Theoretical constraints on calcium silicate domain formation and fluid flow during alteration of basic igneous rocks

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Introduction

In order to interpret palaeofluid flow during metamorphism, it is important to understand the origins of varying styles of rock alteration (in terms of intensity and/or mineral assemblages) which are a feature of many metamorphic rocks. In a wide range of low temperature metamorphic environments, metabasalts and meta-andesites may show the localised (domainal) development of pumpellyite (±quartz) and/or epidote (±quartz) which potentially may be interpreted in terms of fluid flow. In the literature, such domains have been variously ascribed to hydrothermal activity driven by localised heat sources, such as igneous intrusions (e.g Richardson *et al.*, 1987), and to localised channelling of regional metamorphic fluids (e.g Jolly and Smith, 1972). In each case, significant mass transfer occurred in order to modify the chemistry of the rock and generate domains. This in turn implies that significant fluid flow must also have characterised metamorphism. However, in this paper we present new data for recently discovered prehnite-pumpellyite domains from an Ordovician gabbroic sill at Pen Caer in southwest Wales, U.K. (Fig. 1), which suggest that this may not always be the case.

Petrographical and chemical characteristics of the domains

The Pen Caer domains occur near to the roof of the intrusion and are isolated, ovoid to irregularly shaped masses, from 2–50 cm across. These are

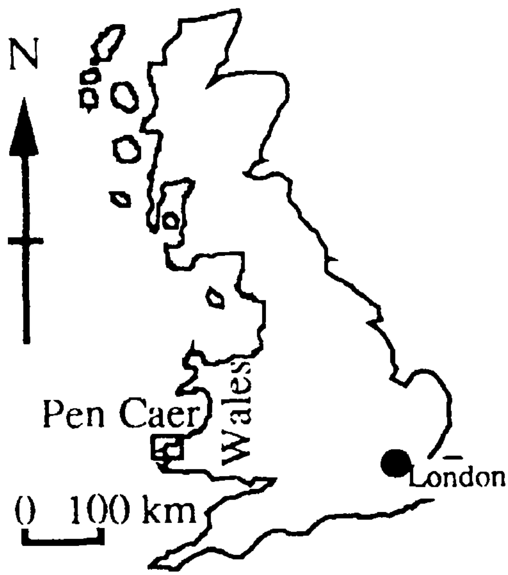

FIG. 1 Locality map showing the domain site at Pen Caer, Wales.

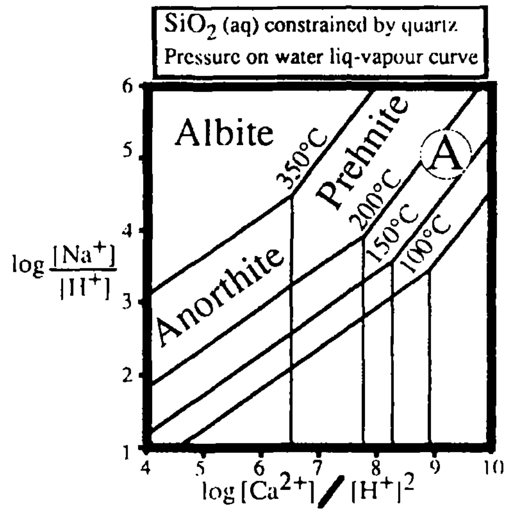

FIG. 2 Movement of a cooling late magmatic fluid might lead to albitisation rather than calc-silicate formation e.g fluid at A moves from the prehnite field to the albite field during cooling.

unrelated to fluid channelways such as fractures, either on a microscopic or macroscopic scale. Primary textures are preserved only as relics, and all primary phases are replaced by a heterogeneous secondary assemblage of the type:

pumpellyite + prehnite (+ quartz + titanite + chlorite ± epidote ± calcite)

Pumpellyite often occurs within prehnite crystals, which in turn often replace feldspar.

The domains contrast with the host gabbro which is much less intensely altered, and has relict primary textures and abundant relict primary phases. A typical Caledonian regional metamorphic imprint is developed and is characterised by a secondary assemblage of the type:

(albite + chlorite) + prehnite + pumpellyite + quartz + titanite ± epidote ± calcite

Compared to the host gabbro, the domains are enriched in Ca, Al, H_2O, *REE*, and other incompatible trace elements, and are depleted in Si , Mg, Na and Cr. Thus, the domains apparently coincide with magmatically fractionated zones within the gabbro.

Discussion

Fluids must have been involved in domain formation owing to the hydrous nature of the secondary assemblages. However, mineralogical considerations suggest that the domains formed at similar temperatures and pressures to the regional metamorphic imprint, at *c*.130–*c*.300°C, and < *c*.2 kbar. Therefore, the chemical contrasts between the domains and the host rock are most probably explained by: 1. mass transfer due to fluid flow; and/or 2. primary chemical differences in the host rock composition. The lack of fluid channelways, or evidence for hydrothermalism elsewhere in the intrusion means that the possible involvement of a hydrothermal fluid in domain formation is not well supported. Similarly, in the absence of fluid channelling or chemical variations in the host gabbro, regional metamorphic fluids alone are unlikely to have caused the development of localised domains. In contrast, any late magmatic fluids would tend to accumulate heterogeneously near to the roof of the intrusion in chemically fractionated zones, and might have contributed to the development of localised alteration. This idea is supported by the field relationships and whole-rock chemistry. However,the temperature dependency of phase relations between albite (representing 'sodic plagioclase'), prehnite (representing secondary calcium silicates) and anorthite (representing 'Ca-plagioclase') is inconsistent with the replacement of fractionated rock by calcium silicates as fluid moves down a temperature gradient from the centre to the roof of the intrusion (Fig. 2). An alternative possibility is that magmatic fluids influenced the chemistry of fractionated zones by controlling the course of magmatic fractionation. Experimental results suggest that relatively water-rich late magmatic melts might crystallise relatively Ca-plagioclase, due to the aqueous solutions moving the plagioclase-pyroxene cotectic towards the feldspar composition (e.g Yoder, 1965). Additionally, thermodynamic considerations suggest that under low temperature metamorphic conditions, Ca-plagioclase would alter to calcium silicates more readily than Na-plagioclase. Thus, the combined action of late magmatic fluids and later regional metamorphic fluids could conceivably give rise to the Pen Caer domains.

Conclusions

The formation of the Pen Caer Domains probably involved: 1) fractionation of magma at temperatures of *c*.1100°C, followed by interaction with late magmatic aqueous fluids, resulting in the formation of Ca-plagioclase-dominated zones; 2) low temperature regional alteration, at temperatures in the range *c*.130–*c*.300°C, and pressures of <2 kbar, causing the preferential alteration of Ca-plagioclase to form prehnite; 3) at similar temperatures and pressures, but during later regional metamorphism, the nucleation of pumpellyite on the prehnite, giving rise to pumpellyite-dominated domains. In contrast to the usually accepted model which explains calc-silicate dominated domain formation as a response to fluid channelling, resulting in high water/rock ratios, the observations reported in this paper suggest that pumpellyite-dominated domains may sometimes form where magmatic fractionation has resulted in locally suitable rock compositions. Under these circumstances, domains may form under conditions of low water/rock ratio.

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