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Petrology and geochemistry of late Precambrian volcanic rocks of the St. David's area, Pembrokeshire, South Wales (U.K.)

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Abstract

Late Precambrian volcanic rocks near St. David's, Pembrokeshire (U.K.) constitute a bimodal basalt-rhyolite assemblage. A new structural interpretation changes the presently accepted stratigraphical succession, the main effect of which is to place the Rhosson basalts at the base rather than at the top of the sequence. The olivine bearing basalts are subaerial and are normative olivine tholeiites. They have immobile element distributions characteristic of non arc environments. Unusual types of basaltic agglomerate and lapilli tuffs are described some of which may be tuff-lavas or hot debris flows. The rhyolitic rocks comprise lavas, breccias and ash flows, the latter being reported for the first time from the Precambrian of this area. They were also subaerially erupted and the bimodal basalt-rhyolite association may be a post calcalkali phase of eruption on continental crust; possibly in an ensialic back arc environment.

Introduction

Rocks of St. David's, Pembrokeshire, form one of the classical Precambrian areas of Britain. They comprise a varied assemblage of volcanic and volcaniclastic deposits, together with mafic and felsic extrusives known collectively as the Pebidian which is at least 1.4 km thick (Green, 1908). Granitic rocks called Dimetian are considered to be intrusive into the Pebidian, although the age difference may not be very great.

The Precambrian age of all these rocks was demonstrated by the presence of their detritus in overlying Cambrian strata (Hicks, 1877, 1884; Green, 1908; Green & Jones, 1911). Radiometric dating of Dimetian diorite and granophyre gave 643 and 587 Ma respectively (Patchett & Jocelyn, 1979) and Pebidian rhyolite 613 Ma (Moorbath in: Shackleton, 1975).

Although Green (1908) divided the Pebidian into five main groups these are not always well defined nor consistent throughout the St. David's and adjacent areas (Williams 1934; Allen, 1985). Such imprecision is the result of inaccessible cliffs, together with deformation, faulting and various forms of alteration. Inland only isolated rock exposures protrude through a blanket of Tertiary and younger deposits which form an extensive 60 m high erosion surface throughout this part of Wales.

We have reinterpreted these rocks in the light of more recent knowledge relating to the nature, origin and composition of volcanic and volcaniclastic deposits (Davies, 1987) and have also modified the currently accepted structure and stratigraphical succession proposed by Green (1908).

