



Recent advances made by reaction experiments on melting of heavily metasomatized hydrous mantle

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ABSTRACT

Mantle-derived magmas are traditionally assumed to originate by melting of an upper mantle consisting of uniform spinel- or garnet peridotite dominated by olivine. However, extensive studies of mantle-derived basalts suggest that the mantle is more mineralogically heterogeneous, so that the genesis of even the most common magmas requires consideration of mixed source regions within the mantle involving pyroxenites and hydrous minerals. We refer to these with the group term metasomes. However, most experimental studies on mantle melting have assumed a homogeneous source composition, presenting a challenge in quantifying the impact of these heterogeneities.

This paper provides a comprehensive review of recent advances in reaction experiments that depart from traditional approaches assuming a homogeneous mantle. We begin by assembling evidence for the existence of metasomes, discussing their formation and integration into basaltic melts.

Further, we introduce the reaction experiments combining peridotite with hydrous assemblages, such as phlogopite, amphiboles, and apatite, leading to more accurate simulations of natural magmatic processes. These experiments reveal that the melting of hydrous metasomes and subsequent melt-peridotite interactions are key to producing the high alkali contents observed in natural lavas. The melting of hydrous metasomes occurs at lower temperatures than peridotite, resulting in diverse melt compositions. The interaction between metasome-derived melts and peridotite further modifies these melts, influenced by the pressure-dependent melting behaviors of minerals like orthopyroxene and olivine. This dynamic process leads to the generation of K- and Na-alkaline melts with varying silica and alkali contents, reflecting the complex interplay of melting and reaction mechanisms in the mantle.

Formation of hydrous metasomes have also been studied by reaction experiments. Experimental studies have predominantly focused on potassium-rich systems due to the geochemical signatures of potassic igneous rocks suggesting sedimentary rock contributions to their sources. These studies simulate interactions between melts and mantle peridotite, particularly in sub-arc regions, leading to potassium-rich metasomes. More experimental studies are needed on sodium-rich alkaline systems to understand the formation of amphibole-rich metasomes and bridge knowledge gaps.

Future studies should emphasize the detailed compositional variability of melts from metasomes, their reactions with peridotites, and comparisons with surface lavas. Understanding the kinetics of these reactions and the melting mechanisms of metasome-derived melts is essential. However, the considerable mineralogical diversity of hydrous metasomes poses a primary challenge facing experimental studies. It underscores the need for more experiments on additional melt source rocks and their reaction with peridotites, as the story about the reaction of melts from hydrous metasomes with mantle peridotites has only just begun.

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1. Introduction

Magmatism is one of the most dramatic geological phenomena, playing a pivotal role in shaping the Earth's surface through volcanic activity and in the evolution of the Earth's interior through material transport. At the heart of this process lies the upper mantle, which acts as a principal source region for a vast array of magma types. The upper mantle is generally modelled as consisting of peridotite of uniform composition, and geophysicists, petrologists and geochemists have shared this view for decades, often for the sake of simplicity. A glance into any textbook on igneous petrology will reveal that most basalts and other mantle-derived igneous rocks are explained as the products of various degrees of partial melting of homogenous spinel – or garnet mantle peridotite, as a function of pressure and temperature. Consequently, mantle-derived melt compositions have been considered a “window into the Earth's thermal state”, forming the empirical basis for various thermobarometers used to understand the planet's thermal conditions (Conticelli and Peccerillo, 1989; Downes et al., 2002; Lee et al., 2009; Mallik et al., 2015). Additionally, basalt compositions are often used to reconstruct the geochemical and mineralogical characteristics of the mantle from which they originate.

Although high-pressure experimental melting studies on peridotite have successfully explained the origin of numerous voluminous melt types, they encounter difficulties in elucidating alkaline melt compositions rich in Na and/or K. These less voluminous melts have been historically accommodated within the “homogeneous mantle” melting model, often referred to as “low degree” melts without much in the way of more detailed explanation. In contrast, extensive research has been dedicated to studying the isotopic and trace-element compositions of more voluminous mantle-derived basalts, resulting in reports of significant mantle heterogeneity.

However, most of these studies lack detailed information regarding the exact mineralogy of the source assemblages involved. Recently, trace elements in olivines from basalts have been used to argue that the source regions of ocean island basalts and flood basalts contain a substantial amount of recycled oceanic crust (Sobolev et al., 2005, 2007) and that a large proportion of the source may consist partially or wholly of pyroxenite. This explanation has also been applied to komatiites that erupted in the first half of Earth's history (Sobolev et al., 2007) which were previously considered to be the foremost examples of extensive melting of homogeneous peridotite. As a result, the notion of mixed source regions has become increasingly vital in explaining the origin of alkaline rocks in all settings (Condamine et al., 2016; Foley, 1992; Mallik and Dasgupta, 2012; Mallik et al., 2015, 2016; Pilet, 2015; Pilet et al., 2008) but also more common rock types, such as mid-ocean ridge basalts (Hirschmann and Stolper, 1996), ocean island basalts (Pilet et al., 2008; Sobolev et al., 2005; White, 2015), and arc lavas (Straub et al., 2008). Despite growing evidence of mixed source regions, experimental studies beyond homogeneous peridotite remain limited (Lambart et al., 2012, 2016; Mallik et al., 2021).

Two general categories of mixed-source regions can be tentatively distinguished: *anhydrous mafic and ultramafic assemblages*, including eclogites, pyroxenitic, wehrlitic and websteritic rocks of various origins (Aulbach et al., 2020; Mallik et al., 2021), and *hydrous mantle metasomes*. Observed by compositional layering in peridotite massifs such as Lherz, Ronda, and Beni Bousera (Downes, 2001, 2007; Fabriès et al., 2001 and references therein), these probably occur at all scales starting at the mm-to-m-scale, particularly in the lithospheric mantle.

Anhydrous ultramafic and mafic assemblages within the mantle include pyroxenites and/or eclogites believed to originate either from subducted oceanic crust (Gervasoni et al., 2017; Kogiso et al., 2003; Sobolev et al., 2005, 2007; Stracke et al., 2003, 2005), or from melt infiltration ($P > 1$ GPa) (Borghini and Fumagalli, 2020; Borghini et al., 2017; Lambart et al., 2012), as well as wehrlites and websterites. Several experimental studies have been dedicated to understanding the partial melting of dry pyroxenites, including examining phase relations,

melting behaviour, solidus temperature, and melt productivity (e.g. Borghini and Fumagalli, 2020; Borghini et al., 2017; Hirschmann et al., 2003; Keshav et al., 2004; Kogiso et al., 2003, 2004; Lambart et al., 2012; Yaxley and Green, 1998). Geochemical models have explored the role of mixed pyroxenite-peridotite mantle sources in the genesis of mid-ocean ridge basalts (MORBs) and ocean island basalts (OIBs) (e.g. Brown and Leshner, 2016; Delavault et al., 2015; Gurenko et al., 2013; Herzberg, 2011; Hirschmann and Stolper, 1996; Lambart et al., 2009, 2012, 2016; Phipps Morgan, 2001; Shorttle and MacLennan, 2011; Shorttle et al., 2014; Sobolev et al., 2005, 2007; Stracke and Bourdon, 2009). Wehrlitic and websteritic compositions are generated by the conversion of lherzolite and harzburgite to orthopyroxene-poor or orthopyroxene-rich olivine-poor rocks by melt-peridotite interaction (e.g. Förster et al., 2017; Green and Wallace, 1988; Grützner et al., 2023; Yaxley and Green, 1998; Yaxley et al., 1998; Borghini et al., 2022).

