Partial melting of metavolcanics in amphibolite facies regional metamorphism

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Metavolcanic rocks containing low-Ca amphiboles (gedrite, cummingtonite) and biotite can undergo substantial dehydration-melting. This is likely to be most prominent in Barrovian Facies Series (kyanite-sillimanite) and occurs at the same time as widespread metapelite dehydration-melting. In lower pressure facies series, metavolcanics will be represented by granulites rich in orthopyroxene when dehydration occurs at much lower temperatures than melting. In higher pressure facies series it is not well known whether metavolcanic rocks dehydrate or melt at temperatures lower or similar to that of metapelites.

1. Introduction

Basaltic and other metavolcanic rocks are often interlayered with metasediments in regional metamorphic terrains. At the "second-sillimanite" dehydration isograd (e.g. Evans and Guidotti 1966) represented by the reaction (figure 1)

$$\text{Mus} + \text{Alb} + \text{Qtz} = \text{Ksp} + \text{Sil} + H_2O$$

(ca. 700° C at P ca 5 kbar; Tracy *et al* 1976; Thompson and Tracy 1979), metapelites often show signs of partial melting through the reaction

$$\text{Mus} + \text{Alb} + \text{Qtz} = \text{Ksp} + \text{Sil} + \text{L}$$

(figure 1)—while amphibolites remain unmelted except where they have been flushed with H_2O (e.g. Percival 1983; Pattison 1991; Mogk 1992). Metapelite melting can occur by dehydration (fluid-absent) melting of muscovite at about 700° C (at ca. 5 kbar, figure 1) followed by biotite at about 750° C, whereas dehydration-melting of hornblende in amphibolites appears to require temperatures near 900° C (e.g. Wolf and Wyllie 1991; Rushmer 1991; Rapp *et al* 1991; Beard and Lofgren 1991; Wyllie and Wolf 1993). H_2O-saturated melting of pelite occurs at relatively low temperatures of about 620° C at 10 kbar. H_2O-saturated melting of tonalite and basalt occurs at temperatures just above this (figure 1).

2. Partial melting of amphibolite-facies cummingtonite and biotite-bearing metavolcanics compared to metapelitic compositions

In parts of the metamorphic high of Central Massachusetts and SW New Hampshire USA, careful studies have been made of the metamorphism of basaltic and other metavolcanics (e.g. Robinson and Jaffe 1969; Robinson *et al* 1982; Spear 1977, 1982). The metamorphism of these rocks has been closely matched to the six zones (I-VI) of metamorphism of metapelites (see Tracy *et al* 1976; Tracy 1978, 1985). In zones IV to VI, metavolcanics of mafic and intermediate composition show signs of partial melting (Hollocher 1985, 1991; Schumacher *et al* 1990). Anastomising veins, small dykes and pods of coarse grained tonalitic rocks in amphibolite are reported from zones V and VI.

Robinson *et al* (1986, p. 235) noted that the partial melts form a few per cent of mafic rocks in zones IV and V, but make up to 15% in