Structure and stratigraphical relationships

The whole area is traversed by a NE-SW vertical

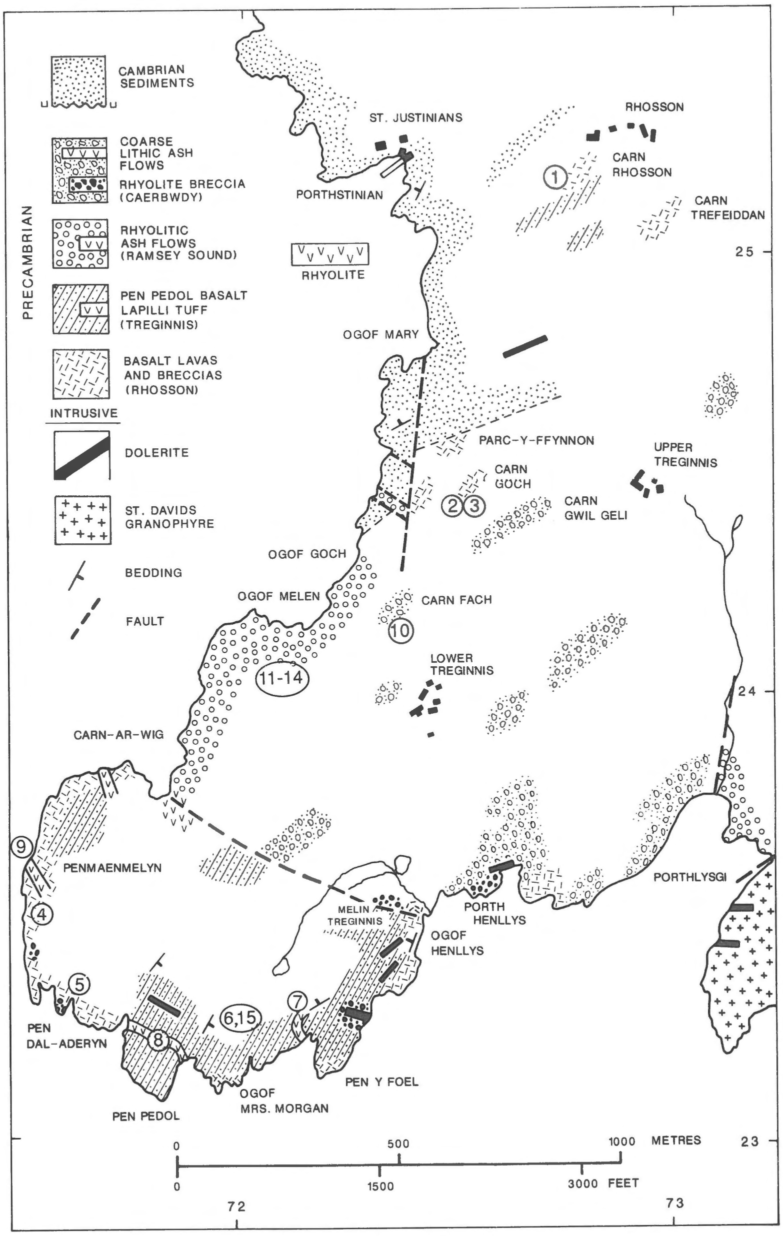

Fig. 1. Rock outcrop map and sampling locations of the area west of St. David's, Pembrokeshire. Modified after Green 1908.

cleavage of varying intensity but bedding is frequently preserved. Between Pen Pedol and Ogof Mrs. Morgan the Treginnis series (our Pen Pedol series) dips consistently SE at various angles to horizontal. Further east near Pen-y-Foel and Ogof Henllys the beds dip NW thus defining a NE-SW trending syncline (Fig. 1). This structure is dissected by numerous high angle thrust faults with associated drag folds producing local zones of tight folding and monoclinal flexures (Bloxam & Dirk, 1988).

Numerous outcrops of basalt around the southern coast, coupled with their abundance as clasts in the overlying Treginnis volcaniclastic rocks, places them at the base of the sequence rather than at the top as proposed by Green (1908) (Fig. 1). Exposures of the same basalts around Rhosson at the NE end of the syncline suggest either a depression in the syncline, and/or the effect of a fault between Carn-ar-Wig and Ogof Henllys (Fig. 1). This depression may be the result of later Hercynian folding along an E–W axis.

The succession according to Green (1908) is, in ascending order; Penrhiw, Treginnis, Caerbwdy, Ramsey Sound and Rhosson Series. Using the same names our succession is; Rhosson, Treginnis (Pen Pedol), Ramsey Sound and Caerbwrdy series. We include Green's Penrhiw Series within our Ramsey Sound Series (Fig. 1).

Mafic Lavas

Hicks (1884) noted '... diabase, tuffs, dykes and sheets' around Carn Rhosson and at several other coastal exposures around the western and southern promontory (Fig. 1). Green (1908) initially considered these basic rocks to be post-Cambrian. However, from relationships at Rhosson and elsewhere, he concluded that they were interbedded with the Pebidian tuffs. (Green in: Cox et al., 1930).

Petrographically all the basalts are similar, but there are some chemical differences (Table 1). The same basalt also occurs abundantly as clasts within the volcaniclastic Treginnis (Pen Pedol) series and we refer to them all as the Rhosson basalts. They

Table 1. Chemical analyses and normative compositions of St. David's (Rhosson type) basalts. Total iron as FeO with 1.5% iron as Fe_2O_3 allocated to normative ilmenite (Irvine & Baragar 1971). (1 Carn Rhosson; 2, 3 Carn Goch; 4 Penmaenmelyn; 5 Pen Dal-Aderyn; 6 clast in Pen Pedol Series, Ogof Mrs. Morgan.)

Wt. %	1	2	3	4	5	6
SiO_2	45.25	49.45	51.93	47.19	47.83	47.40
TiO_2	1.50	1.76	1.60	1.66	1.58	0.97
Al_2O_3	15.47	14.12	16.61	16.82	16.20	17.00
FeO	10.78	12.10	8.66	11.46	9.93	10.44
MnO	0.17	0.21	0.08	0.16	0.17	0.16
MgO	9.16	11.49	7.02	9.03	7.81	8.27
CaO	10.02	3.55	4.87	5.49	9.37	5.44
Na_2O	1.89	4.48	4.64	2.26	2.18	3.40
K_2O	0.70	0.17	0.39	2.51	1.64	1.84
H_2O^+	3.97	3.12	3.53	3.47	2.73	3.53
TOTAL	98.91	100.45	99.33	100.05	99.44	98.45
ppm						
Cr	360	269	205	215	201	200
Ni	113	78	69	71	66	58
Zr	57	49	61	59	64	57
Y	26	19	22	18	19	21
Sr	268	86	313	175	260	181
Rb	9	7	4	28	13	32
% Norm						
cor	–	–	–	0.4	–	–
or	3.9	1.1	2.2	15.0	9.4	10.5
ab	16.2	38.2	38.7	18.8	17.8	28.8
an	31.4	17.5	23.6	27.2	30.0	25.8
di	14.8	–	0.4	–	13.5	0.6
hy	7.4	9.9	21.8	9.7	10.0	–
ol	15.6	24.8	3.4	19.9	11.4	24.6
mt	2.0	2.0	2.0	2.0	2.0	2.0
il	2.8	3.3	3.0	3.0	3.0	1.8