This review focuses on the second type, namely heavily metasomatized hydrous mantle domains that are dominantly related to the origin of Na- and K-alkaline melts. They are manifested in veins and dykes particularly rich in mica and amphibole and referred to as “hydrous metasomes”. The term was likely first introduced with usage by Haggerty and Wyllie (Haggerty, 1986, 1989; Wyllie, 1987), and has since been widely accepted in interpretations of the origin of the most extreme alkaline lavas like lamproites, lamprophyres and kimberlites (Förster et al., 2017; Mitchell, 2020; Tappe et al., 2008). Hydrous metasomes describe non-peridotitic, often pyroxene-rich ultramafic rocks containing significant amounts of hydrous phases, predominantly amphibole and phlogopite, along with various exotic accessory minerals like apatite, ilmenite, perovskite, Ti-magnetite, armalcolite, priderite, ilmenite, rutile, dolomite etc. Thus, the metasomes are often summarised as “hydrous pyroxenites” that play a major role in the vein+wall rock melting model (Ezad et al., 2024a, 2024b; Foley, 1992; Foley and Ezad, 2024). They can be generated in different geodynamic settings, including intracontinental rifting (Grützner et al., 2013; Vaselli et al., 1995; Muravyeva and Senin, 2016), plume-lithosphere interaction (Tappe et al., 2023) and subduction (e.g. Casalini et al., 2022; Prelević et al., 2013; Sekine and Wyllie, 1982a, 1982b, 1983; Wyllie and Sekine, 1982) (Fig. 1). Tectonically, they can be situated in cratonic and non-cratonic continental lithosphere. Later melting of these hydrous metasomes gives rise to the alkaline basaltic lavas. The significance of easily fusible hydrous metasomes extends far beyond their presumed volumetric abundance in the mantle, because their low melting temperatures and widespread distribution within the lithospheric mantle may facilitate magma generation without the need for substantial lithospheric thinning or elevated mantle potential temperatures in the form of plumes (Ezad et al., 2024a). A typical example is the location of kimberlites above the zones of the strongest precursory metasomatism (Dasgupta et al., 2007; O'Reilly and Griffin, 2013), following the same paths used by earlier generations of stalled magmatic episodes, which resulted in metasomatising events. Heavily metasomatized mantle areas substantially influence the physical longevity of the whole lithosphere (Wang et al., 2015). Accordingly, the occurrence of magmatism at sites of maximum metasomatism of the lithospheric mantle signifies the initiation of its physical destruction (Wang et al., 2015) or faulting within these zones (Vaughan and Scarrow, 2003).

This paper offers a comprehensive review of experimental advances that use reaction experiments designed as alternatives to traditional approaches rooted in the homogeneous mantle paradigm. The primary focus of these experiments is on testing the hypothesis that the melting events in the upper mantle that lead to the formation of Na- and K-alkaline lavas, originate from metasome-rich mixed-source regions. A key novelty of this approach is the paradigm shift from considering peridotite as the sole melting source of Na- and K-alkaline lavas to the recognition of the involvement of non-peridotitic assemblages rich in hydrous minerals in addition to peridotite. This shift has revealed significant gaps in our current understanding of the melting processes involving hydrous metasomes and the subsequent interaction between

melts and the mantle, and the reaction experiments have already produced some unexpected results.

2. Heavily metasomatized hydrous mantle and its magmatic products

Mantle metasomatism refers to the process of mineralogical and geochemical enrichment through the interaction of fluids and melts with mantle peridotite (Bailey, 1982; Lloyd and Bailey, 1975). Early key publications of Lloyd and Bailey (1975), Menzies and Hawkesworth (1987) and Nixon (1987) significantly contributed to our understanding of this process. Regarding the nature of mantle fluids, depending on lithosphere thickness (off- vs. on-craton), metasomatism covers a wide spectrum, from silicate to carbonate melts (Bali et al., 2002; Guzmics et al., 2008; Pyle and Haggerty, 1994; Rosatelli et al., 2007; Schiano et al., 1994; van Acherbergh et al., 2001, 2002, 2004), with varying types and concentrations of dissolved fluids and solutes, including brines, C-O-H species, and sulphur-bearing components (Andersen et al., 1984, 1987; O'Reilly et al., 1990; O'Reilly and Griffin, 2013). In terms of geochemical processes, metasomatism may result from the consumption of oceanic crust and sediments lying on it within the mantle, deep or shallow recycling of continental crust and deep carbon recycling. The role of stagnant subducted slabs in the mantle transition zone has also recently been linked to mantle metasomatism (Yang et al., 2012). However, a comprehensive discussion of these topics would necessitate a publication of significantly greater scope than the current one.

In a more recent summary of the topic, O'Reilly and Griffin (2013) modified and expanded Dawson's (1980) traditional classification into modal metasomatism (new mineral growth) and cryptic metasomatism (element enrichment only), to include stealth metasomatism that comprises the restoration of the near-original composition by metasomatic refertilization. Here we further extend the list of metasomatism types, coining the name "channel metasomatism" to describe the formation of veins, dykes and zones comprising (hydrous) metasomes. This is mostly manifested as a main channel or conduit formed by the solidification of silicate melts at mantle depths. Therefore, the formation of hydrous metasomes may be considered as a counterpart to pyroxenite emplacement described from orogenic and ophiolitic massifs (Bodinier and

Godard, 2014; Downes, 2007) and xenoliths (Gonzaga et al., 2010). Many of these mantle pyroxenites are interpreted as being formed by high-pressure magmatic segregations that reacted to variable extents with the host peridotite. A similar mode of origin may apply for at least some of the hydrous metasomes (Dawson and Smith, 1977; Fitzpayne et al., 2018, 2019; Grützner et al., 2013, 2023; Pilet, 2015).

Numerous lines of evidence support the existence of hydrous metasomes in the mantle and their involvement in the source of alkaline mantle-derived rocks:

- i. The most convincing evidence takes the form of xenoliths of hydrous metasomes and composite metasome/peridotite xenoliths found in basalts (Fig. 1). The mineralogy of these veins varies and, besides "normal" mantle phases, may include amphibole, mica, spinel, apatite, zircon, and titanium-rich minerals (Dautria et al., 1987; Frey and Prinz, 1978; Griffin et al., 1997, 2000; Irving, 1980; Menzies and Beswick, 1978; O'Reilly and Griffin, 2000; Wass, 1979; Wass and Roge, 1980; Wilshire and Shervais, 1975). K-rich metasomes, known to occur as phlogopite-clinopyroxenites, glimmerites, phlogopite-wehrlites and phlogopite-websterites, are frequently related to orogenic processes (Fig. 1) (Conticelli et al., 2009; Prelević et al., 2013). In non-cratonic intracontinental rift environments, metasomes are characterized by phlogopite- and calcic amphibole-rich assemblages, including phlogopite-wehrlites, hornblende and amphibole-clinopyroxenites (e.g. Aulbach et al., 2020; Dautria et al., 1987; Grützner et al., 2013; Shaw and Eyzaguirre, 2000; Shaw et al., 2005; Vaselli et al., 1995; Yaxley et al., 1998) (Fig. 1). In cratonic regions, discrete assemblages dominated by hydrous minerals and clinopyroxene have been divided into two types named MARID (Mica-Apatite-Richterite-Ilmenite-Diopside) and PIC (Phlogopite-Ilmenite-Clinopyroxene) (Fitzpayne et al., 2018; Grégoire et al., 2002). In the MARID suite, hydrous minerals usually form much more than half of the rock and the amphibole is the alkali-amphibole (K-richrichterite) (Dawson and Smith, 1977), whereas in the PIC suite clinopyroxene is more common and K-richrichterite is absent (Grégoire et al., 2002).
- ii. Interpretive evidence indicating the spread of metasomatism is derived from the geochemical characteristics of the K- and Na-

