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Geochemical and source characteristics of the Tintagel Volcanic Formation

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The Lower Carboniferous metavolcanic greenschists of the Tintagel Volcanic Formation (TVF) are confirmed as a single cogenetic suite of fractionated alkali basalt lavas and volcaniclastics. The volcanics are highly altered and absolute element abundances have been diluted in highly carbonated samples, although ratios of stable incompatible elements remain constant. The TVF displays the following chemical features: uniform incompatible element ratios (Zr/Nb ~ 6; La/Nb ~ 0.8; La/Ta - 10) and light REE (chondrite-normalized) enrichment with relatively uniform $(La/Yb)_N$ ~6-8; in this respect they are comparable with Upper Devonian basalts from N Cornwall and Devon. Relative to MORB the TVF rocks exhibit progressive incompatible element enrichment patterns with a positive Nb-Ta anomaly that are characteristic of an intraplate environment and an enriched OIB-type mantle source. There is no chemical evidence for crustal contamination.

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Introduction

The Tintagel Volcanic Formation (TVF) is a series of highly foliated meta-lavas and volcaniclastics (Dearman *et al. 1970;* Freshney *et al. 1972),* exposed on the north Cornish coast between Trebarwith Strand and Boscastle. The local stratigraphy within the Tredorn Nappe (Stewart *1981)* comprises a Dinantian succession of the Barras Nose Formation, the Tintagel Volcanic Formation and the Trambley Cove Formation, all of which are tectonically overlain by light grey Upper Devonian slates. The sequence has a polyphase deformation history (Sanderson *1979;* Selwood and Thomas *1986)* and was metamorphosed in the lower greenschist facies (Robinson and Read *1981)* as indicated by the characteristic assemblage of chlorite-muscovite-calcite-epidote-biotite.

Recently, Robinson and Sexton *(1987),* using statistical techniques on a small chemical data set collected from the TVF, demonstrated that most major and some trace elements were mobile during post-magmatic alteration and metamorphism. However, using the least mobile trace elements they showed that the TVF represented a single, fractionated basic suite of alkali basalt lineage. This primary feature of the TVF is confirmed by our data collected from throughout the outcrop.

Objectives

Some *59* samples of metavolcanic greenschists and associated metasediments were collected from the TVF outcrop at Trebarwith Strand, Barras Nose and Gullastem and analysed for major and trace elements by XRF Spectrometry (at University of Keele), REE (by ICP Source Spectrometry at R.H.B.N. College, University of London) and Hf, Sc, U, Th and Ta (by INAA at Universities Research Reactor, Risley). A representative selection of analysed TVF samples is shown in Table 1.

We wished to determine (a) whether the TVF represented a single chemical suite (cf. Robinson and Sexton *1987)* throughout its entire outcrop, (b) if the metavolcanic greenschists contained a chemically recognizable contaminant from either the associated metasediments or continental crust, and (c) the nature of the source region and subsequent eruptive environment relative to Upper Devonian metabasalts from south-west England.

Lithological variation

Within the metavolcanics two main lithotypes can be recognised: (a) homogeneous, fine-grained, well foliated, completely recrystallised greenschists, and (b) heterogeneous, often coarser-grained, layered greenschists with variably sized lenses and phacoids of basaltic lava in a recrystallized foliated matrix.

Petrographically, the less-deformed lenses exhibit relict primary volcanic textures including glassy matrix, quenched crystals and phenocrysts. Preliminary examination indicates that both plagioclase phyric basalts and minor fine-grained dolerites constituted the original volcanics. Although they have an overall basic composition and could have originally represented a series of pillow lavas and sills, they could equally have been accumulations of pillow breccias and tuffaceous volcaniclastics with basaltic clasts.

Geochemical features

Chemical fractionation

Previous work (Robinson and Sexton *1987)* showed that the TVF is a cogenetic alkali basalt suite with chemical variation governed by olivine-plagioclase fractionation. These results are confirmed by our data which show linear covariance between pairs of stable incompatible elements indicative of a single chemical series with alkaline characteristics. The comagmatic nature of the TVF is also supported by REE patterns that are typical for rocks related via crystal fractionation. Samples from all the main outcrops show parallel, light REE-enriched (chondrite-normalized) patterns indicative of either plagioclase (petrographically observed) or olivine fractionation. However there is no evidence to support the suggestion that the TVF is composed of less-evolved material at the top of the volcanic sequence (Robinson and Sexton *1987).* The lower absolute abundances recorded are the result of differential dilution by secondary calcite in this part of the sequence. In particular, samples with high calcite contents (> 15 modal%), have their trace element concentrations considerably reduced. However, the ratio between any two immobile incompatible elements remains constant suggesting the ratio has not been changed by alteration. In this context element ratios are generally a more reliable geochemical parameter than the absolute abundances. In particular the TVF is characterized by relatively constant immobile incompatible element ratios such as, Zr/Nb ~ 6, La/Nb ~ 0.8 and $(La/Yb)_N$ ~ *6-8,* displaying a moderate light-to-heavy REE fractionation.

