Melting of pelitic sediments at subarc depths: 1. Flux vs. fluid–absent melting and a parameterization of melt productivity

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ABSTRACT

To evaluate the potential of subducted sediments to contribute melts for mantle metasomatism in the subarc region we have experimentally studied and reviewed the melting behavior of pelites at subarc depths. Our experimental data set completes previous studies such that all combinations of fluid-saturated or -absent melting with or without H_2O and CO_2 are now investigated. Experiments were conducted at 3–4.5 GPa, 750–1200 °C with varying proportions of H_2O (0.7–4.4 wt.%) and CO_2 (0–4 wt.%), the maximum amount of H_2O stored away in phengite being ~0.9 wt.% For all pelites, the onset of melting is controlled by an assemblage of phengite + jadeitic cpx + quartz/coesite ± fluid. The wet solidus locates at 715 to 830 °C, 3 to 4.5 GPa, increasing by ~30 °C with CO_2. The fluid-absent pelite solidus is at 890 to 1040 °C, 3 to 4.5 GPa, decreasing little with CO_2. To 5 GPa, quartz-saturated pelites yield highly siliceous meta- to slightly peraluminous granites.

To all available experiments we fitted (i) 3rd order polynomials to describe the fluid-saturated and fluid-absent solidi, and (ii) equations to parameterize melt productivity in sediments as a function of temperature, pressure, bulk H_2O- and CO_2-contents (valid for 2–5 GPa). For H_2O-contents leading to fluid-saturation at subsolidus conditions, melt productivity at the solidus increases with pressure and depends strongly on the amount of H_2O available: experimental and calculated melt fractions (F) are 2–17 and 23–38 wt.% at 2.5–5 GPa, 2 and 15 wt.% bulk H_2O, respectively. As calcite remains stable above the fluid-saturated solidus, partial melting does not lead to complete decarbonation. Near the solidus, the silicate melt may only transport 0.05 to 0.6 wt.% bulk CO_2. Fluid-absent melting yields 15–30% melt at the solidus with phengite melting out immediately above the solidus.

Warm thermal subduction models predict temperatures that just cross the wet solidus in hot subduction zones but not in intermediate to cold ones. The only realistic scenario for extracting sediment melts from subducting slabs is flux melting where fluid is added from metamorphic reactions in underlying slab lithologies. With the meta-basaltic layer being fully dehydrated when sediments reach melting temperatures, the only viable mechanism for H_2O delivery is serpentine breakdown in the subducting oceanic peridotite. However, if sediments melt in the descending slab, the same slab will almost completely dehydrate. We thus conclude that sediment melting in descending slabs cannot be a general process as otherwise the Earth interior would dry out on geological time scales. Alternatives are cold sediment diapirs rising into the mantle wedge or trace element transfer by supercritical liquids at >5 GPa, the latter propelled by partial peridotite dehydration.

1. Introduction

1.1. Sediments at subarc depths

Depending on temperature, subducting slabs experience various stages of devolatilization through formation of H_2O-rich fluids, melts or supercritical liquids (Schmidt and Poli, 1998; Stern, 2002; Hacker et al., 2003; Schmidt et al., 2004; Kessel et al., 2005; Klimm et al., 2008). The released liquids remove highly incompatible trace components (e.g. LILE, LREE, Th, U) from the slab and induce metasomatism

in the overlying mantle, ultimately leading to the characteristic arc signature in magmas derived from a re-enriched mantle wedge. Based on correlations between enrichments in e.g. Rb, K, Ba, Th, Pb and Sr in deep sea sediments and arc magmas (Plank and Langmuir, 1993), large contributions of subducted sediments to the arc magma trace element budget of some arcs have been inferred (Plank, and Langmuir, 1998; Plank, 2005; Labanieh et al., 2012). Commonly, this correlation is used to postulate sediment melting (Plank, 2005), although supercritical liquids at higher pressures (>5 GPa, Fig. 1) are at least as efficient for trace element transfer as hydrous melts (Kessel et al., 2005; Schmidt and Poli, 2014), in particular when phengite is completely dissolved in such fluids (Schmidt et al., 2004). A logic deduction from the sediment melting imperative is that slab surface temperatures need to be