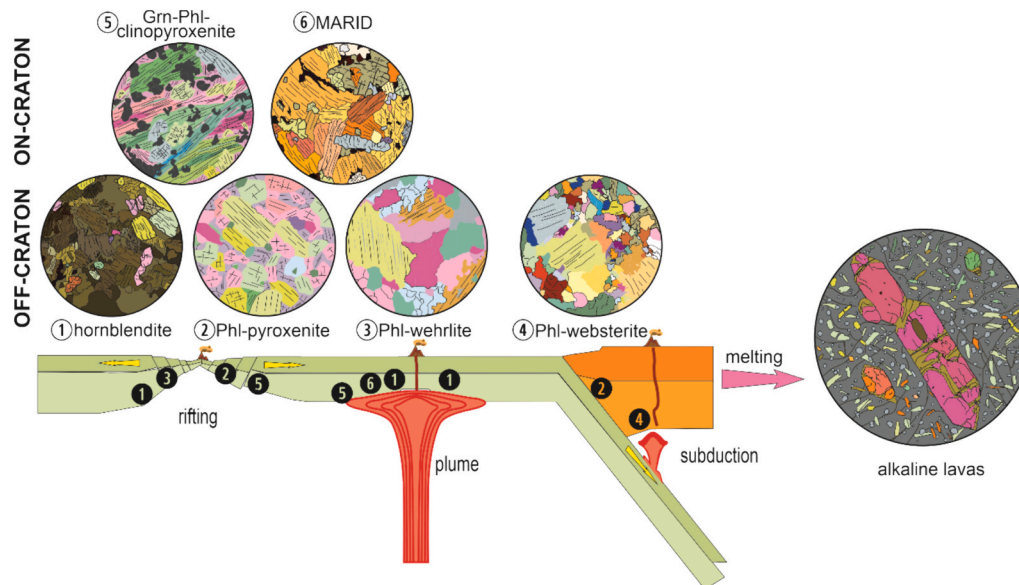


Fig. 1. Variety of hydrous metasomes. They can be generated in different geodynamic settings and lithosphere ages, including intracontinental rifting (Downes, 2001; Downes et al., 2004; Grützner et al., 2013), plume-lithosphere interaction (Lloyd et al., 1991; Shaw and Eyzaguirre, 2000; Shaw et al., 2005, 2018; Shaw and Klugel, 2002; Tappe et al., 2023; Witt-Eickschen et al., 1998, 2003; Witt-Eickschen and Kramm, 1998; Zangana et al., 1997, 1999) and orogenesis (Conticelli and Peccerillo, 1989; Dallai et al., 2019; Downes et al., 2002; Fan et al., 2021; Morishita et al., 2003; Prelević et al., 2015; Zanetti et al., 1999). Later melting of the metasomes will give rise to the alkaline basaltic lavas.

alkaline lavas. Numerous lines of evidence support the involvement of metasomes in the source of ultrapotassic alkaline rocks. Firstly, extremely high K_2O and K_2O/Na_2O cannot be reproduced in experiments using a homogeneous mantle composition (Mallik et al., 2015; Novella and Frost, 2014) (Fig. 2a). Liquidus experiments have failed to demonstrate multiple saturation in the four peridotite minerals- olivine, orthopyroxene, clinopyroxene and garnet/spinel (Foley, 1990). Finally, trace element and isotope compositions of the volcanic rocks indicate thorough source mixing of two or more components in the source (Prelević et al., 2013). This is also coupled with the recurrence of potassium-rich volcanism in several volcanic provinces where magmatic activity with similar geochemical signature coincides with major tectonic episodes within the region, implying that the metasomatized regions were stored within the mantle lithosphere for long periods (Gülmez et al., 2016; Scarrow et al., 2009; Sokol et al., 2020; Vaughan and Scarrow, 2003) and their episodic activation represents an integral aspect of the broader tectonic development.

In the case of Na-alkaline lavas occurring in continental and oceanic areas, a traditional view is that these lavas are produced by extremely small degrees of partial melting of a peridotitic mantle source (Hart et al., 1971). This, however, has been radically changed after discovering that the trace element and isotopic signatures of high Na/K alkaline basalts from intraplate continental and oceanic settings imply derivation from a source that is more enriched than a depleted mantle. Moreover, the compositional continuum in terms of SiO_2 and alkalis from nephelinites and basanites to alkali olivine basalts and tholeiites that is universally observed in intraplate volcanoes has also been interpreted in terms of the variable degree of partial melting of a common mantle source (Caroff et al., 1997a, 1997b; Lustrino et al., 2002; Wilson et al., 1995a, 1995b). This has never been reproduced in experiments on mantle lithologies (Pilet, 2015), again pointing to more

complex source conditions for the Na-alkaline lavas (Fig. 2b).

- iii. Geophysical signatures of metasomatized mantle domains can be identified in certain regions through seismic and gravity tomography, high heat flow, and magnetotelluric signals (Förster and Selway, 2021; O'Reilly and Griffin, 2013; Özyaydin and Selway, 2022). For example, the LLAMA model (Anderson, 2011) (Laminated Lithologies and Aligned Melt Arrays), which utilizes high-resolution body wave tomography, suggests a heavily metasomatized base of the lithosphere where hydrous components are segregated into lamellae through shear instead of being randomly mixed, resembling a marble cake-like scenario.

3. Reaction experiments investigating the generation of K- and Na-alkaline melts

High-pressure, high-temperature experiments are fundamental tools for simulating the conditions under which rocks form and equilibrate. Modern experimental petrology employs various setups, including internally heated pressure vessels, piston cylinders, multi-anvil apparatuses, and diamond-anvil cells (Boyd and England, 1960; Kawai and Endo, 2003; Walker et al., 1990). These setups encompass the entire pressure-temperature range where rock melting and evolution may occur. Traditionally, high-pressure experimental melting studies have utilized peridotite to explain the origin of the main melt types. After the melting of dry peridotite failed to produce many alkaline melt types, volatile species, particularly H_2O and CO_2 , were added to accommodate strongly alkaline melts in the peridotite model (e.g. Pilet, 2015, and references therein). However, these studies encountered difficulties in synthesizing the most extreme K- and Na-alkaline melts. Recent advancements have resulted in numerous experimental studies employing reaction experimental setups, opening new research pathways and overcoming previous limitations.