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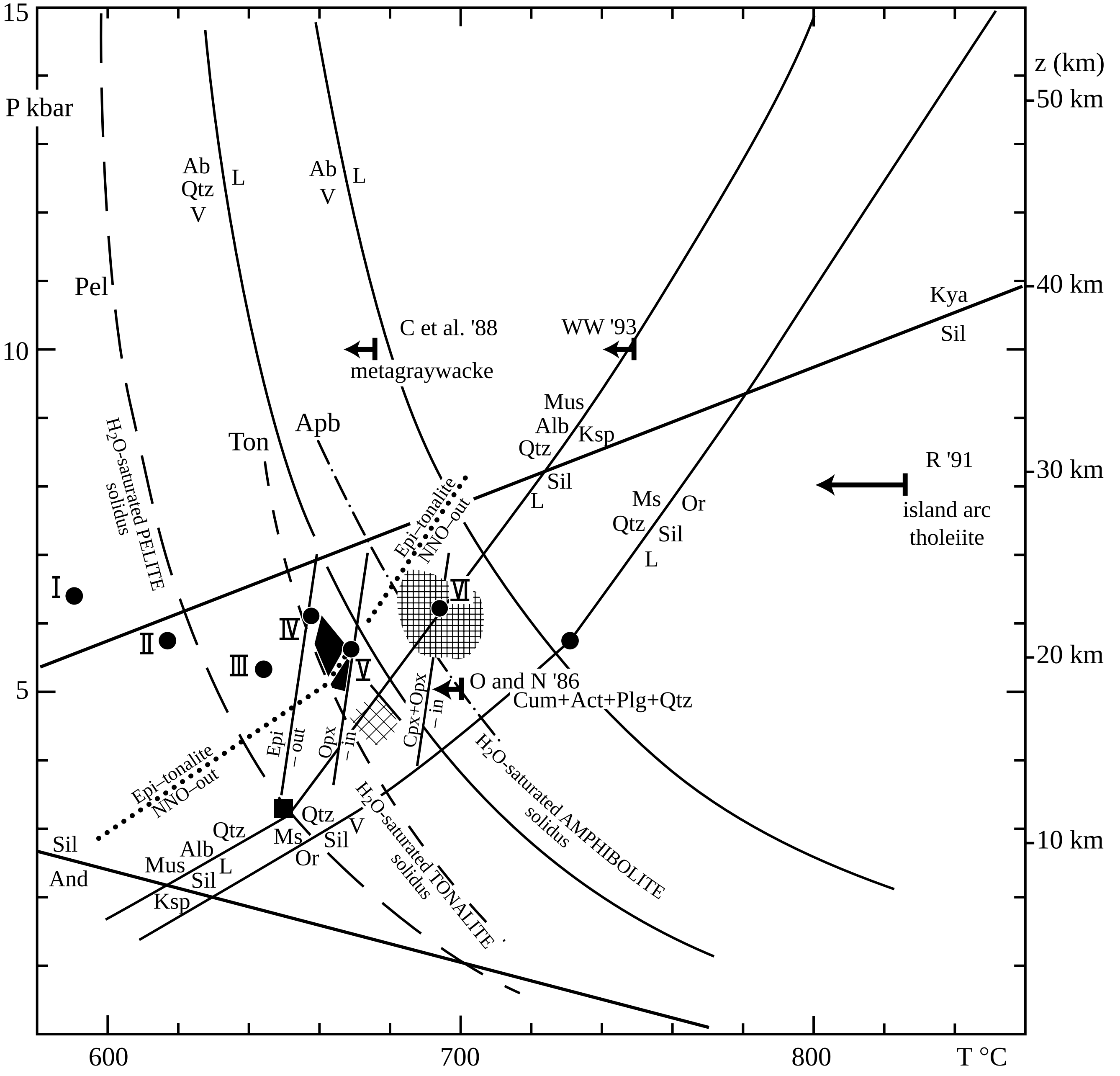

Figure 1. Some experimental and regional metamorphic constraints for beginning of partial melting in metavolcanics.

Experimental constraints:

Ab $(NaAlSi_3O_8)$+ Qtz (SiO_2) + V (H_2O) = L and Ab $(NaAlSi_3O_8)$ + V (H_2O) = L from Huang and Wyllie (1975);

Al_2SiO_5 (Kya-Sil, And-Sil from Holdaway 1971);

muscovite dehydration and melting for mica and feldspar in KNASH (Mus, Alb, Ksp) and in KASH (Ms, Or, from Thompson and Algor 1977 figure 8 p. 262, reactions 14 and 19, 3 and 4);

Pel = H_2O-saturated PELITE solidus (data summarised by Thompson 1982; Thompson and Connolly 1995).

