Melting of pelitic sediments at subarc depths: 2. Melt chemistry, viscosities and a parameterization of melt composition

Max W. Schmidt *

Institute of Geochemistry and Petrology, Department of Earth Sciences, ETH, 8092 Zuerich, Switzerland

ABSTRACT

The now numerous experimental studies on sediment melting at sub-arc pressures provide the data necessary to model melt compositions. These vary systematically as a function of melt fraction (F) to F = 0.6. Compositional bands as a function of melt fraction are relatively narrow for all major oxides except for the alkalis where pressure and H_2O-contents lead to variations by a factor of 3–5. Most sediment melts are meta- to slightly per-aluminous granites with 71–77 wt.% SiO_2 (on a volatile free basis), 12–16 wt.% Al_2O_3, and 8–12 wt.% total $Na_2O + K_2O$; MgO + FeO increase from 0.5 near the solidus to ~3.0 wt.% at F = 0.6, while CaO remains <2 wt.% for carbonate-free compositions and is 3–6 wt.% (at F = 0.6) for the more Ca-rich bulk compositions saturated in calcite. Concerning alkalis, H_2O and relatively low pressures (2.5–3 GPa) favor sodic melts (K_2O/Na_2O wt-ratios down to 0.5) while high pressures, low volatile contents and CO_2 result in more potassic melts (K_2O/Na_2O up to 5). The relative compositional uniformity of these high pressure partial sediment melts results from the fact that they are in equilibrium with phengite + jadeitic cpx + garnet + quartz/coesite. Notable exceptions are partial melts at 4–5 GPa under CO_2-rich and/or fluid absent conditions which are distinctly alkaline granites, and melts from a bulk composition that loses SiO_2-saturation at the solidus which are alkaline-rich phonolites.

Melt compositions from experiments with a H_2O-saturated solidus can be fit by simple second degree polynomials that converge to the average bulk composition at F = 1.0. For Al_2O_3 a dependency on H_2O, and for Na_2O, K_2O and SiO_2 dependencies on H_2O and pressure are necessary to reproduce the experimental melt compositions. These equations predict melt compositions for an average bulk sediment from solidus temperatures to F = 0.6. The averaging built into such a fit corresponds to the averaging taking place across a pile of heterogeneous subducted sediments.

The hydrous granites forming at the wet solidus are highly mobile: The high H_2O-contents (15–30 wt.%) resulting from flux melting yield melt viscosities of $10^{-1.5}$–$10^{0.5}$ Pa·s. Porous flow, a rather slow melt migration mechanism, would lead to extraction of as little as a percent of melt within centuries, rendering mass transfer almost immediate with fluid fluxing.

1. Introduction

The subduction of sediments and of granitic crust that is added to the slab by subduction erosion is largely responsible for the reintroduction of lithophile elements such as K, Rb, Ba, Th, U, and Zr into the mantle. Nevertheless, there is a raging debate how much of this material is recycled on a subduction short circuit into arc magmas, hence back to the arc crust, and how much enters into the deep mantle then convecting on time scales of Gyrs.

It has been argued that e.g., Ba and Th are almost quantitatively recycled in the subarc and that for an effective recycling process regarding these key traces, sediment melting would be required (Plank, 2005; Labanieh et al., 2012). To understand whether this is realistic, thermal models have been calculated for all major present day subduction

zones (Abers et al., 2006; Syracuse et al., 2010) indicating that in about 1/3 of the cases slab surface temperatures would slightly overstep temperatures of the wet sediment solidus (W1300 model of Syracuse et al., 2010). Other thermal models (Arcay et al., 2007) do predict much colder slab temperatures. Secondly, it is questionable whether barely reaching the solidus is sufficient to extract key traces from the sediments. Behn et al. (2011) argued that trace element depletion in sediments requires several hundred degrees more than just solidus temperatures. Third, supercritical liquids forming above the endpoint of the wet sediment solidus near 5.0 GPa (Schmidt et al., 2004; Hermann and Spandler, 2008) have trace solubilities in excess of melts (at least in basaltic bulk compositions, Kessel et al., 2005a), providing a viable alternative transport medium.