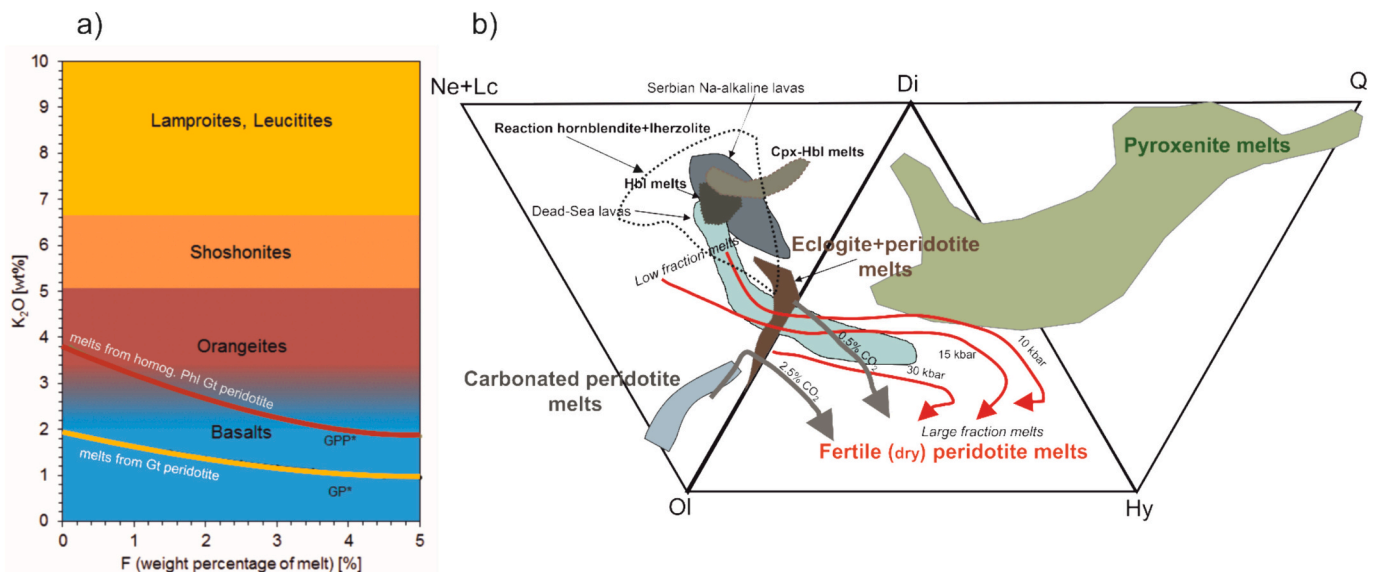


Fig. 2. Summary of previous experiments that have tried to produce K- and Na-alkaline melts. a) Neither melting of garnet peridotite (GP*) nor homogeneous garnet phlogopite peridotite (GPP*) produces melts with $K_2O > 4$ wt% and $K/Na > 2$ (modified from Novella and Frost, 2014); Direct melting of sediment-peridotite mixtures produces melts with K_2O of up to 5 wt% but with high SiO_2 contents > 65 wt% (Conticelli and Peccerillo, 1989; Dallai et al., 2019; Mallik et al., 2015, 2016; Wang et al., 2017a). b) CIPW normative diopside, olivine, hypersthene, nepheline + leucite and quartz variations of the some intracontinental basalts (Cvetković et al., 2013; Ma et al., 2011) and experimental melt compositions (modified from Ma et al., 2011) from various sources, including phlogopite-bearing peridotite (Downes, 2001; Mengel and Green, 1989), carbonated peridotite (Dasgupta et al., 2007; Hirose, 1997), hydrous peridotite (Downes et al., 2004; Fan et al., 2021; Hirose and Kawamoto, 1995), silica-deficient garnet pyroxenite (Hirschmann et al., 2003), silica-excess pyroxenite (Pertermann and Hirschmann, 2003; Tsuruta and Takahashi, 1998), hornblende, clinopyroxene-hornblende and reaction hornblende+lherzolite (Grützner et al., 2023; Pilet et al., 2008). Arrows show partial melting trends, at different pressures based on the compilation of Thompson et al. (2005). The plot demonstrates that a compositional continuum ranging from nephelinites (most Ne + Lc rich melts) to basanites, alkali olivine basalts, and tholeiites, representing Na-rich melts, has never been achieved on the four-phase mantle lithologies.

In the following sections, we discuss the methodologies employed in these experiments, key findings, and their implications for understanding the generation and evolution of K- and Na-alkaline melts. We also explore the potential applications of these findings in natural settings and their relevance to broader geological processes.

3.1. Reaction experiments and their design

Pioneering reaction experiments were designed to investigate melt mobility during melt-mantle infiltration and melt-peridotite reactions under the pressure-temperature (P-T) conditions found in the upper mantle (Daines and Kohlstedt, 1994; Morgan and Liang, 2005; Odling, 1995; Rapp et al., 1999; van den Bleeken et al., 2010; Yaxley and Green, 1998). Also, there are several reaction experiments studying melt-peridotite interaction and pyroxenite-peridotite partial melting in an anhydrous mantle (Borghini and Fumagalli, 2020; Borghini et al., 2017, 2022) in subalkaline systems. More recently, this approach has been applied to alkaline melts (as discussed below). Three types of reaction experiments have been conducted: (1) those simulating metasome+mantle melting (Fig. 3a), (2) those simulating the formation of hydrous metasomes (Fig. 3a, b), and (3) flow-through experiments investigating the compositional change of melts due to reaction as they pass through peridotite (Fig. 3c).

In reaction experiments relevant to mantle melting, the capsule, composed of noble metal(s), generally contains two layers. The lithology of choice for melting (such as metasome, sediment, or basaltic glass) is placed at the bottom of the noble metal capsule, with a layer of either lherzolite or harzburgite above it (see Fig. 3a). A second setup may also be applied, particularly when Si-rich sediments are used whose melt has a high viscosity, which lowers the melt-peridotite reactivity. In this method, the two rocks are intimately mixed by mixing powders (Fig. 3b): the results can be compared to layered experiments, confirming equilibrium where the results of the mixed experiments correspond to the reaction zones in layered experiments (Mallik and Dasgupta, 2012; Wang et al., 2017a).

Characterizing the resultant melt compositions by analyzing quenched materials (former melt) from these experiments is crucial for a comprehensive understanding of the melt composition generated during the reaction. However, this aspect has proven to be the most

challenging, because in alkaline- and volatile-rich systems, rapid and abundant crystal growth occurs during the short quenching period after turning off the heating to the experiment. This growth, which is more problematic with mixed H₂O + CO₂ volatiles (Dasgupta et al., 2007; Pintér et al., 2021), includes both individual crystals and overgrowths on equilibrium crystals. As a result, this quench modification can significantly distort melt compositions (Green, 1976), leaving little glass to analyze. Novel experimental techniques applied in reaction experiments, whether for producing metasomes or melting them, include the calibration and utilization of a rapid-quench piston-cylinder apparatus, along with modified, complex internal capsule designs. Rapid-quench pressure vessels feature additional cooling channels arranged cylindrically around the tungsten carbide core, through which pre-cooled liquid circulates, ensuring a rapid quenching interval (Ezad et al., 2023).

3.2. Reaction experiments simulating metasome + peridotite melting

In order to generate K- and Na-alkaline melts with sufficient quantities of alkalis, P₂O₅, TiO₂, and F, and incompatible elements to explain natural magma compositions, the experimental studies traditionally combined peridotite with hydrous minerals commonly found associated in mantle xenoliths like phlogopite, amphiboles, and apatite (Conceição and Green, 2004; Condamine et al., 2016). Despite these ad hoc modifications, these experiments have struggled to produce the extremely high K₂O and K₂O/Na₂O ratios characteristic of the most alkaline-rich lavas, such as lamproites, kamafugites, ultramafic lamprophyres, and orangites (see Fig. 2a).

A more effective model for generating K- and Na-alkaline melts involves the melting of discrete metasome assemblages within the peridotite (Foley, 1992; Meen et al., 1989). Various metasome types can melt to produce alkaline melts, but there are too few experimental studies on the melting temperatures of these lithologies, on characterizing the resulting melt compositions as well as on constraining the geochemical nature and extent of melt-peridotite interaction. Initial experimental studies focused on mica- and/or K-richrichterite- and pargasite-pyroxenites (Foley et al., 1999; Funk and Luth, 2013; Lloyd et al., 1985; Luth, 1997), and MARIDs (Konzett et al., 1997; Sweeney et al., 1993). These experiments indicate that as long as K-richrichterite is present in the metasome mineral assemblage, the melt has a composition



Fig. 3. The capsule with a schematic illustrations of three types of experimental setup used in reaction experiments. a) Layered setup comprising of sediment or metasome + peridotite. Noble metal capsule is loaded with layers of which the one lithology of choice (metasome, sediment or basaltic glass (1)) is placed in the bottom, and a layer of either lherzolite or harzburgite (2) is placed above; b) Mixed sediment + peridotite (5). In this setup, the two lithologies are intimately mixed; c) flow-through setup, which resemble the layered one with the addition of a melt trap. (3)- a graphite inner capsule; (4)- a noble metal outer capsule; (6)- a vitreous carbon melt trap; (7)- peridotite, and (8)- alkaline melt (glass).

similar to this amphibole (Foley et al., 2022). Similarly, the melting of Ca-amphibole-bearing assemblage leads to melts of nephelinite-melilite composition because pargasite dominantly melts (Foley et al., 1999). There is now a consensus that the melting temperatures of any olivine-

free rocks with abundant hydrous phases lie below that of hydrous peridotite so that melt-peridotite reactions are expected to follow (Ezad et al., 2024a; Foley and Ezad, 2024).