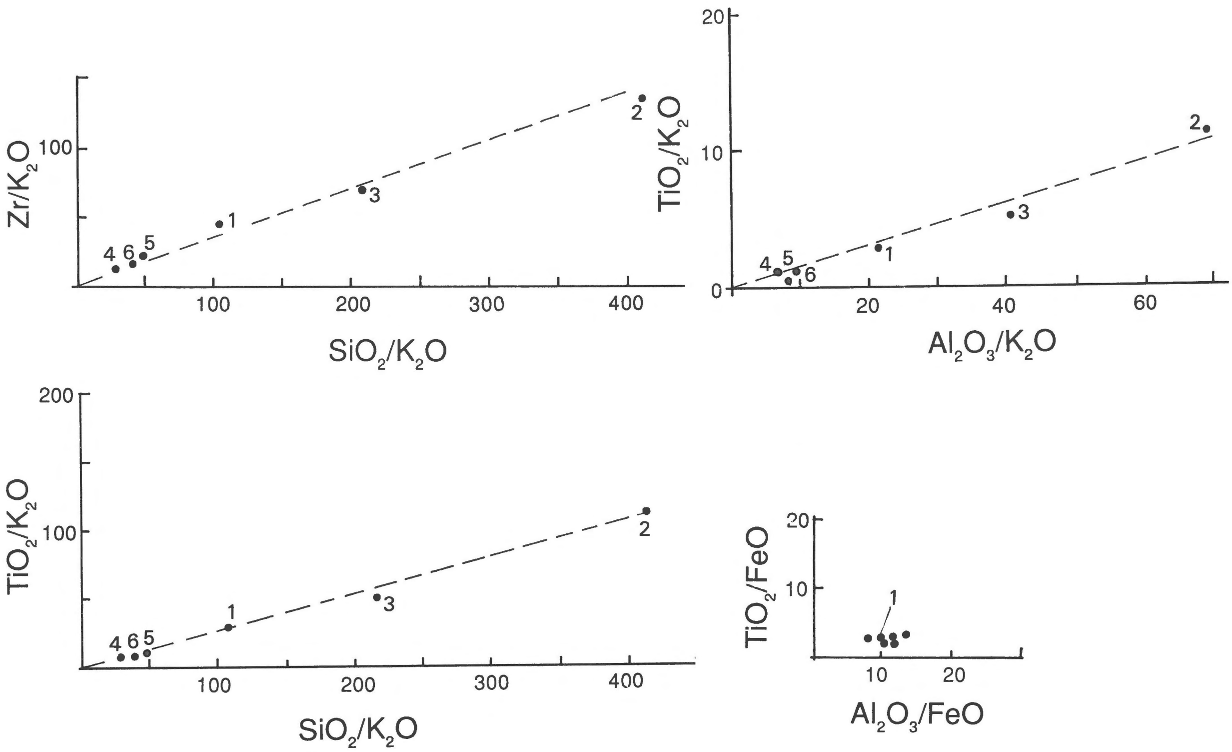

Fig. 2. Representative molecular ratio plots of mobile K to relatively immobile Al, Si, Ti and Zr. (Beswick & Soucie 1978, Davies et al. 1979).

are fine grained and vary from shades of green to black. At Carn Rhosson and Carn Goch the flows are ropey and braided and the margins distinguished by dark purple amygdaloidal oxidized zones. Rubbly autobrecciated vesicular flows are also exposed at the latter localities and in cliff-top exposures between Carn-ar-Wig and Penmaenmelyn.

Around Porth Henllys basaltic flow breccias comprise a mottled purple-red groundmass supporting green olivine basalt clasts ranging from 1 mm to over 3 cm. The clasts are rounded to subangular, highly vesicular, flow banded and strongly epidotized. Many clasts are separated by only a few millimetres and can often be reassembled into larger individuals. The groundmass is a fine haematized debris composed of variously disintegrated basaltic material. The extensive oxidation of the basalts, together with their structural features, suggest that they were subaerial flows.