Incompatible element patterns and mantle sources

The top diagram of Fig. 1 is a "spidergram" showing four representative TVF samples normalized to MORB values (after Saunders and Tarney 1984) for a range of incompatible elements, together with Ni and Cr. A number of features are exhibited:

(a) The samples have closely parallel patterns with most elements being progressively enriched relative to MORB. The general parallelism implies that the samples from the three main localities are genetically related by fractional crystallization. The large negative Sr anomaly is most probably an alteration feature, although together with the small negative Eu anomaly could be indicative of plagioclase fractionation, which is confirmed by the

Table 1: Representative chemical data for metavolcanic greenschists from the Tintagel Volcanic Formation. Major elements in wt%, trace elements in ppm.

Sample number	TV-1	TV-2	TV-9	TV-10	TV-15	TV-16	TV-35	TV-36
Locality code*	BN	BN	G	G	TS	TS	TS	TS
SiO_2	43.8	46	41.5	44.3	38.8	37.9	43.9	40.9
TiO_2	3.32	2.68	2.01	2.45	1.76	1.64	2.41	2.09
Al_2O_3	21.4	17	14.8	15.2	13.6	12.4	14.5	14
Fe_2O_3t	15.1	13.3	12.2	11.6	10.9	10.8	9.52	12.5
MnO	0.14	0.12	0.16	0.13	0.11	0.12	0.11	0.13
MgO	4.7	6.47	8.58	6.93	10.3	11.4	1.95	3.17
CaO	1.81	4.29	8.7	7.83	9.4	9.86	10.9	11.1
Na_2O	0.2	0.38	1.3	3.59	1.76	1.03	4.84	2.71
K_2O	4.16	2	1.73	0.71	1.42	1.4	2.05	2.3
P_2O_5	0.31	0.47	0.31	0.53	0.26	0.16	0.6	0.33
LOI	5.29	6.94	8.01	7.59	11.8	12.7	9.28	11
Total	100	99.6	99.3	101	100	99.4	100	100
Ba	31	30	307	29	37	72	450	303
Cr	173	124	150	256	438	408	120	49
Cu	12	17	95	44	53	82	23	29
Ga	27	20	17	17	19	16	19	21
Nb	42	36	28	37	22	23	28	29
Ni	73	76	106	144	254	244	51	46
Pb	31	25	17	15	10	11	12	15
Rb	132	60	36	11	27	30	56	58
Sr	85	83	468	306	158	163	267	292
V	197	159	224	214	202	187	268	183
Y	40	42	30	36	26	24	39	33
Zn	163	157	111	106	92	98	72	101
Zr	330	274	161	224	129	125	180	171
Cs	10.2	7.3	5.6	3	6.6	9.6	2.42	3.45
Hf	8.2	6.5	4	5.5	3.5	3.2	4.8	4.2
Sc	29.2	23.6	30.3	23.6	27.5	25.1	23.2	20.1
Ta	2.85	2.53	1.66	2.48	1.4	1.37	1.9	1.83
Th	2.9	2.49	2.16	3.09	2.02	1.9	2.37	1.96
U	0.79	0.67	0.67	0.95	0.71	0.62	1.09	0.78
La	24.7	28.8	15.8	26	14	12.5	18.2	24.5
Ce	66.1	68.9	38.2	59.8	33.3	30.1	46	52.4
Pr	8.2	8.54	4.75	7.3	4.2	3.71	6.27	6.46
Nd	38.6	40.2	22.8	33.6	19.9	17.8	30.5	29.9
Sm	8.49	8.59	4.74	6.71	4.16	3.7	6.56	5.96
Eu	2.63	2.67	1.63	2.12	1.33	1.23	2.05	1.7
Gd	8.68	9.34	5.42	7.08	4.73	4.3	7.31	6.41
Dy	7.42	7.59	4.9	5.89	4.16	3.79	6.11	5.18
Ho	1.47	1.53	1.03	1.2	0.86	0.8	1.25	1.06
Er	3.9	4.11	2.86	3.31	2.41	2.23	3.44	2.95
Yb	2.94	3.25	2.3	2.65	1.91	1.82	2.7	2.28
Lu	0.37	0.45	0.31	0.36	0.27	0.25	0.35	0.3

* BN = Barras Nose, G = Gullastem, TS = Trebarwith Strand

presence of plagioclase phenocrysts in many lava lenses. Variation in normalized Ni and Cr also suggest mafic fractionation between the illustrated samples, with TV-18 being the most primitive. The greater degree of scatter shown by K, Ba and Rb is due to mobility during alteration.