Unfortunately, there is a dearth of experimental studies on the

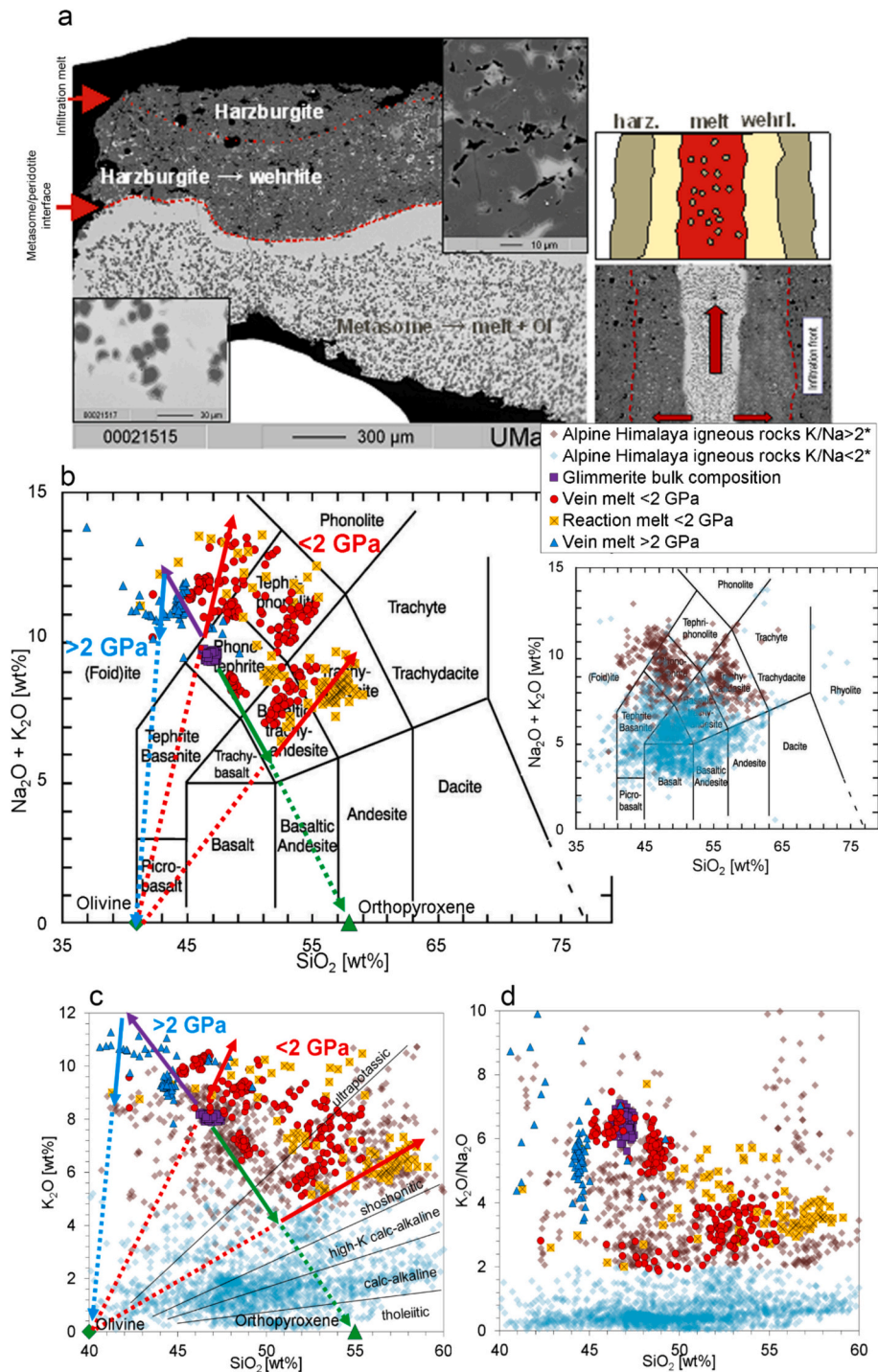


Fig. 4. Detailed presentation of the results of reaction experiments designed to investigate the origin of extremely K-rich melts (Fan et al., 2021; Förster et al., 2017). a) Backscattered electron images of glimmerite-harzburgite reaction experiments performed at 2 GPa. During the reaction experiments, two major processes were observed: incongruent melting of phlogopite from the metasome to produce peritectic olivine, and orthopyroxene digestion by melt-peridotite interaction. Three zones are apparent in the capsules: (1) the metasome is transformed into a mush of Ol + melt; (2) between the original lithologies, an interface has been formed; above the interface is a wehrlitic zone generated by the infiltration of the harzburgite by the melt (melt-peridotite interaction); (3) the uppermost zone is composed of non-metasomatized harzburgite. The processes in the capsule also resemble the formation of veins in the lithosphere and melt-peridotite interaction. b) The final composition of the melts at <2 GPa is a result of the interplay between two processes that change vein melts to reaction melts: (i) olivine crystallization and (ii) orthopyroxene digestion. These drive the melt towards very high K₂O (c), high K₂O/Na₂O (d) at moderate SiO₂ at <2 GPa (red circles), while at >2 GPa, orthopyroxene crystallization follows olivine digestion, leading to low SiO₂ (blue triangles).

reaction between the melts derived from different metasome assemblages and peridotite, whereas theoretical studies have attempted to predict the mineralogical effects of such interactions (Pilet, 2008, 2015; Pilet et al., 2005; Sekine and Wyllie, 1982a, 1982b, 1983; Wyllie and Sekine, 1982).

Recently, a series of reaction experiments investigating the origin of K-alkaline melts has been conducted at temperatures ranging between 1100 and 1450 °C and pressures 1–5 GPa, combining harzburgite with MARID metasome (Förster et al., 2017, 2018). These experiments revealed the existence of two distinct melt compositions within a single charge (Fig. 4a): one derived from the melting of the metasome dominated by the incongruent melting of phlogopite (and amphibole when present), and the other produced by the interaction between this melt and peridotite, controlled by the dissolution of either orthopyroxene (at $P < 2$ GPa) or olivine (at $P > 2$ GPa) (Fig. 4b). Hydrous minerals in the initial metasome, such as amphibole and phlogopite, melt incongruently resulting in the peritectic production of olivine at < 2 GPa, or orthopyroxene and garnet at > 2 GPa (Förster et al., 2017, 2018). This significantly influences the resultant melt composition: at lower pressures, the melt will be rich in silica, whereas at higher pressures the silica content is lower (Fig. 4b). Similarly, melt resulting from the reaction of the metasome-melt with the peridotite is buffered either by Opx or Ol from the peridotite; at lower pressures, this is due to the assimilation of orthopyroxene, accompanied by the crystallization of olivine, whereas at higher pressure the opposite occurs.

The synergetic effect of these two processes - incongruent melting of hydrous minerals and selective digestion of peridotite minerals - leads to the generation of high-silica ultrapotassic melts with SiO₂ contents of up to 60 wt% and K₂O/Na₂O ratios up to 10 that are mildly SiO₂-undersaturated to -saturated at lower pressures. Conversely, at higher pressures, it drives the melt to a lower-silica composition, highly SiO₂-undersaturated which is still ultrapotassic (K₂O/Na₂O ratios up to 10) partly also due to the uptake of Na in clinopyroxene (Fig. 4c, d). In both cases, the MgO content decreases. The ultimate melt composition will have a near-constant SiO₂ concentration at constant pressure but will differ as a function of pressure. This variation in silica saturation is a reminiscence of the pressure-controlled generation of tholeiites versus alkali basalts from depleted and enriched peridotite, as observed in classical experiments by Jaques and Green (1980), in which increased SiO₂-undersaturation and alkalinity correlate with higher pressure (greater depths) and a lower percentage of partial melting.

The compositional differences between direct melts of the metasome and melts resulting from the melt-peridotite reaction also lead to substantial variations in density and viscosity, with the metasome-derived melt being more buoyant and easily extractable than the one produced by the interaction between the melt and peridotite because of the more alkaline composition and higher volatile contents. The trace element composition of these melts is primarily controlled by the mineralogical constitution of the metasome (Foley and Ezad, 2024).