Dotted line shows experimentally investigated upper temperature stability limit for epidote (Epi) in tonalite with excess H_2O, at $fO_2 \sim$ NNO (Schmidt and Thompson 1996, figure 5, p. 471);

Ton = H_2O-saturated TONALITE solidus (Wyllie 1977; Schmidt and Thompson 1996); Apb = H_2O- saturated AMPHIBOLITE solidus (Wyllie 1977; Wolf and Wyllie 1991; Wyllie and Wolf 1993).

Arrows show where partial melting studies found melt at the indicated temperatures:-

675° C, 10 kbar – metagreywacke with H_2O-CO_2 fluid (C *et al* '88 = Conrad *et al* 1988);

750° C, 10 kbar – amphibolite dehydration melting (WW '93 = Wyllie and Wolf 1993);

825° C, 8 kbar – island arc tholeiitic dehydration melting with cummingtonite, biotite, hornblende (R '91 = Rushmer 1991);

zone VI. They contain about 40% coarse grained quartz with rutile needle inclusions, about 35% dark gray plagioclase (An_{20}-An_{45}) containing oriented opaque oxide exsolution lamellae and about 15% mafic minerals, that include biotite (Bio), cummingtonite (Cum), hornblende (Hbl), gedrite (Ged), garnet (Gar), magnetite (Mag), ilmenite (Ilm), orthopyroxene (Opx) and clinopyroxene (Cpx). Low-Ca amphiboles are more commonly known from several types of volcanics (e.g., Wood and Carmichael 1973; Wones and Gilbert 1982).

The melting reactions, in zones IV and V of the metamorphic high of Central Massachusetts, were interpreted as being dehydration-melting (fluid-absent) reactions by Robinson *et al* (1986, p. 251) and Schumacher *et al* (1990, p. 228)

$$\mathrm{Cum + Bio + Plg + Qtz = Hbl + Gar + L,\ or}$$
$$\mathrm{Cum + Plg = Hbl + Opx + L,\ and}$$
$$\mathrm{Hbl + Qtz = Opx + Cpx + Plg + melt.}$$

More recently Schumacher *et al* (1990, p. 227) have reinterpreted the partial melting to represent H_2O-present melting—because the P and T conditions obtained by geothermobarometry coincide with Wyllie's (1977) location of the H_2O-saturated solidus for tonalite (figure 1). Schumacher *et al* (1990, p. 226) locate invariant points in Fe and Mg end member systems on the basis of the intersection of the H_2O-saturated solidus reactions

$$\mathrm{Cum + Plg +/- Qtz + H_2O = Hbl + garnet + melt,\ and}$$
$$\mathrm{Cum + Plg +/- Qtz + H_2O = Hbl + Opx + melt,}$$

with the dehydration reaction

$$\mathrm{Cum + Hbl + Gar + Qtz = Opx + Plg + H_2O.}$$

For calculated geobarometric pressure of 5 to 6 kbar these reactions are deduced from mineral geothermometry to have occurred between 655 and 670° C.

Epidote disappears at zone IV (Schumacher *et al* 1990, p. 221) and so is not involved in metavolcanic dehydration melting in Central Massachusetts (in contrast to epidote's involvement in melting at higher pressures, Schmidt and Thompson 1996). Staurolite and gedrite occur only in low-Ca, high-Al mafic rocks in zones I and II. Staurolite is thus not involved in dehydration melting at pressures of 6 kbar although it is involved in metapelite dehydration melting higher pressures (Koons and Thompson 1985; Thompson and Connolly 1995; Spear *et al* 1999).

3. Experimental studies of partial melting of cummingtonite and biotite-bearing assemblages compared to amphibolites

Amphibolites containing only hornblende with plagioclase + quartz melt close to 900° C in dehydration-melting studies from 5 to 10 kbar (e.g. Wolf and Wyllie 1991; Rushmer 1991; Rapp *et al* 1991; Beard and Lofgren 1991; Wyllie and Wolf 1993). Many metavolcanic rocks contain low-Ca amphiboles and biotite, the dehydration melting of which could well occur at lower temperatures than that of hornblende in amphibolites.

