CORRESPONDENCE

Exotic hornfelses from the Land's End aureole

SIR,—In a recent paper on the cordierite–anthophyllite hornfelses of the Land's End aureole, Chinner & Fox (1974) argue that they have been derived isochemically, from previously degraded basaltic material, during subsequent contact metamorphism. I would agree that the presence of complex multiphase assemblages and small scale compositional domains does *suggest* that the parental material might have been chemically heterogeneous prior to contact metamorphism. In view of the work by Vallance (1967) on similar rocks, this mode of derivation seems more plausible than (long-range) internal Fe–Mg metasomatism (Tilley, 1935; Floyd, 1965).

While accepting the isochemical development of the cordierite–anthophyllite hornfelses, I would like to discuss the nature of the parental material and also to broaden the discussion to include the calc-silicate hornfelses which are intimately associated with the hornblende hornfelses (greenstone hornfelses). It could be argued that these Ca hornfelses represent the isochemical derivatives of calciferous portions of the degraded basaltic material. Thus both the Mg–Fe hornfelses (anthophyllite- and cummingtonite-bearing) and the Ca hornfelses (calc-silicate-bearing) could logically be derived from different portions of the previously degraded basalt. Although attractive, this scheme presents problems as will be discussed below.

Table 1 shows averaged chemical data for the different hornfelsic types of initially magmatic origin in the aureole (Tilley, 1935; Floyd, 1965; and unpublished data by Floyd). The actinolite hornfelses are the commonest contact metamorphic products of both dolerite sills and pillow lavas, and in the former case may contain relict clinopyroxene and exhibit sub-ophitic texture. Relative to this group, the Mg–Fe hornfelses are enriched in Mg and Al, and depleted in Si, Ca, Sr and Cu – features not dissimilar to that recorded during basalt degradation and spilitization (Melson & Van Andel, 1966; Cann, 1969; Vallance, 1969). It is interesting to note that while the anthophyllite hornfelses show a marked increase in Mg and Fe, the Cr and Ni values are very low. If these hornfelses had been formed by metasomatism then it might be expected that the ferromagnesian trace elements would have also been enriched during this process. It seems more likely that they were lost during early degradation and excluded from the minerals (particularly chlorite) that formed. In this context Melson, Thompson & van Andel (1968) have reported that Cr, Ni and Co are marginally lower in submarine spilitic rocks relative to the fresh basalt parents. Similarly both Cu (Floyd, 1968) and U (Wilson & Floyd, 1974) are very low relative to the other hornfelses and reflect mobilization at some early stage and/or during contact metamorphism. The Ca hornfelses are depleted still further in Si and have low Al, Mg, Ba, Co and Ni values. They are also more highly oxidised than any of the other hornfels groups. Although Ca is characteristically high there is not a sympathetic increase in Sr.

I would now like to discuss the most likely parental material and its generation prior to the development of the Mg and Ca hornfelses. Due to lack of suitably degraded material within the aureole, this will necessitate reference to variably altered basic magmatic rocks (dolerites and pillow lavas) outside.

Figure 1 shows that with regard to Ca and Mg there is a 'continuum' of compositions from the calc-silicate hornfelses through to the anthophyllite hornfelses. The negative relationship between Ca and Mg in these hornfelses (excluding the metamorphic actinolite hornfelses) is similar to that for degraded 'basalts' composed (for the sake of argument) of variable mixtures of epidote and chlorite – two very common alteration products. Allowing for the presence of other secondary products the hornfels continuum could be explained in terms of the variable distribution of principally epidote and chlorite, which on contact metamorphism produced the extreme Ca and Mg hornfelses, as well as the hornblende hornfels suite.

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Table 1. Average chemical composition of various hornfelses from the Land's End aureole. Oxides in weight % and trace elements in p.p.m.

	Actinolite hornfelses	Hornblende hornfelses	Cumming-tonite hornfelses	Antho phyllite hornfelses	Calc-silicate hornfelses
SiO_2	48.03	43.27	44.57	44.38	37.91
TiO_2	2.60	2.40	2.54	2.28	2.86
Al_2O_3	14.13	15.22	15.74	17.43	11.88
Fe_2O_3	1.10	2.30	1.41	2.51	4.45
FeO	10.63	10.15	10.35	13.58	8.09
MnO	0.20	0.26	0.17	0.11	0.58
MgO	8.37	8.98	11.23	12.08	6.42
CaO	7.93	12.01	6.42	2.16	23.56
Na_2O	2.67	1.95	3.02	2.34	0.30
K_2O	1.96	2.08	1.74	0.87	0.64
P_2O_5	0.38	0.57	0.57	0.33	0.89
H_2O^+	2.00	1.62	2.38	2.18	1.94
No. of samples	8	26	17	7	4
Bfiz	140	253	224	146	75
Co	38	41	47	44	25
Cr	152	192	231	56	100
Cu	157	72	49	31	102
Ga	24	21	22	24	23
Ni	109	138	106	29	78
Sc	22	12	13	33	12
Sr	230	196	149	80	184
V	228	200	256	263	179
Y	33	37	33	30	45
Zr	142	333	295	194	276
No. of samples	8	22*	11	5	5