Under the microscope the basalts have well developed flow textures defined by pseudomorphs of plagioclase phenocrysts and microphenocrysts replaced by finely granular epidote and sericite. A characteristic feature of all the basalts are euhedral pseudomorphs after olivine up to 3 mm composed of chlorite, iron oxide and epidote. Olivine as a groundmass phase could not be definitely confirmed. The groundmass is difficult to resolve but consists essentially of penninitic chlorite and fine granular epidote. Basalt clasts from the Treginnis series around Pen Pedol differ only in being less epidotized.

Geochemistry of the mafic lavas

The major elements Si, Ti, Al, Fe and Mg are within the range of abundance for normal basalts, but Ca, Na and K are very variable and, with the exception of samples 1 and 5, are outside this range (Table 1). The mobility of K to relatively immobile Si, Al, Ti, and Zr is shown in Fig. 2. The same

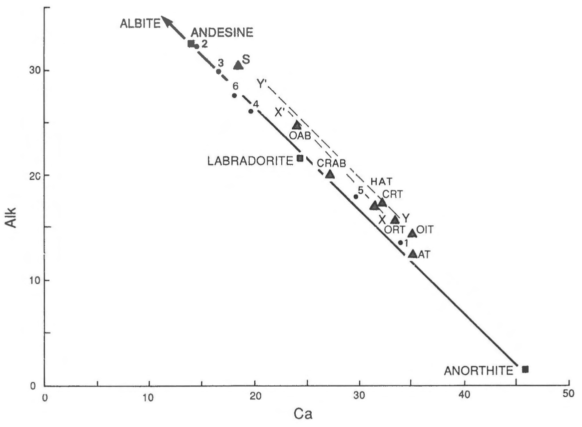

Fig. 3. Atomic proportions of Na + K (Alk) vs Ca for the Rhosson basalts 1 to 6 (dots). Trends (dashed lines) X–X′ and Y–Y′ are those for increasingly spilitized (albitized) basalts (Cann 1969, Vallance 1974). Triangles are the positons of fresh reference basalts from Condie (1982): AT = arc tholeiite; OIT = ocean island tholeiite; ORT = ocean ridge tholeiite; HAT = high alumina tholeiite (calcalkali tholeiite); CRAB = continental rift alkali basalt; OAB = oceanic alkali basalt; S = shoshonite.

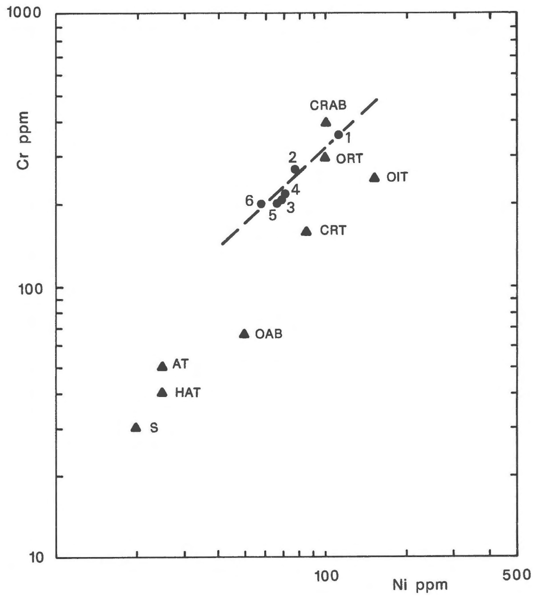

Fig. 4. Cr vs Ni plot for Rhosson basalts (dots). Reference basalts (triangles) as for Fig. 3.

applies to Na so that plots involving alkalies cannot be used to establish precise basaltic kindred. However, Fe is relatively immobile as is probably Mg (Fig. 2), which is reflected in an almost constant Fe/Fe + Mg ratio of 0.6.

Except for sample 6, which is an olivine basalt, the remainder are normative olivine tholeiites. Low Ca will tend to produce more normative hypersthene and olivine at the expense of normative diopside as evidenced in samples 2, 3, 4 and 6. The content of CaO, which is normally 9 to 11% in fresh basalts, provides a guide to the extent of alteration since breakdown of feldspar (albitization) will reduce Ca and increase alkalies at relatively constant Al. The relationship $^1/_2$ (Al + Ca + Alk) to Ca to Alk, normalized to 100 provides a measure of the changes involved. Plots of Ca vs Alk from this system are given in Fig. 3. The St. David's basalts fall almost exactly along a line joining plagioclase compositions. Data for spilitic alteration (albitization) of basalts follow the same trend as do plots of fresh increasingly alkaline reference basalts. On the basis of this major element data we select sample 1 and probably 5 as the most representative of original compositions.