In a companion study (Mann and Schmidt, 2015–this volume), we experimentally investigated the role of different melting regimes at subarc depths and, compiling all available data, quantified melt fraction as a function of pressure, temperature and volatile contents. The

* Tel.: +41 44 632 7988.
E-mail address: max.schmidt@erdw.ethz.ch.

experimentally observed and modeled melt productivities led to the conclusion that only fluid-saturated wet melting could deliver significant melt fractions within the realm of temperatures predicted by Syracuse et al. (2010) for warm subduction zones. Fluid-saturation could only be achieved through flushing by fluids originating lower in the subducting lithosphere, e.g., by serpentine dehydration. A second possibility to melt sediments to large extents would be the rise of cold diapirs into the mantle wedge (Gerya and Yuen, 2003; Behn et al., 2011; Marschall and Schumacher, 2012). The buoyancy of such diapirs, necessary for their ascent, may in part be driven by partial melts, hence also the driving force of such diapirs may involve melting.

Prograde partial melting is largely controlled by the availability and composition of volatiles. In principal, it is sufficient to distinguish between fluid-present and fluid-absent melting and to consider H_2O and CO_2 as the dominating volatiles (Yoder and Kushiro, 1969; Clemens and Vielzeuf, 1987; Vielzeuf and Schmidt, 2001). Fluid-saturated melting requires the availability of a fluid, to be delivered from metamorphic reactions in deeper sources. In contrast, the concept of melting fluid-absent subsolidus assemblages is based on rock volumes whose mineralogy corresponds to fluid-saturation, i.e., contains hydrous phases (and possibly carbonates), but a significant amount of fluid itself is not available. This concept acknowledges that prograde metamorphism leads to devolatilization, any fluid rising from its source rock, leaving behind a fluid-saturated mineral assemblage with hydrous phases and/or carbonates but with very little fluid. In the case of subarc depths sediments, the principal hydrous phase is phengite, i.e., Si-rich white potassic mica. With a stoichiometric molar K:H ratio of 0.5, micas accommodate 1 wt.% H_2O for every 2.6 wt.% bulk K_2O, leading to H_2O-contents of 0.7–1.2 wt.% at fluid-absent subsolidus conditions for typical pelites with 1.8–3 wt.% K_2O (Shaw, 1956). Phengite coexists with sodic cpx, quartz/coesite, garnet, ± kyanite, calcite when CO_2 is present, and a variety of accessories such as rutile, zircon, monazite, apatite and thorite (Hermann and Rubatto, 2009; Skora and Blundy, 2010). It is indeed greatly facilitating the understanding of melt compositions that subsolidus assemblages for all subarc depths sediments appear to be identical, although mineral compositions and modes may vary as a function of composition.

The contribution of sediment melts to the geochemical arc cycle relates to their major and trace element chemistry. The purpose of this study is to provide a parameterization of the major element geochemistry of partial sediment melts at subarc depths, which in turn provides the basis for estimating melt viscosities and melt migration velocities as well as for modeling the melt transport capacity with respect to trace elements. The latter is crucially linked to retention of traces in residual accessories and hence to mineral saturation, which in turn can again only be understood if the major element melt chemistry is known.

2. Data set

2.1. Data sources

Fluid-saturated and fluid-absent melting of metasediments (Fig. 1) at crustal depths, where muscovite and biotite are the principal hydrous phases, has been thoroughly investigated in the 80s and 90s (to ~1.5 GPa, e.g., Vielzeuf and Holloway, 1988; Vielzeuf and Montel, 1994). In contrast, sediment melting at subarc depths was scarcely investigated until the turn of the millennium and only moved into the focus over the last ten years. For H_2O-saturated melting, Nichols et al. (1994) provided a first phase diagram. Schmidt et al. (2004), Auzanneau et al. (2006), Hermann and Spandler (2008), Skora and Blundy (2010), Tsuno and Dasgupta (2012), and Mann and Schmidt (2015–this volume) investigated melting reactions and melt compositions of H_2O-saturated sediments (Table 1). Thomsen and Schmidt (2008a), Tsuno and Dasgupta (2012), Tsuno et al. (2012), Skora et al. (2015) and Mann and Schmidt (2015–this volume) studied compositions with H_2O and CO_2, Tsuno and Dasgupta (2011) with CO_2-only and Spandler et al. (2010) a volatile free composition. Table 1 and Fig. 2 give an overview of pressure–
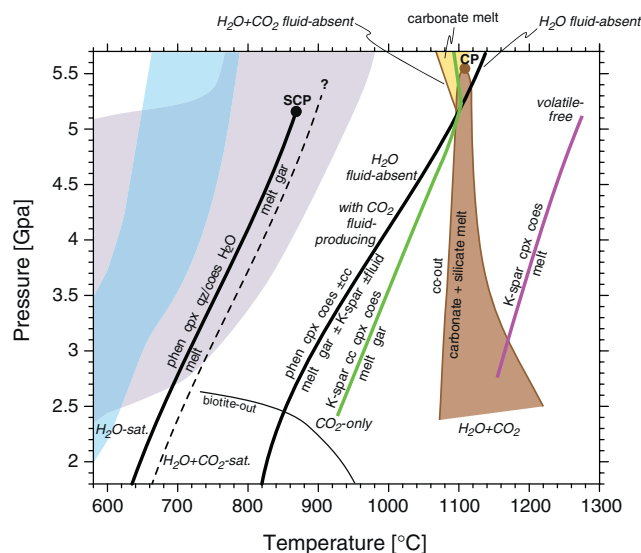