* Less for some trace elements—

What evidence outside the aureole is there for such degraded rocks? In massive sills low-grade hydrous alteration is common and takes two forms: (*a*) development of epidote–chlorite-actinolite (e.g. Cudden Point sill, S. Cornwall; Floyd & Lees, 1972) and (*b*) development of chlorite–calcite (e.g. Ryecroft sill, Devon; Morton & Smith, 1971). As seen from Figure 1 the chemical variation shown by these sills is not sufficient to develop the anthophyllite or calc-silicate hornfelses directly by isochemical metamorphism. Contact metamorphism of the altered Cudden Point sill could however, account for some of the variation seen in the hornblende and cummingtonite hornfelses.

Pillow lavas in Cornwall (e.g. at Pentire Point and Mullion Island) are mainly composed of an albite–chlorite–calcite–Fe oxide matrix with variable chlorite, calcite and silica vesicular infillings. The field (Fig. 1) of pillow lava rims (unpublished data by Floyd which contain the highest percentage of matrix and amygdaloidal chlorite, are again relatively low in Mg and high in Ca to be the direct isochemical equivalents of the anthophyllite hornfelses. However, on extracting the Ca equivalent to the CO_2 content of these samples (i.e. removing secondary calcite) and replotting the results, a similar level of Ca to that in the anthophyllite hornfelses is obtained. It will be noted that only two pillow lava selvages (representing a small portion of the total pillow only) from Mullion Island (Vallance, 1965) have directly comparable Ca and Mg contents to the anthophyllite hornfelses. Other than invoking the Mg metasomatism of the 'decalcified' pillows, how can they attain the required Mg content? One main difference between

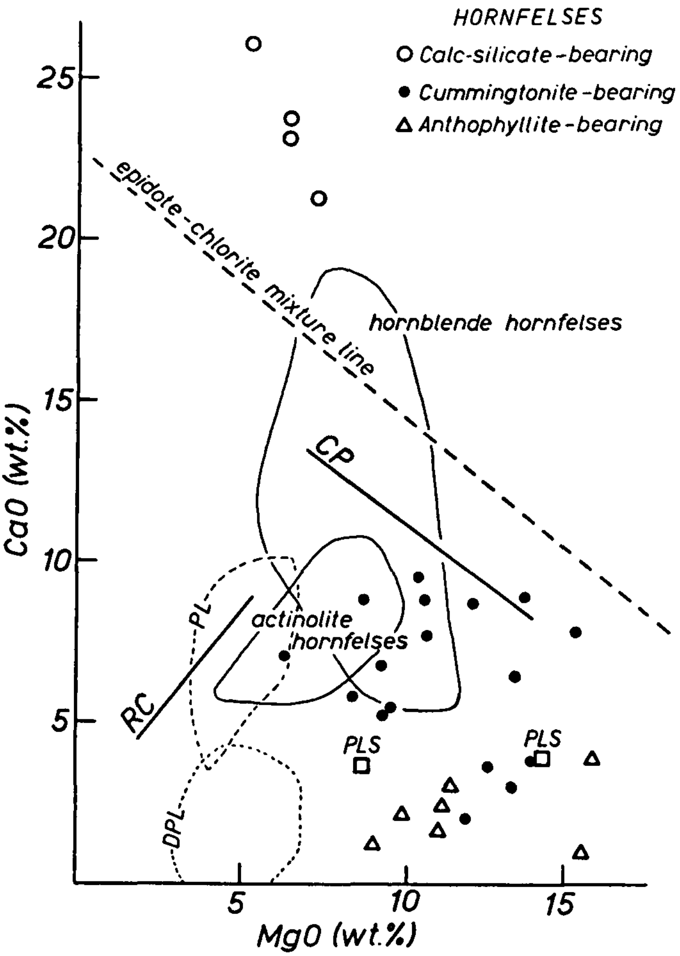

Figure 1. Comparison of the distribution of Ca amd Mg in various Land's End aureole hornfelses with altered dolerite sills (CP, Cudden Point; RC, Ryecroft) and pillow lavas (PL, pillow lava field; DPL, 'decalcified' pillow lava field; PLS, pillow lava selvages, Mullion Island) from outside the aureole. Epidote–chlorite 'mixture line' represents the distribution of Ca and Mg in variable mixtures of epidote and chlorite in altered rocks entirely composed of these two minerals.

the pillow lavas and sills outside the aureole is that they have suffered relatively little shearing compared to the Mg, Ca and some hornblende hornfelses developed within the aureole. As the pillows studied here have 'retained' high Ca contents (largely due to secondary calcite), extensive shearing and penetration by fluids might remove the Ca in solution and concentrate the chlorite-rich portions into zones sufficiently high in Mg. Shearing, in this case, is considered an important pre-requisite for the isochemical development of the anthophyllite hornfelses in particular. Similar arguments could be applied to the chlorite-rich marginal zones of some sheared dolerite sills which, although having the required Mg content, would need to lose considerable Ca. In a few rare cases anthophyllite can be seen in unsheared aureole rocks (e.g. at base of Carn Moyle cliff), although here it clearly replaces or is later than the metamorphic hornblende in the parent hornfels.