The successful explanation of the production of Na-alkaline melts from peridotitic mantle sources has also proven to be challenging. Alternative approaches have been explored, including volatile-induced melting and the melting of hydrous mantle lithologies. Only two series of reaction experiments combining lherzolite with amphibole-clinopyroxene metasomes (hornblendite) representative of a “sodic” hydrous metasome in the mantle have been conducted (Grützner et al., 2023; Pilet et al., 2008). Again, the incongruent melting of amphibole from the metasome is pressure-controlled resulting in the production of peritectic olivine at < 2 GPa, and orthopyroxene and garnet at > 2 GPa. These melts further change through melt-peridotite interaction, exhibiting a range of compositions from foidite to phonotephrite from pressures of 1 to 4 GPa and temperatures of 1100 to 1300 °C. All resulting melts are alkaline and nepheline normative. At 1 GPa and temperatures exceeding 1100 °C, amphibole controls the melt composition, generating basanites. Between 1000 and 1100 °C, amphibole is destabilized, leading to the formation of phonotephritic melts through decompression

and breakdown products. Increasing pressure gives rise to SiO₂-poorer foidite compositions. In the garnet stability field, the metasome and lherzolite residues transform into wehrlite, meaning that wehrlite formation within the garnet stability field does not necessarily indicate a separate metasomatic process involving reaction with carbonate melts (Yaxley et al., 1991; Rudnick et al., 1993) but may instead be a direct consequence of alkaline melt generation in the mantle (Grützner et al., 2023).

In summary, investigating metasome melting and melt-peridotite interactions provides important pieces of information about the melting behaviour of realistic rock mixtures in the mantle, demonstrating that the melting of mixed source regions involves more than simply producing two types of melts and mixing them. Instead, the reaction process is dynamic and melt compositions are dominantly pressure controlled, influenced by the interplay of incongruent melting of hydrous minerals and selective digestion of peridotite minerals, leading to a complex variation of melt compositions and physical properties. The melt compositions resemble the compositional variations observed in K- and Na-rich lavas from different regions. For example, the variation in K-enrichment is reported in the coeval ultrapotassic, shoshonitic, and mildly K-enriched lavas in the Alpine-Himalayan belt, where the lamproites show the most extreme compositions with ≥ 9 wt% K₂O, while potassium concentration decreases towards shoshonites and high-K-calk alkaline lavas (e.g. Conticelli et al., 2009). Variable extents of metasome melting and melt-peridotite interaction could explain the compositional variation of these coeval lavas.

3.3. Reaction experiments simulating the production of hydrous metasomes

Experimental studies simulating the formation of hydrous metasomes by reaction have thus far predominantly concentrated on potassium-rich systems. In contrast, research on sodium-rich alkaline systems is limited, primarily relying on theoretical considerations derived from empirical data. The emphasis on potassic systems was driven by radiogenic isotope signatures of potassic igneous rocks which appear to require the input of sedimentary rocks in their sources (Nelson et al., 1986; Prelević et al., 2013) so that melts of sedimentary rocks were prioritised in reaction experiments.

In the course of orogenic processes (Fig. 1), the geochemical influence of melts and fluids originating from recycled continent-derived material present in the sediment layer atop the subducting slab on the geochemical composition of arc basalts is well recognized (Currie et al., 2007; Elliott, 2004; Patino et al., 2000; Plank and Langmuir, 1998; Plank, 2014; Tatsumi and Kogiso, 2003) and physicochemical conditions for melting are fairly well-constrained (Hermann and Spandler, 2007; Nichols et al., 1994; Poli and Schmidt, 2002). Beyond fluid-fluxed partial melting, intensive interactions between melts and the mantle peridotite in the sub-arc region can result in the development of potassium-rich metasomes (Prelević et al., 2013 and references therein). This concept is supported by the geochemistry of volcanic associations in heavily metasomatized mantle regions, such as the Alpine Himalayan orogenic belt (Casalini et al., 2022; Chung et al., 2001; Conticelli et al., 2009; Lu et al., 2013; Lustrino et al., 2011; Turner et al., 1996; Wang et al., 2017b) or Variscan orogenic belts (Soder and Romer, 2018). The products of these magmatic associations are characterized by universal enrichment of potassium coupled with the ubiquitous and unambiguous geochemical signature of the upper continental crust: high K₂O up to 12 wt%, ⁸⁷Sr/⁸⁶Sr up to 0.723, εNd as low as -13 as well as highly forsteritic olivine (Fo up to 93%) with δ¹⁸O_{V-SMOW} values up to +11.5 ‰. These orogenic areas are also characterized by the presence of extremely enriched lithospheric mantle exemplified by hydrous mantle xenoliths (Bianchini et al., 2011; Conticelli and Peccerillo, 1989; Dallai et al., 2019, 2022; Downes et al., 2002; Fan et al., 2021). These data collectively establish an organic connection between mantle-derived volcanism and massive continental crust recycling that must have played a

crucial role in the preconditioning of the mantle source along these orogenic belts.

While the reaction between crustal melt and the mantle is an undisputed process, pinpointing the specific segment of the arc architecture where this enrichment occurs, the associated pressure-temperature (P-T) path and the underlying physical and chemical mechanisms remain elusive. This is especially critical as the crustal signature and ultrapotassic geochemical characteristics are rarely demonstrated by typical arc lavas that directly accompany subduction, but are more commonly associated with post-collisional volcanic sequences. One proposed mechanism suggests the accumulation of mixed “cold plumes” beneath the orogenic wedge, consisting of tectonic mélanges originating from deeper subduction channels. According to this model, subducted sediments may be stripped from the subducting slab and ascend into the overlying mantle, thereby transporting fertile subducted crustal materials into the hotter zones of the mantle wedge above the subducting plate (Cruz-Urbe et al., 2018; Marschall and Schumacher, 2012). Alternatively, recent studies suggest the fore-arc mantle as a potential site for this interaction, presenting various scenarios concerning the physical mechanisms involved (Förster et al., 2021; Förster and Selway, 2021; Gülmez et al., 2016; Vigouroux et al., 2008).

The subduction of sedimentary material, potentially containing carbonates and silicates, initiates devolatilization and melting processes, giving rise to fluids and/or melts that metasomatize the overlying mantle (Grove et al., 2012; Poli and Schmidt, 2002; Tatsumi and Kogiso, 1997, 2003). This interaction may involve hydrous silicate melts, aqueous fluids, and supercritical siliceous, carbonatitic, and alkaline

solutions (Kessel et al., 2005; Scambelluri and Philippot, 2001; Tatsumi and Kogiso, 1997; Thomsen and Schmidt, 2008), leading to the formation of hydrous metasomes (Sekine and Wyllie, 1982a, 1982b, 1983; Wyllie and Sekine, 1982). Various micaceous metasomes, including glimmerites, phlogopite-wehrlites, and websterites, likely form through reactions between K-rich liquids from siliciclastic sediments and peridotite, resulting in layered structures and veins (Conticelli and Pecceirillo, 1989; Foley, 1992; Prelević et al., 2013). Conversely, dolomite-bearing phlogopite-wehrlites may arise from reactions with carbonate-rich metasomatic liquids (Ammannati et al., 2016; Gülmez et al., 2023) (Fig. 1).