Rushmer (1991) showed that dehydration of an "island arc tholeiite" (ibid, mode on p. 44) containing hornblende (44wt%) + plagioclase (32wt%) + quartz (17wt%) with cummingtonite (5wt%), biotite (1wt%), ilmenite (1wt%) and zoisite (< 1wt%), contained 10 vol% glass at 825°C, 8 kbar, with Opx, Cpx, Qtz and residual hornblende (figure 1). Oba and Nicholls (1986) studied synthetic cummingtonite $(Mg,Fe)_7Si_8O_{22}(OH)_2$ and actinolite $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$, for both of which Mg/(Mg+Fe) = 0.5, reacting with An_0, An_{20}, An_{40} plus quartz, and excess of H_2O at 5 kbar (fO_2 at QFM). They reported glass at the lowest temperature of their runs (700° C) for all compositions studied (figure 1). Conrad *et al* (1988, p. 774) reported clinoamphibole + orthoamphibole + biotite + plagioclase + quartz in experiments on a greywacke composition at 675° C at PH_2O = 10 kbar, for $X^{vap}_{H_2O} = 1.0,\ 0.75$ (figure 1). Kenah and Hollister (1983, p. 158) deduced temperature conditions close to 700° C, P = 3 − 7 kbar for anatexis in the Central Gneiss complex in British Columbia. They also identified melting reactions involving biotite, hornblende and cummingtonite (ibid, p. 149).

Figure 1 caption. (Continued)

700° C, 5 kbar – cummingtonite + actinolite + plagioclase + quartz with excess H_2O (O and N '86 = Oba and Nicholls 1986).

The labels I to VI indicate the P-T conditions for the six regional metamorphic zones of Central Massachusetts, U.S.A. (Tracy *et al* 1976; Tracy 1978; Hollocher 1985, 1991; Robinson *et al* 1986; Schumacher *et al* 1990). The deduced limits for Epi-out (point IV), Opx-in (point V), and Opx + Cpx-in (point VI) are from observations summarised by Schumacher *et al* (1990, figures 9.14 and 9.18) — the illustrated reaction slopes for which may well be drawn too steeply and possibly the appropriate reactions should have dP/dT slopes like the metapelite dehydration-melting reactions.

4. Partial melting of metavolcanics in relation to metamorphic facies series

The metamorphic high of Central Massachusetts and SW New Hampshire, USA, is part of a Kyanite-Sillimanite Barrovian Facies Series. This particular pressure range for metamorphic *P-T-t* paths encounters substantial overlap between dehydration reactions and H_2O-saturated solidi (figure 1). This means that dehydration-melting occurs very close in temperature to H_2O-saturated melting. It is most likely that some local H_2O-recycling occurred between the different partially melted rock types (e.g. Thompson 2001a, 2001b). Partial melting of metavolcanics may be widespread but is most commonly to be expected in Barrovian Facies Series. Lower pressure Facies Series (Andalusite-Sillimanite) exhibit dehydration at much lower temperatures than even H_2O-saturated melting, and the metavolcanics would appear as granulites without showing evidence for melt depletion. Higher pressure Facies Series (e.g. medium to high pressure amphibolites, or even blueschist to eclogite, show much higher temperatures for dehydration-melting than the H_2O-saturated solidi and would exhibit persistence of amphibolite rather than granulite to much higher temperatures (Thompson 1998a, 1998b).

5. Conclusions

The Barrovian Facies Series whose P-T-t paths pass through the 4 to 6 kbar range (15 to 20 km depth for lithostatic pressure gradients, $P = 1 \times \rho_{\text{rock}}\, gh$) would exhibit the highest degrees of partial melting of metavolcanics, in addition to metapelites and metapsammites (Thompson 1988, 1990). More detailed studies of such medium pressure metamorphic terrains are desirable as they would be expected to show overlap of dehydration-melting with H_2O-saturated melting, and be most likely to be the chemical source regions for mid-crustal granites.

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