(b) The relatively enriched "humped" pattern with a pronounced Nb and Ta positive anomaly is characteristic of within plate settings (Pearce 1983) and in particular ocean island basalts (OIB) and their mantle source (Wood *et al.* 1979; Bougault *et al.* 1980; Tarney *et al* 1980; Hofmann 1986). In the lower diagram TV-18 is compared with two primitive alkali basalts from within plate oceanic settings which precludes contamination by continental crust. Although the absolute abundances of elements vary, the shapes of the three patterns are quite similar and suggest that the TVF volcanics were derived from an enriched OIB-type mantle source, clearly distinct from a MORB-type source.

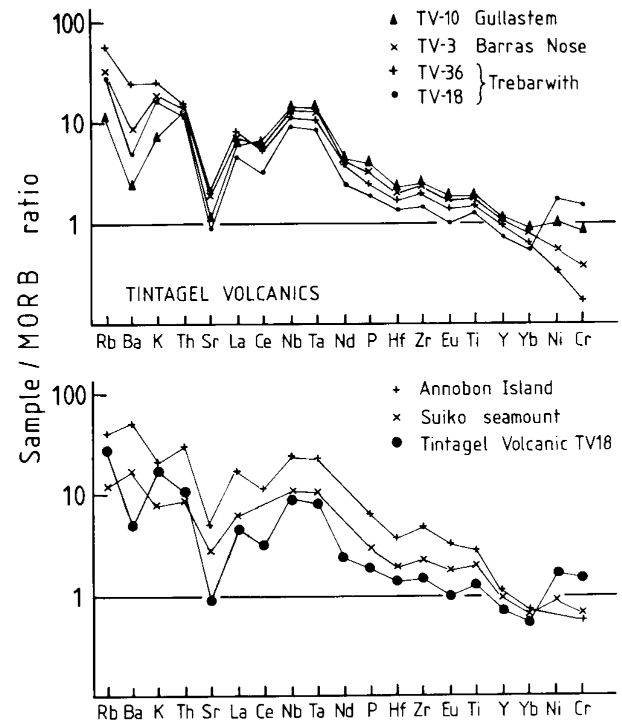

Figure 1. MORB-normalized multi-element diagram of representative basic volcanics from different sectors of the Tintagel Volcanic Formation, N. Cornwall. Lower diagram compares a typical Tintagel volcanic (TV-18) with intraplate alkali basalts from Annobon Island, Gulf of Guinea (Liotard *et al* 1982) and Suiko seamount, EmperorHawaiian chain (Cambon *et al.* 1980). MORB normalizing factors from Saunders and Tarney (1984).

An enriched source for TVF relative to primitive mantle is indicated by Nb/U (~50) and La/Ta (~10) ratios that are remarkably similar to OIB sources (~47 and ~9 respectively, Bougault *et al.* 1980; Hofmann 1986). Hofmann (1986) has suggested that a Nb-Ta-enriched source could be generated with the retention of these elements in refractory Ti oxides during continental crust formation at island arcs. These enriched portions of mantle are then recycled as OIB "plums" (Morris and Hart 1983) and form the source for oceanic island basalts.

Crustal contamination

The TVF and the associated pelitic metasediments form two discrete chemical groups indicating that there is no mixing between them. Also, the contents of P, Ba and Th in the volcanics do not reach the high levels expected if contaminated with pelitic sediments. Contamination by continental crust is often associated with a negative Nb-Ta anomaly (Thompson *et al.* 1983) and consequently an increase in La/Ta and La/Nb coupled with a decrease in Nb/U, none of which are observed in the TVF.

At this stage and without the benefit of isotopic data contamination with continental crust and country rock is thought to have played a negligible part in the evolution of the TVF.

