–17.

Pitcher, W. S. and Berger, A. R. (1972) *The geology of Donegal* (Wiley, New York and London).

Rast, N. and Crimes, T. P. (1969) *Tectonophys* **7**, 277–307.

——O'Brien, B. H., and Wardle, R. J. (1976) Ibid. **30**, 315–38.

Schleicher, H. and Lippolt, H. J. (1981) *Contrib. Mineral. Petrol.* **78**, 220–4.

Shaw, D. M. (1968) *Geochim. Cosmochim. Acta*, **32**, 593–602.

Streckeisen, A. L. (1973) *Geotimes*, **18**, 26–30.

Thorpe, R. S. (1972) *Bull. Geol. Soc. Am.*, **83**, 3663–8.

——Beckinsale, R. D., Patchett, P. J., Piper, J. D. A., Davies, G. R., and Evans, J. A. (1984) *J. Geol. Soc. London*, **141**, 521–36.

Tuttle, O. F. and Bowen, N. L. (1958) *Geol. Soc. Am. Mem.* **74**.

Vance, J. A. (1961) *Bull. Geol. Soc. Am.* **72**, 1723–8.

Winchester, J. A. and Floyd, P. A. (1977) *Chem. Geol.* **20**, 325–43.

Wright, A. E. (1969) In *North Atlantic Geology and Continental Drift* (Kay, M. ed.) Am. Assoc. Petrol. Geol. Mem. **12**, 93–109.

Yoder, H. S. and Eugster, H. P. (1955) *Geochim. Cosmochim. Acta*, **8**, 225–80.