Several studies have been conducted to simulate the sediment recycling process. Initially, these experiments aimed to replicate the typical geochemical signatures of arc lavas (Cruz-Urbe et al., 2018; Marschall and Schumacher, 2012; Woodland et al., 2018) whereas more recently, there has been a shift in focus towards explaining the production of potassium-rich metasomes (Förster et al., 2019b, 2020, 2021; Förster and Selway, 2021; Rebaza et al., 2023; Zhang et al., 2020). In these experiments, a layer of sedimentary lithology was combined with the peridotite. The reaction of volatile-bearing partial melts of the sediments with peridotite typically results in the production of reaction zones rich in hydrous minerals, with thicknesses ranging from 30 to 1000 μm (Fig. 5). The composition and mineralogy of these reaction zones depend on factors such as the initial ratio of carbonates to silicates, bulk water content, pressure, and temperature. Furthermore, the initial ratio of sediment to peridotite and the viscosity of the melts involved affected the degree to which the reactions continued to

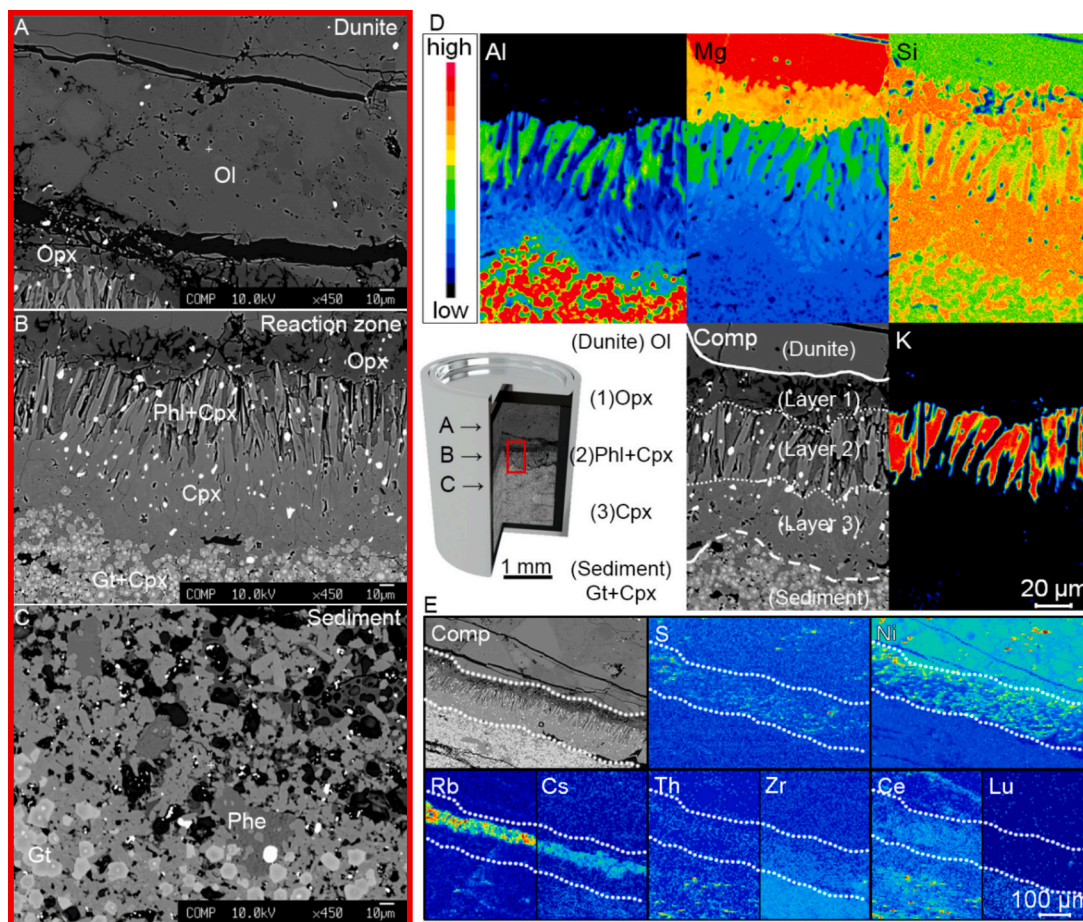


Fig. 5. Reaction experiments producing metasomes by reaction of sediment-derived melts with peridotite (Fan et al., 2021; Förster et al., 2019a). (left) Backscattered electron (BSE) images show the presence of the reaction interface as a bright film layer between peridotite and crustal rocks in a harzburgite-sediment reaction experiment; (right) Closer view (D is a microprobe element map and BSE, E is ICP-TOF) revealing the compositional layering at the reaction interface, formation of the veinlets, the presence of the metasomatic phlogopite and clinopyroxene, and distribution of trace elements (E) in this zone.

completion. Low-viscosity carbonate melts easily travel throughout the experimental capsule (Gervasoni et al., 2017), whereas silica-rich melts may result in only a very thin reaction zone during the duration of an experiment (Wang et al., 2017a, 2017b).

The resulting phases within the reaction zone include phlogopite, amphibole, clinopyroxene, orthopyroxene, and sometimes magnesite and/or dolomite (Förster et al., 2021; Gülmez et al., 2023; Zhang et al., 2020). Carbonates and salts may occur in the reaction zone as well (Chen et al., 2023; Förster et al., 2019a; Wang et al., 2023), probably explaining the abundance of salts in inclusions in diamonds (Weiss et al., 2015). Importantly, in the experiments with increased amounts of carbonates, the formation of immiscible and conjugate carbonatitic and silicic extremely K-rich melts was observed, which flux the mantle to develop hydrous minerals and dolomitic melt (Gülmez et al., 2023). The occurrence of very potent metasomatizing agents, such as conjugate carbonatitic and silicic melts and their potential physical separation, offers a potential for fractionation of several canonical trace element ratios such as Th/La, observed in Si-saturated ultrapotassic lavas (Tommasini et al., 2011). The effect of multiple episodes of peridotite-melt reactions through sequential additions of hydrous-silicic slab partial melts has been also investigated (Rebaza et al., 2023). It was observed that, following the initial formation of olivine-free mica-rich pyroxenites along with amphibole and quartz/coesite in the reaction zone which equilibrated with rhyolitic-hydrous melts, subsequent melt addition led the system to reach a melt-buffered state, where peridotite-melt reactions ceased. In other words, the sediment-derived melt may be transported unchanged through these lithological heterogeneities from the reaction zones. This implies that metasomes formed as products of peridotite-melt reactions in the sub-arc mantle can serve as later-stage melt pathways, allowing infiltrating melts to preserve their geochemical signatures without modification (Foley and Pertermann, 2021), in a similar way to dunite channels aiding in the extraction of MORB from the mantle (Kelemen et al., 1995).

Detailed examination of the geochemistry of the reaction zones have been performed in several recent studies (Förster et al., 2019b, 2020, 2021; Förster and Selway, 2021; Gülmez et al., 2023) revealing their consistent enrichment in K, Ca, Al, and Si. These zones usually consist of three layers sandwiched between the two starting materials: an orthopyroxenite layer at the leading edge of the reaction zone in contact with the depleted peridotite, a phlogopite-clinopyroxenite symplectite layer, and a layer comprised of clinopyroxene/orthopyroxene symplectite (Fig. 5). The majority of potassium is concentrated in the second layer, which also accumulates most of the incompatible trace elements (Fig. 5). The selective incorporation of elements into these metasomatic layers closely mirrors the chemical patterns found in potassium-rich magmas. Experiments of varying durations have provided rough estimates of the growth rate of the metasomatic front, which ranges from 1 to 5 m per thousand years (Förster et al., 2021).

In non-cratonic intracontinental rift environments, hydrous metasomes are considered essential precursors of highly Na-alkaline magmatism (Lloyd and Bailey, 1975; Wass and Roge, 1980). These metasomes are characterized by amphibole-rich assemblages, including hornblende and amphibole-clinopyroxenites, and may result from either the percolation and differentiation of low-degree volatile-rich melts within the lithosphere (Bodinier et al., 1987; Nielson et al., 1987, 1993; Wilshire, 1987), or the accumulation of less refractory or near-liquidus minerals during magma flow (Irving, 1980; Wass and Roge, 1980). Fractional crystallization experiments at lithospheric mantle pressures (0.93–1.5 GPa) starting from a nepheline-normative liquid (Pilet et al., 2010) or orthopyroxene-normative liquid (Nekvasil et al., 2004) demonstrate that amphibole-bearing cumulates similar to hydrous metasomatic veins can be produced by differentiation of any basaltic melt, regardless of whether the melt is alkalic or subalkalic. The critical factor is that the basaltic melt needs to contain approximately 1 wt% H₂O, which is likely for melt produced at a low degree of partial melting from the asthenospheric mantle. A dynamic model (Pilet et al.,

2008) suggests a causal relationship between the generation and digestion of amphibole-rich metasomes. According to this model, the initial melting in the asthenosphere produces precursor metasomatic melts that percolate and differentiate along the lithospheric thermal gradient, modifying it. These metasomatic “cumulates” later contribute to the composition of low-silica alkaline magmas, explaining the observed compositional variations in alkaline volcanoes. Also, melt-peridotite reaction plus dilution explains the compositional continuum observed in alkaline volcanoes.