Cr and Ni show good positive correlation plotting on a line which includes typical ocean ridge and continental rift basalts (Fig. 4). They occupy the non-arc field on a Ti vs Cr diagram (Fig. 5) and are similarly categorized on a Ti-Cr-Zr plot (Fig. 6).

Mafic volcaniclastic rocks

These rocks are best developed between Pen Pedol and Pen-y-Foel, forming precipitous cliffs but only limited exposures inland (Fig. 1). The same rocks occur in the north of the area around Carn Rhosson. Green (1908) recognised the mafic character of these volcaniclastic rocks which form the major component of his Treginnis Series and which we term the Pen Pedol Series. They overlie the basaltic group and at Rhosson exhibit interbedding with the basaltic lavas. Their relative age is also confirmed by the abundance of Rhosson-type basalt clasts that they contain.

The coarse varieties are poorly sorted with no or very weak normal grading and crude massive bedding is defined mainly by green basaltic pumaceous lapilli with a few rounded clasts of rhyolite, rhyolit-

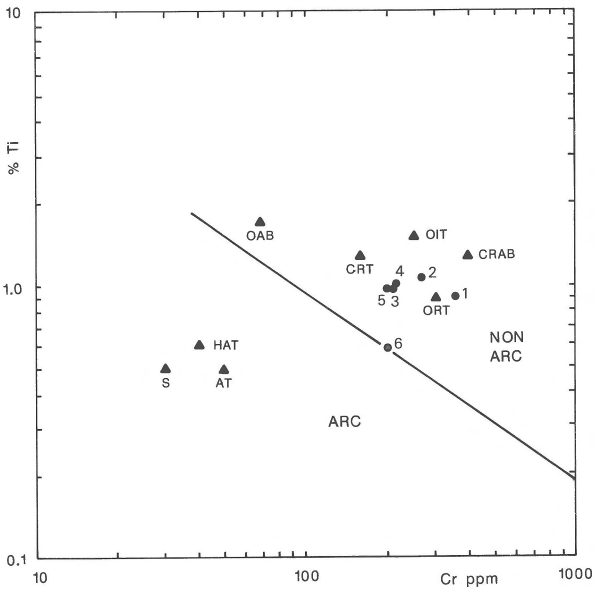

Fig. 5. Ti vs Cr plot for Rhosson basalts (dots). Reference basalts (triangles) as for Fig. 3 (Pearce, 1975).

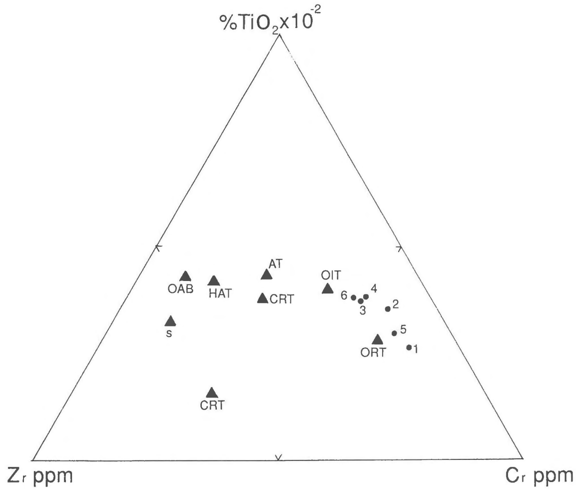

Fig. 6. Ti-Cr-Zr plot for Rhosson basalts (dots). Reference basalts (triangles) as for Fig. 3. (Bloxam & Lewis 1972).

ic ash, Rhosson basalt and occasional dolerite. The clasts are supported by a fine rusty-red ash to lapilli-sized matrix. Although they may contain occasional clasts of up to 60 cm, the average grain size is about 20 mm.

As the grain size decreases matrix-supported pumice forms the only essential component and a uniform grain size of 5 to 8 mm develops. The pumice becomes increasingly flattened and discoidal with an average length : width ratio of 5 : 1; the strong parallel orientation producing a lineation which drapes around large clasts (Fig. 7). The exposures are too discontinuous to provide detailed sections, but it is likely that the whole sequence comprises many such coarse to fine units.

The green flattened vesicular pumice has ragged margins against the red groundmass which often invades and partially fills some of the marginal vesicles. The pumice comprises epidotized flow-aligned feldspar microphenocrysts set in a matrix of chlorite and opaque oxides. This matrix was probably a glass. The margins of the pumice are commonly in the process of shredding into smaller pieces that become red and join the matrix which is composed essentially of fragmented pumice down to the level of individual epidotized feldspar crystals. The matrix-supported, flattened and flow-like nature of the pumice suggest that they represent flows of fragmented, hot, vesiculated material. Some of these features are also typical of rhyolitic ash flows. Since they consist mainly of basaltic pumice and its fragmentation products, there is some resemblance with highly autobrecciated and frothy tuff-lavas, many of which are also characterized by a red strongly oxidized groundmass (Shirinian, 1966). These, along with the coarse ungraded matrix-supported varieties, may be the products of basaltic debris flows and lahars.