With regard to the Ca hornfelses, mineralogical replacement textures indicate that they are metasomatic, as calciferous minerals replace previously developed hornblende hornfelses (Floyd, 1965). In these hornfelses relict hornblende is replaced by diopside and grossularite, and diopside may occur within large garnet porphyroblasts. Strongly zoned epidote is sometimes associated with garnet in lenses. Prograde clinozoisite and sphene are found within large poikiloblasts of zoned axinite, which may itself be replaced by calcite. Plagioclase developed in diopside-rich areas is labradorite rather than the andesine of the adjacent hornblende hornfelses. In general there is a progressive sequence of calciferous mineral replacement among the Ca hornfels suite. It seems likely that the Ca required was mobilized during the extensive shearing phase and metasomatized the contact hornfelses during metamorphism.

Due to the 'retention' of moderate Ca contents by the degraded rocks outside the aureole and also the mineralogical replacements observed within the aureole, the above scheme seems more likely than a direct isochemical metamorphism of the Ca-rich portions of previously degraded basalts for the generation of the Ca hornfelses. This does not rule out the isochemical development of some hornfelses (e.g. the more Ca-rich hornblende hornfelses) from degraded basalts composed of a mixture of Ca- and Mg-rich materials.

I therefore propose the following general scheme for the development of both the Mg and Ca hornfelses.

1. Low-grade hydrous degradation of basaltic pillow lavas and sills. In this case 'retaining' moderate levels of Ca due to the development of secondary calcite and/or epidote.

2. Extensive localized shearing prior to granite emplacement (greenstone shear foliation dips away from contact all round granite).

3. Contact metamorphism and variable removal of Ca in solution. Non-sheared, partly degraded basalts are contact metamorphosed to actinolite and hornblende hornfelses depending on grade.

(*a*) Chlorite-rich areas are isochemically metamorphosed to anthophyllite hornfelses. (If Si-poor and Al-rich, spinel and diaspore also developed).

(*b*) Chlorite–epidote–calcite areas isochemically metamorphosed to hornblende and cummingtonite hornfelses with variable Ca content, depending on the initial chlorite to epidote+calcite ratio. (If Si-poor, spinel also developed).

4. Completely mobilized Ca progressively metasomatizes earlier hornfelses to produce the calc-silicate hornfels suite.

The range of exotic hornfelsic types thus depends on the relative mobility of the Ca ion within variably degraded basaltic rocks during contact metamorphism. Late Ca migration is also indicated by the development of grossularite–clinozoisite, grossularite–tourmaline and epidote–axinite–sodic hornblende veins within the hornfelses.

Some mineralogical features of the cordierite–anthophyllite hornfelses, not mentioned by Chinner & Fox (1974), may indicate minor (possibly very local) movement of Mg and Fe. (*a*) Cordierite porphyroblasts replace earlier labradorite and enclose strings of stellate anthophyllite (Tilley, 1935). (b) Anthophyllite appears to be of two generations in the finer-grained Mg hornfelses: early small stellate clumps (often set in a very fine-grained biotite matrix) and also large prisms (sometimes biotitized) that grow across the main foliation. (*c*) In a few cases anthophyllite appears later than spinel, growing across and replacing large grains. (*d*) Large clinochlore prisms appear to pre-date associated anthophyllite and also replace an early phlogopitic biotite which occurs as small optically continuous relicts within it. The mineral paragenesis appears complex with replacement and close association of early and late phases. In this context the equilibrium between spinel, cordierite and anthophyllite margins (Chinner & Fox, 1974, p. 404) probably took place at a late stage when exchange with circulating fluids was possible.

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Slickensides and slickenlines

SIR – A recent article (Weaver, 1974) prompts me to draw attention to the current confusion concerning the meaning of the term *slickenside*. The International Tectonic Dictionary (Dennis, 1967, p. 136) gives a definition which indicates that a slickenside is a polished surface (i.e. a planar structure). Unambiguous definitions with the same meaning are given by Billings (1972, p. 201), Spencer (1969, p. 70) and Stokes & White (1935, p. 191). Such a definition is obviously implied by the use of the word *side* as part of the term, and is in agreement with the original meaning (cf. Conybeare & Phillips, 1822, p. 348; Lyell, 1874, p. 64). Other geological dictionaries concur with this meaning of the term (American Geological Institute, 1957, p. 269; Challinor, 1967; p. 231; Schieferdecker, 1959, pp. 111, 173) as do some published descriptions (e.g. Lindström, 1974). It is generally accepted that two other types of structure are commonly associated with such surfaces, namely linear structures in the form of striations or grooves, and minute step structures at a high angle to the lineations. These features are believed to reflect the displacement direction on the surface.

However, it is common in the more recent literature to find the term slickenside used

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