In cratonic regions, MARID and PIC metasomes are generated through multiple episodes of low-degree mantle melting, which can incorporate rare components into the source regions of later magmas (Fitzpayne et al., 2018, 2019). This is particularly relevant for diamond-bearing rocks such as kimberlites, ultramafic lamprophyres and lamproites found in the ancient cores of continents (Tappe et al., 2007, 2008, 2016). The ultimate origin of these metasomatic assemblages and the K-rich liquids generating them remains puzzling (Fitzpayne et al., 2018, 2019). Viable models suggest that they form either by pervasive metasomatic alteration of peridotites, based on incompatible element fractionation and mineral compositions similar to metasomatized mantle peridotites (PIC), or by magmatic processes, a conclusion based on the layered textures (MARID) and the occurrence of rare composite xenoliths (MARID; Waters et al., 1989). Assemblages similar to MARID have been produced in experiments in which geochemically depleted peridotite (harzburgite) was reacted with a hydrous carbonate melt at 5 GPa pressure (Pintér et al., 2021). The reaction zone was rich in clinopyroxene but also contained phlogopite and K-richrichterite. Regardless of their origin, both metasome types are considered to be precursory to mafic alkaline magmatism and inevitable ingredients in the source of mantle-derived potassic magma compositions like kimberlites, lamproites, orangeites and ultramafic lamprophyres (Tappe et al., 2007, 2008, 2016, 2023).

To sum up, hydrous metasomes are generated through a complex interplay of geological processes involving subduction, sediment recycling, and mantle metasomatism. Future experimental studies should focus on sodium-rich alkaline systems to understand the conditions and processes that lead to the formation of amphibole-rich metasomes. This will help bridge the knowledge gap and provide a more comprehensive understanding of metasomatic processes across different geochemical environments.

3.4. Flow-through reaction experiments

A less commonly employed method in reaction experimentation is the flow-through experiment, wherein a melt trap is positioned at the opposite end of the capsule to the melt (Fig. 2c). In this setup, the initial pore space in the melt trap acts as a suction pump, drawing melt through the peridotite. Foley and Pertermann (2021) utilized this configuration to explore the extent of the reaction between a lamproite melt and peridotite as it passes through. This method offers the advantage of analyzing the quenched melt collected in the trap to determine the melt composition after its reaction with the peridotite. It was observed that the initial lamproite melt experienced a significant loss of K₂O due to phlogopite crystallization via reaction along channels in the peridotite. Consequently, it was inferred that lamproites found at the surface likely did not traverse normal peridotite, indirectly suggesting that lamproitic melts are improbable to originate from a source abundant in peridotite but rather from one dominated by phlogopite-rich metasome.

3.5. Outlook

Reaction experiments hold promise in elucidating the origin of hydrous metasomes themselves, as well as the composition of melts and rocks resulting from the reaction of peridotites with metasome-derived melts. The progression in tracing the origin of alkaline melts involves answering several consecutive questions: (1) What is the diversity of

mineral assemblages in hydrous metasomes, and how are they distributed in different tectonic settings? (2) What is the composition of melts generated from these metasome assemblages? (3) To what extent do these melt compositions react with peridotite, and how do their compositions evolve?

The fundamental difference in terms of experimental planning is whether the melt is produced in sufficient abundance in experiments to permit its chemical analysis. If it is not, then results may be relevant to questions 1 and 3; if it is, then results can help to answer questions 2 and 3. In the last few years, there have been several experimental studies of the melting of hydrous metasome assemblages (Funk and Luth, 2013; Foley et al., 2022; Foley and Ezad, 2024), but the scope of assemblages known from xenoliths is large and many remain unstudied in experiments. These can be investigated separately or as part of layered reaction experiments, and we need more, particularly those incorporating accessory phases such as apatite and different Fe-Ti-oxides. Where the proportion of melt is small, the melt is often used up in experiments, but these are useful to identify reaction products that may resemble hydrous metasomes known from xenoliths (e.g. Förster et al., 2019b; Pintér et al., 2022). Reaction with melts intermediate in composition between carbonatite and silicate has been shown to produce metasomes with more garnet and Fe-Ti-oxides (Gervasoni et al., 2017; Pintér et al., 2022), whereas reaction with hydrous carbonatite produces more clinopyroxene together with phlogopite and K-rich feldspar (Pintér et al., 2022).

In experiments in which melt is abundant and survives the reaction experiment, the melts derived from different sediments and mantle rocks can be studied, directly addressing question 2 above, and the effect of reaction on the evolving melt composition can be assessed as long as quenching issues can be solved or circumvented so that the melt composition can be effectively determined. Here, progress should be facilitated by the proliferation of recently developed rapid-quench piston-cylinder apparatuses (Ezad et al., 2023). Isolation of the melt in melt traps consisting of fine-grain diamond or amorphous carbon improves the quenching behaviour of melts and can be used to investigate melt evolution in flow-through experiments (Foley and Pertermann, 2021).

The primary challenge facing experimental studies of hydrous metasomes currently is their considerable mineralogical diversity compared to the relative simplicity of peridotites. This underscores the need for more experiments on additional melt source rocks and their reaction with peridotites: the story about the reaction of melts from hydrous metasomes with mantle peridotites has just begun.

4. Conclusions

1. Metasomatism of the mantle results not only in the addition of hydrous minerals to peridotite but also in many ultramafic rocks that cross-cut mantle peridotite. These are referred to as “hydrous metasomes”, consisting of veins and dykes that are particularly rich in mica and amphibole combined with anhydrous peridotitic minerals, situated within the peridotite.
2. Melting of metasomes and the interaction of melts derived from them with mantle peridotite may explain the generation of Na- and K-alkaline melts as an alternative to the homogeneous mantle model.
3. The melting temperatures of metasome assemblages are consistently below that of peridotite; the melt produced from these assemblages is extremely alkaline and very reactive with the surrounding peridotite, and undersaturated either in orthopyroxene (at pressures <2 GPa) or olivine (at pressures >2 GPa).
4. An important emerging result is that the melting of mixed source regions is not simply a question of producing two melt types and mixing them; the melt produced in the rock with the lower melting temperature reacts with the second rock, initially at temperatures below its own melting temperature. This changes the mineralogy of the host and modifies the melt composition, which takes up some of the host-rock components

5. Reaction experiments have shown that minerals can occur in reaction zones that would not be stable in either rock alone, such as salts (Förster et al., 2019a).
6. Hydrous metasomes universally comprise minerals that always melt incongruently (amphibole and phlogopite), immediately producing peritectic phases that substantially change the resulting melt composition.
7. How hydrous metasomes are formed within the mantle remains poorly understood. In the case of sediment recycling, it is important to improve the constraints on which mineral assemblages result from the recycling of different sediments and what the melting temperatures of these assemblages are as a function of pressure.
8. Future experimental studies need to be designed to delineate the compositional variability produced by the melting of hydrous metasomes in detail. They will need to outline which reactions occur between the melts of olivine-free ultramafic rocks and surrounding peridotites, which hybrid melts form by the melting of the metasome-rich mantle, and how similar these melts are to lavas seen at the surface in terms of major, trace element geochemistry, as well as in their olivine geochemistry.
9. Finally, the kinetics of reactivity of metasome-derived melt with peridotite and the melting mechanisms need to be thoroughly investigated.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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