Eruptive setting

The secondary calcite effect can have important consequences for the discrimination of tectonic environment if only the Ti-Y-Zr diagram (Pearce and Cann 1973) is used. As seen in Fig. 2 the calcite-poor samples plot in the within-plate field (cf. Robinson and Sexton 1987), whereas the calcite-rich samples are pulled towards the Y apex and apparently suggest a different tectonic environment. Although excess calcite proportionally dilutes the

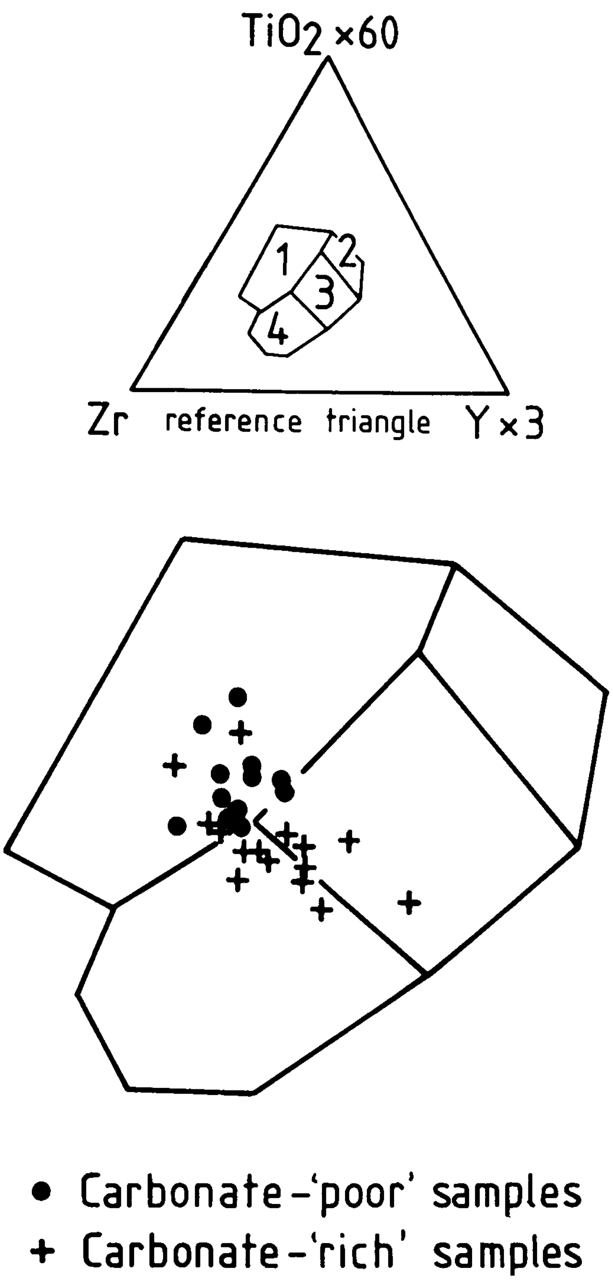

Figure 2. Variable distribution of Tintagel volcanics in the tectonic discrimination diagram of Pearce and Cann (1973) depending on their secondary carbonate content. Fields are: 1= intraplate basalts; 2 = predominantly arc tholeiites; 3 = predominantly mid-ocean ridge basalts; 4 = predominantly arc calc-alkali basalts.

absolute abudances of all covariant trace elements, in extreme cases Y can be mobilized via CO_2 complexing and slightly enriched during secondary carbonation.

Using only calcite-poor samples, the diagrams in Fig. 3 both demonstrate the within-plate (and alkaline) character of the TVF. The high La/Y and Nb/Y ratios are typical of alkaline provinces in continental environments and suggest the Lower Carboniferous basin was ensialic (cf. Leeder 1982). With the exception of some metabasalts from S. Cornwall, a within-plate tectonic setting is characteristic of Hercynian volcanics from Cornubia (Floyd 1982, 1983).

Comparison with Upper Devonian basalts

Floyd (1984) demonstrated that the incompatible element chemistry of Cornubian basaltic volcanics varied with tectonic province. As exhibited in Fig. 4 Upper Devonian and S. Cornish melange basalts can be discriminated in terms of Zr and Nb. The Lower Carboniferous TVF from N. Cornwall plots with their Upper Devonian analogues from the same area and suggests a similar mantle source was being tapped throughout Upper Palaeozoic volcanic events.

Conclusions

1. The TVf is a single, cogenetic, fractionated alkaline basaltic suite of lavas and/or basic volcaniclastics.

2.They exhibit (MORB-normalized) progressive incompatible element enrichment patterns characterized by a positive Nb-Ta anomaly and a negative Sr anomaly. Their chemical features indicate they were derived from an enriched OIB-type mantle source and erupted in a within-plate setting.