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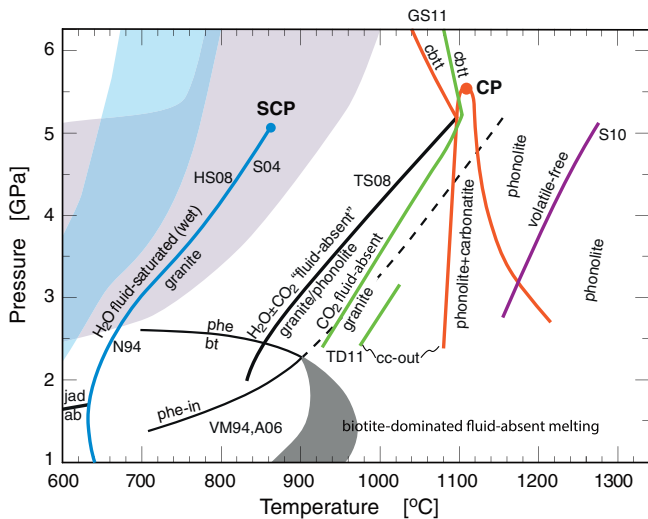
Fig. 1. Experimentally determined solidi of pelites containing varying proportions of H₂O and CO₂. The shaded blue area indicates subduction zone temperatures as modeled by Arcay et al. (2007), the lilac area those of the Syracuse et al. (2010) W1300 model. Blue: Wet melting of pelites with H₂O as the only volatile component terminates near 5 GPa in a second critical point (SCP) (data from: N94 — Nicholls et al. 1994, HS08 — Hermann and Spandler, 2008, S04 — Schmidt et al., 2004, to 5 GPa). At P < 2.5 GPa the location of the wet solidus is based on the data of Nichols et al. (1994). Bold black line: melting of fluid-absent subsolidus assemblages for a pelite + H₂O ± CO₂ system (TS08, Thomsen and Schmidt, 2008a, to 5 GPa). Note that this solidus is truly fluid-absent for H₂O as the only volatile but produces a fluid phase for compositions with H₂O + CO₂. Orange: Solidus melts are silicic at pressures to 5 GPa and carbonatitic at P > 5 GPa (Grassi and Schmidt, 2011a; GS11). At 3–5 GPa conjugate carbonatite and silicate melts may coexist at ≥1080–1200 °C (Thomsen and Schmidt 2008a; Tsuno et al., 2012; Skora et al. 2015). Green: pelite + CO₂ system without H₂O (TD11, Tsuno and Dasgupta, 2011, 2.5–3 GPa; GS11, Grassi and Schmidt, 2011a, >5 GPa). Purple: volatile free pelite solidus (S10, Spandler et al., 2010). So far, fluid-absent melting of CO₂-free sediments has only been studied at P < 2.5 GPa where it is controlled by biotite (thin black lines: reactions derived for greywackes: VM 94, Vielzeuf and Montel, 1994; A06, Auzanneau et al., 2006). Abbreviations: ab: albite; bt: biotite; cbtt: carbonatite melt; jad: jadeite; phe: phengite.

sufficiently high. Consequently, thermal models have been formulated to understand which parameter space allows for sediment melting temperatures (Syracuse et al., 2010; van Keken et al., 2011). Behn et al. (2011) argue that overstepping the solidus temperature of the sediments by a small amount would be insufficient to effectively transfer trace elements. Their compilation of sediment composition as a function of temperature yields significant depletion only 250–300 °C above the solidus, thus requiring temperatures of e.g. 930–980 °C at 2.5 GPa for efficient trace element transfer. As such temperatures are generally not realized, even in the warmest thermal models (Fig.1), a possible solution could lie in the incorporation of sediments into the mantle wedge through a cold diaper mechanism (Gerya and Yuen, 2003; Marschall and Schumacher, 2012). Such diapirs expose sediments to >1000 °C and elegantly remove the above temperature imperative for subducting slabs. Nevertheless, the buoyancy and hence rise of such diapirs may be also driven by partial melt, requiring knowledge of melt fractions in P–T space.