Fig. 1. P–T-locations of solidi of metasediments for all combinations of H_2O and CO_2 as volatiles. The H_2O-saturated or wet solidus is given as compiled by Mann and Schmidt (2015–this volume), based mainly on data from Nichols et al. (1994), Schmidt et al. (2004), Hermann and Spandler (2008) and Skora and Blundy (2010). The wet melting reaction (1) changes at ~4 GPa from eutectic to peritectic and terminates in a critical endpoint near 5 GPa. The fluid-saturated solidus with $H_2O + CO_2$ is only determined at 3 GPa, where it locates ~30 °C higher than the wet solidus. It is unknown if this solidus has a critical endpoint. The melting of fluid-absent subsolidus assemblages (reaction 2) is given as compiled by Mann and Schmidt (2015–this volume) and appears to not vary substantially in temperature with or without CO_2. This solidus is truly fluid-absent with H_2O as the only volatile but with $H_2O + CO_2$, fluid-absent subsolidus assemblages produce a fluid upon melting. The solidus for CO_2-only was determined by Tsuno and Dasgupta (2011) at 2.5–3 GPa and by Grassi and Schmidt (2011) at 5.5–22 GPa. Note that at 5–5.5 GPa, melts from pelites with CO_2 change from silicic to carbonatitic (yellow field, for details see Grassi and Schmidt, 2011). Also shown is the (brown) field of coexisting carbonatite + silicate melts from Thomsen and Schmidt (2008a), Tsuno et al. (2012) and Skora et al. (2015); at lower temperatures, calcite is stable, at higher temperatures a single CO_2-rich silicate melt. The volatile-free solidus is from Spandler et al. (2010). Abbreviations: cc: calcite; coes: coesite; cpx: clinopyroxene; gar: garnet; K-spar: potassium feldspar; phen: phengite.

temperature conditions, volatile composition and degree of melting investigated by the above authors. Table 2 gives the bulk compositions used. Similarly relevant are studies on H_2O-saturated melting of granitic crust (Huang and Wyllie, 1981; Hermann, 2002) and of simplified sediment model compositions (e.g., Huang and Wyllie, 1974; Hermann and Green, 2001; Thomsen and Schmidt, 2008b) at subarc depths.

2.2. The phase diagram of sediment melting at subarc pressures

Fig. 1 summarizes solidus reactions for different volatile conditions. The depicted H_2O-saturated (wet) solidus temperature increases from 668 °C at 2.5 GPa to 858 °C at 5.0 GPa and satisfies all available experiments within 15 °C (Eq. (1) and Table 4 of Mann and Schmidt, 2015–this volume). The $H_2O + CO_2$-saturated solidus was only studied at 3 GPa (Skora et al., 2015) and found to locate approximately 30 °C higher than the wet one (Fig. 1). The melting of fluid-absent assemblages occurs only at 855 to 1085 °C at 2.5 to 5.0 and does not appear to vary much in temperature with addition of CO_2.

Apart from the governing melting reactions, the following salient features of the phase diagram are noteworthy: Schmidt et al. (2004) and Hermann and Spandler (2008), on H_2O-saturated melting, have obtained a discontinuous change from (fluid-)quench to hydrous glasses at 5.0 and 4.5 GPa, respectively, the critical endpoint to the sediment solidus is hence likely to occur just above 5 GPa. Note that such an endpoint does not exist for fluid-absent conditions (for an illustration see Schmidt and Poli, 2014, their Fig. 9). In $H_2O + CO_2$-bearing sediments the solidus melt changes from silicic to carbonatitic between 5 and 5.5 GPa (Grassi and Schmidt, 2011; Tsuno et al., 2012). Furthermore,