A further constituent of the Pen Pedol series are alternating purple and red banded deposits. They are very fine grained, parallel-laminated and average 5 cm thick. Relics of cuspate shard-like bodies, occasional bomb impact sags and graded bedding suggest ash fall deposits, some of which could have been in shallow water.

Felsic volcanic rocks

Felsic volcanic rocks occur mainly as volcaniclastic deposits but small outcrops of rhyolitic lava occur at Pen Pedol and Pen-y-Foel (Fig. 1). Discontinuous lenses and patches of rhyolitic material in the ash flows are widespread but are seldom more than

30 cm thick. The Pen-y-Foel rhyolite flow is about 8 m and that at Pen Pedol about 2 m thick. The former is exposed on a steep cliff face where it is interfolded with adjacent mafic volcaniclastic deposits of the Pen Pedol series. It forms small exposures on the cliff top and is traceable for only a few metres. The flow banding dips steeply to the E or NE. Another thin rhyolitic flow occurs in association with the Rhosson basalts, although their precise relations are obscured.

In thin section rhyolites contain phenocrysts of sanidine and albite with flow-aligned feldspar microphenocrysts. The groundmass is microcrystalline and composed of microlitic or micrographic quartz and feldspar which probably represents an originally glassy mesostasis in which occasional relicts of spherulitic texture can be distinguished. Sericitic mica and some chlorite are also present in the groundmass, the former outlining what may be the remains of former perlitic cracks.

Other possible flows occur in association with rhyolitic ash flows at Carn Fach and Carn Gwil Geli NE of Lower Treginnis. These are fine grained porcellanitic and, in the absence of definitive texture cannot be readily identified as flows. They are seldom thicker than 30 cm and form thin lenses or veneers within the rhyolitic ash flow tuffs. They may be rheomorphic in origin.

Rhyolitic ash flows

Rhyolitic tuffs, some of which are ash flows, occupy the NW coast from Carn-ar-wig to Ogof Goch, with sporadic exposures inland towards Lower Treginnis (Fig. 1). The fine grained tuffs are in places intercalated with coarser varieties formerly regarded as conglomerates. All belong to the Ramsey Sound series of Green (1908) and are pale buff-coloured or red to purple fragmental rocks with a crude banding formed by discontinuous white or pale green vitreous streaks which impart a eutaxitic texture. Most are mixtures of vitric, lithic and crystal material. Although affected by movement, crystal and lithic clasts are not broken or recrystallised, but the groundmass is strongly sericitized. Quartz, about 2 mm in diameter is the commonest clast, generally angular, cracked, embayed and invaded by the groundmass, and lithic clasts of Rhosson basalt and rhyolite are frequent.

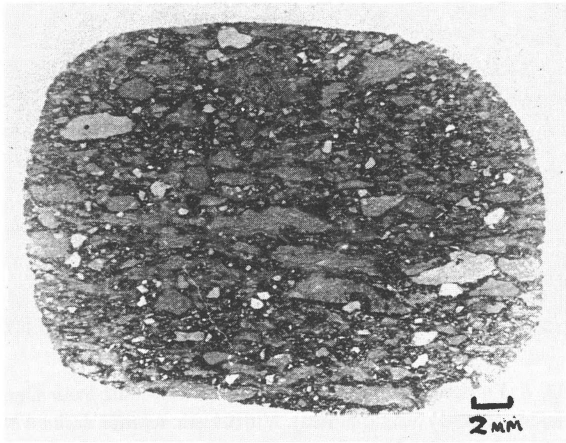

Fig. 7. Photomicrograph of a thin section of pumice flow or tuff lava, Pen Pedol (Treginnis) Series. Flattened basaltic pumice with a few lighter coloured rhyolite and quartz clasts in an oxidised matrix of finer grained basaltic debris (ordinary light).

In thin sections (Fig. 8) flow alignment is defined by sub-parallel orientated cuspate, elongate and bubble-shaped fragments which are often stacked against crystal and lithic clasts. The sericitization picks out the shards which are considered to have been originally vitric. These shards are set in a cryptocrystalline groundmass composed of grey polarizing quartz-feldspathic material and sericite. Some samples contain large fiamme-like clasts up to 2 cm long of elongated vesicular pumice almost entirely replaced by sericite.