1.2. Mineralogy of sub-arc slab sediments

The most important factor that controls melting in clastic sediments is their content of H₂O and CO₂ as well as the volatiles liberated and added from the underlying lithologies of the subducting lithosphere. During subduction to 20–50 km, metamorphic dehydration causes a strong loss of H₂O from the slab. At depth >70 km subducted metapelitic sediments contain ≤1.5 wt.% H₂O but subduction to ~300 km does not cause much further devolatilization (Ono, 1998). In Fe-bearing metasediments the dominant near-solidus hydrous phase to ~2.5 GPa is biotite (e.g. Vielzeuf and Holloway, 1988; Vielzeuf and Montel,

1994; Auzanneau et al., 2006) while at sub-arc depths of 90–170 km (corresponding to ~2.7–5 GPa) this is phengitic white mica (Schmidt et al., 2004). Hence, in the subarc most clastic sediments have an assemblage of phengite + cpx + garnet + quartz/coesite ± kyanite ± accessories. Phengite is not only the major carrier of K at these depths (Schmidt, 1996) but also that of many large ion lithophile trace elements such as Rb, Ba, Be, B, Cs and Sr (Domanik et al., 1993; Sorensen et al., 1997; Hermann and Rubatto, 2009). Its stability thus controls whether these elements are released into melts and transferred to the mantle wedge.

1.3. Melting regimes and volatiles

Possible melting regimes in prograde metamorphic rocks have been intensively investigated in the 70s and 80s (e.g. Yoder and Kushiro, 1969; Brown and Fyfe, 1970; Clemens and Vielzeuf, 1987; for a discussion see Vielzeuf and Schmidt, 2001). Thermodynamically, it is useful to distinguish assemblages or reactions by the presence or absence of phases, in this case fluid-present or fluid-absent (see Fig. 2). Practically, melting regimes are considered as fluid-saturated when a significant amount of excess fluid is present at subsolidus conditions. In this case, the minimum melting temperature occurs for systems with H₂O as the only volatile, i.e. at the wet solidus ("3" in Fig. 2a,b). At the high pressures characteristic for sub-arc slabs, a limited amount of available aqueous fluid may be entirely dissolved in the silicate melt such that all fluid is consumed at the solidus and further melting with increasing temperature is not fluid-saturated anymore (from "3" to "2"in Fig. 2a, b). This is also the case in most experimental studies using 1.5–7 wt.% H₂O, amounts that dissolve completely in the melt near the solidus. As high-pressure rocks may only retain minuscule amounts of fluid themselves, significant fluid-saturated melting requires influx of fluid, preferentially H₂O from metamorphic reactions in the hydrated basaltic or peridotitic layers of the oceanic lithosphere below.

The absence of significant amounts of excess fluid leads to a fluid-absent melting situation through a peritectic reaction ("2" in Fig. 2a, b), defined as the melting of a subsolidus assemblage that contains hydrous phases (e.g. biotite or phengite) and possibly carbonates ("5" in Fig. 2a) but not a fluid. This corresponds to a prograde mineral assemblage that always remains fluid-saturated but continuously loses almost all of excess fluid produced through metamorphic reactions. If H₂O is the only volatile, fluid-absent melting is also termed "dehydration melting", an unfortunate term as dehydration of the rock volume in question does not occur, or alternatively as the equally unfortunate "hydrate breakdown melting" which is not synonymous to fluid-absent melting as the latter does neither require the complete destabilization of hydrate minerals nor will necessarily all hydrous minerals decrease in their mode across a fluid-absent melting reaction in complex natural systems.

With CO₂ as a volatile component, the question of fluid-saturation is complicated through the fact that a fluid-absent subsolidus assemblage including phengite and calcite leads to the production of melt and fluid at the solidus, i.e. the solidus itself becomes fluid-saturated even if a fluid-absent subsolidus assemblage is molten. As will be discussed below, this latter fact has some consequences on carbon recycling in subduction zones.

1.4. Previous experimental work

Previous high pressure experiments on the melting of sediments at subarc conditions with various amounts of H₂O and CO₂ are summarized in Fig. 1. Studies on wet melting, i.e. saturated in aqueous fluid, resulted in a wet solidus at 710–860 °C at 3.0–4.5 GPa (Nichols et al., 1994; Schmidt et al., 2004; Hermann and Spandler, 2008; Skora and Blundy, 2010). In these experiments, phengite coexists with melt over 150–200 °C and disappears at 890–980 °C. At ~5 GPa wet melting of pelites is terminated by the endpoint to the solidus, the so-called second