3. There is no trace element evidence for crustal contamination or pelitic sediment mixing in the volcanics.

4. The TVF rocks have an incompatible element chemistry similar to Upper Devonian basalts from N. Cornwall and Devon.

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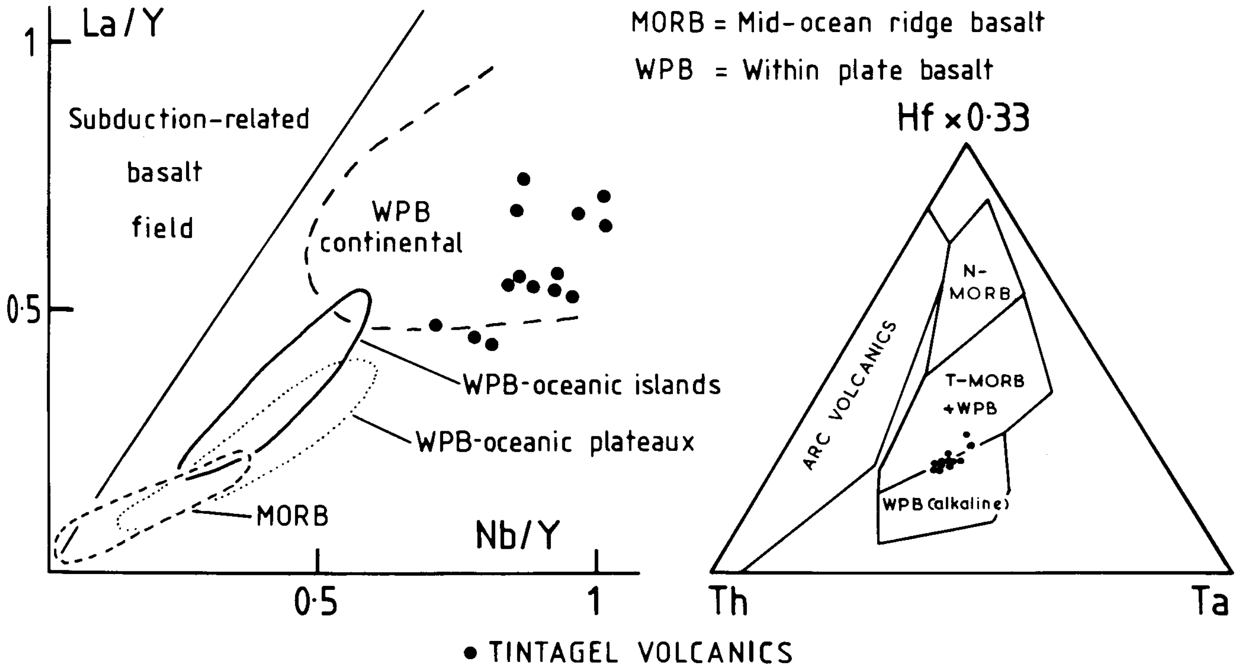

Figure 3. Chemical discrimination of the Tintagel basic volcanics eruptive setting as a within-plate alkaline province. Immobile element ratio diagram based on data from the literature (Floyd, unpublished) and only includes tholeiitic basalts for the oceanic island environment; oceanic alkali basalts overlap with the continental field that includes both magma types. Hf-Ta-Th diagram from Wood (1980).

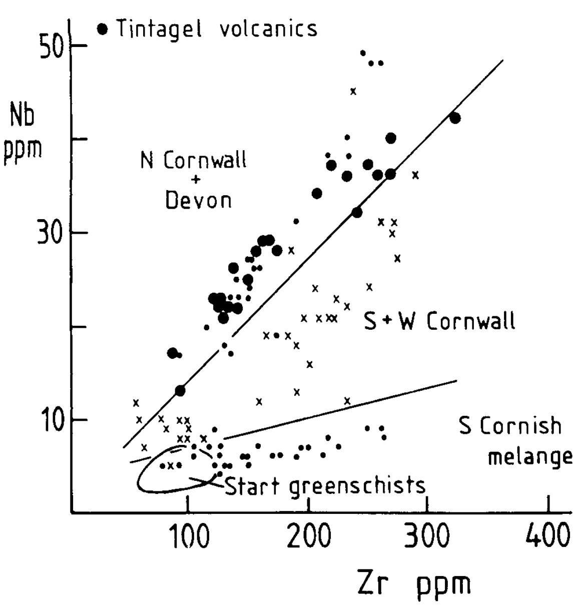

Figure 4. Comparison of Lower Carboniferous Tintagel basic volcanics with Upper Devonian basalts from Cornwall and Devon, as well as S. Cornish melange metabasalts and Start Point greenschists. Comparative data from Floyd (1983) and unpublished.

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