Outcrop discontinuity prevents more precise definition of these deposits, although variations in grain size and the relative proportions of vitric and lithic components change in the space of a few centimetres. Fine grained white porcellanitic lenses are composed of a felsitic quartz-feldspar mosaic and may represent rheomorphic rhyolitic melts or the precipitates of highly siliceous aqueous fluids.

The purple and red tuffaceous rocks at Porthlysgi are too strongly cleaved for precise determination. They are more tectonized than the other rocks due in part to fault zones along their junction with the St. David's granophyre. They are volcaniclastic

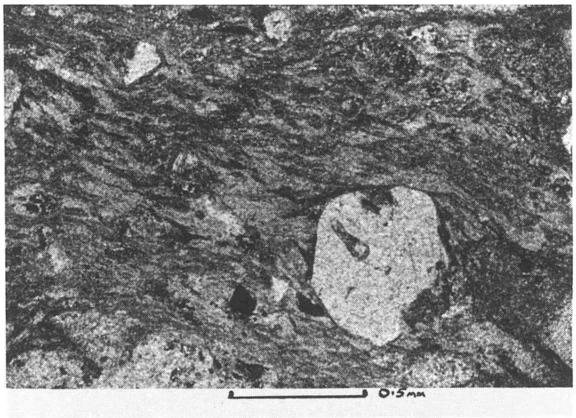

Fig. 8. Photomicrograph of rhyolitic ash flow tuff from Ogof Melen (Ramsey Sound Series). Vitroclastic texture defined by flattened sericitized rhyolite shards which wrap around a prominent quartz clast (ordinary light).

in character and contain elongated clasts up to 5 mm long which appear to be highly sericitized and haematized pumice.

Coarse lithic tuffs and rhyolite breccias

Rocks forming much of the SE part of the area include many of uncertain origin among which are Green's (1908) Caerbwdy 'conglomerate'. However, these are not obviously sedimentary but have characteristics similar to the ash flows that they overlie.

At the carn to the SW of Lower Treginnis two ash flows each about 1 m thick are interbedded with these coarse tuffs which are matrix supported, containing clasts of spherulitic rhyolite and rhyolitic ash flows. There is some size sorting and the groundmass, which includes crystal clasts, is fine grained and felsitic. The lithic clast to matrix ratio is 0.5 or more compared to less than 0.2 in the ash flows.

As the proportion of lithic clasts increases to more than 85% by volume the rocks become rhyolite breccias. Typical examples form isolated carns near Port Henllys, Pen-y-Foel and Melin Treginnis. Several have a lithic clast to groundmass ratio approaching 1.0 and are considered to be autobrecciated rhyolite flows.

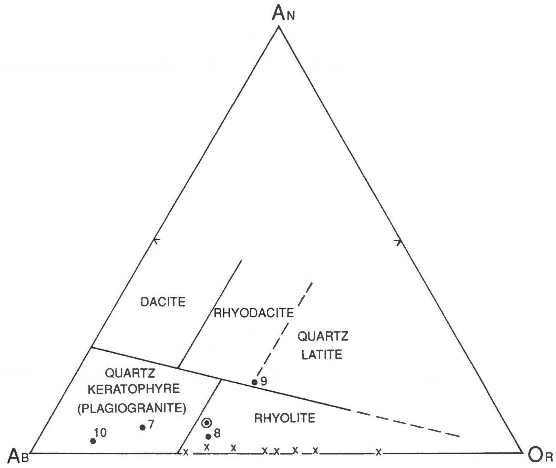

Fig. 9. Normative Or-Ab-An plots (O'Connor 1965) of the rhyolitic lavas 7–10 (dots) and their average (dot in circle). Crosses are for the relatively less altered Cwm Bach rhyolites (Bloxam & Dirk 1988).

Geochemistry of the felsic rocks

The chemical composition of four rhyolites (Table 2, 7–10) occupy the fields for quartz keratophyre (plagiogranite and trondhjemite) and rhyolite (Fig. 9). They contain less K than rhyolites believed to be of similar age at Cwm Bach 10 km to the east, although both have similar Rb contents (Bloxam & Dirk, 1988).

K and to a lesser extent Na, vary directly with Si in felsic igneous rocks but in the present case they show no systematic correlation with Si, suggesting that they do not represent original abundances. There is also a positive correlation between K and Rb in the majority of magmatic rocks except for those affected by hydrothermal alteration which have K/Rb ratios less than the 'normal trend' ratio of 230 (Shaw, 1968; Beus & Oyzermann, 1965). Loss of K but relatively constant Rb was demonstrated for the Cwm Bach rhyolites which have an average K/Rb ratio of 136 (Bloxam & Dirk, 1988).

The present rocks have about the same Rb content as the Cwm Bach rhyolites and K/Rb ratios of 65 to 110 (Table 2). The original K_2O content required to produce a K/Rb ratio of 136 in samples 7 to 10 is respectively 3.2, 3.8, 3.9, and 2.1% (average 3.2%) which is comparable to the average K_2O

content of 3.8% in the Cwm Bach rhyolites (Bloxam & Dirk, 1988).

The rhyolites contain more Rb and have lower K/Rb ratios than felsic rocks of oceanic and island arc type, while the preponderance of rhyolite over mafic rocks suggests the presence of continental crust (Jakes & White, 1972; Wilson, 1978). The high SiO_2 content (> 66%) is also characteristic of Andean rather than island arc magmatism (Jakes & White, 1972). In addition, the absence of andesitic rocks in the Precambrian of this area suggests that the bimodal basalt-rhyolite magmatism may be a post calcalkali phase of eruption on more stabilized continental crust (Christiansen & Lipman, 1972).

The analysed ash flow tuffs (Table 2; 11–15) have, as expected, a wider chemical dispersion towards more quartz and corundum normative compositions as a result of varying igneous/clastic admixture.

Summary and conclusions

The late Precambrian volcanic rocks to the west of St. David's, Pembrokeshire, form a syncline in which the lowest exposed rocks are the Rhosson basalts. These exhibit the structural characters of subaerial flows and their red, highly oxidized nature is also suggestive of original subaerial weathering. The basalts are olivine tholeiites with non arc trace element abundances. The succeeding ungraded, matrix supported, mafic agglomerates and lapilli tuffs are thought to include hot debris flows and lahars, but the precise origin of others is uncertain. The red colouration of much of this succes-

Table 2. Chemical analyses and normative compositions of St. David's rhyolitic rocks. (Rhyolite flows: 7 Pen-y-Foel; 8 Pen Pedol; 9 Penmaenmelyn; 10 Carn Fach. Rhyolitic ash flows and tuffs: 11 to 14 Ogof Melen; 15 Ogof Mrs. Morgan)

Wt. %	7	8	9	10	11	12	13	14	15
SiO_2	76.06	73.04	75.27	76.70	78.43	79.93	74.12	72.83	74.98
TiO_2	0.22	0.17	0.40	0.36	0.28	0.25	0.58	0.42	0.54
Al_2O_3	11.77	11.39	11.69	10.87	11.37	11.85	13.41	12.85	11.53
FeO	2.52	2.68	1.91	2.62	2.17	1.56	2.05	2.77	2.30
MnO	0.13	0.12	0.04	0.02	0.03	0.03	0.02	0.05	0.04
MgO	0.23	0.27	0.64	0.60	0.26	0.20	1.63	1.55	0.51
CaO	0.66	0.40	2.87	0.94	0.50	0.43	0.60	0.33	0.50
Na_2O	4.74	3.45	2.86	5.55	4.72	4.45	1.19	2.10	3.45
K_2O	1.83	2.77	3.33	1.08	2.05	1.52	0.41	3.06	0.91
K_2O^+	1.02	1.09	1.11	1.55	0.72	0.00	1.51	1.86	0.65
TOTAL	99.18	95.38	100.12	100.29	100.53	100.22	95.52	97.55	95.41
ppm									
Zr	333	381	335	152					
Y	28	29	29	23					
Sr	93	77	66	85					
Rb	205	241	245	138					
% Norm									
qtz	37.7	39.0	38.5	36.1	40.0	45.9	60.6	43.8	48.0
cor	0.8	1.9	–	–	0.4	2.1	9.9	5.2	3.9
or	10.8	16.3	19.6	6.3	12.1	8.9	2.4	18.0	5.3
ab	40.1	29.1	24.2	46.9	40.0	37.6	10.0	17.7	29.1
an	3.2	1.9	9.2	1.5	2.4	2.1	2.9	1.6	2.4
di	–	–	4.2	2.6	–	–	–	–	–
hy	4.8	5.3	2.3	4.3	4.1	2.9	6.8	8.2	4.6
il	0.4	0.3	0.7	0.6	0.5	0.4	1.1	0.8	1.0

sion is also indicative of subaerial deposition. Indeed, younger Cambrian strata are frequently red/purple due to incorporation of such material. The rhyolites and rhyolitic ash flows and breccias were also subaerially emplaced and the bimodal basalt-rhyolite association may be a post calcalkali phase of eruption on continental crust; possibly in an ensialic back arc environment.

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