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Invited review article

Element recycling from subducting slabs to arc crust: A review

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ABSTRACT

Subduction zones not only return oceanic lithosphere into the mantle, but are also sites where chemical components are transferred from the downgoing plate back to the surface in arc crust and, to a lesser extent, fore-arc and back-arc basins. Understanding of subduction-zone processes has evolved significantly over a relatively brief 40-year research history, thanks to combined insights from experimental petrology, geophysics, numerical and thermodynamic modelling, arc magma geochemistry and studies of high- and ultrahigh-pressure metamorphic rocks. Early models considered aqueous fluids produced by metamorphic devolatilisation of the slab to be responsible for directly transferring chemical components of the slab into the overlying mantle wedge, as well as fluxing melting of the mantle wedge to produce arc basalt. Subducting crustal rocks were considered too cold to melt under most circumstances. However, the latest generation of thermal modelling combined with improved understanding of the chemistry and phase petrology of subduction-zone fluids and melts indicates that conditions for deep slab melting are likely met in subduction zones, provided that free fluid is available at sub-arc depths.

We outline a model to explain element transfer out of subducting slabs that involves serpentinite subduction and slab partial melting. Serpentinite is likely to comprise part of the subducting slab, either as downgoing oceanic lithosphere that was hydrated at, or near, the seafloor, or as down-dragged fore-arc mantle wedge that was initially hydrated at shallow levels by aqueous fluids emanating from underthrust crustal rocks. Slab coupling with convecting asthenospheric mantle at sub-arc depths leads to slab heating and devolatilisation of deep slab serpentinite and/or hydrated mélange atop of the slab. Interaction between these fluids and coesite–phengite eclogite at the top of the slab produces hydrous slab melts, which then migrate out of the slab to ultimately contribute to arc magma generation. In this scenario hydrous slab melts dominate element transfer from the slab to arc magmas, although serpentinites (and/or related hybrid mélange rocks) are the initial source of H_2O and some trace elements (e.g., B, Cl, As, and Sb). This model conforms to petrological and geophysical constraints on deep subduction conditions, and in general is consistent with the geology of blueschist-and eclogite-facies terranes and key geochemical and isotopic features of arc lavas.

Contents

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1. Introduction

Plate tectonics provides a unifying theoretical framework from which we can understand geological phenomena as diverse as mantle differentiation, the evolution of continents, oceans and atmosphere, and the global distribution of earthquakes, volcanos, metalliferous ore deposits and hydrocarbon reservoirs. From this perspective, plate tectonics has allowed proliferation of life on Earth and the sustenance of modern societies. A fundamental component of the plate tectonics model is the subduction of oceanic lithosphere into the mantle at convergent plate margins. This process ensures a transient surface residence (currently <0.2 b.y.) of oceanic lithosphere, but throughout the Phanerozoic (and possibly back to the Archean; van Hunen and Moyen, 2012) has played a crucial role in growth of new continental crust, which has much greater preservation potential (mostly >1 b.y.). The recycling of elements from the subducting plate back to the overlying crust, atmosphere and oceans is arguably the most important of geochemical cycles on Earth (Fig. 1). It is well recognised that relatively oxidised and volatile-rich crustal materials – and possibly hydrated mantle rock – are drawn into subduction zones and undergo metamorphic and chemical alteration at depth. The fluids and/or melts released from subducting slabs play a crucial role in the generation of arc magmas and, ultimately, new continental crust (e.g., Taira et al., 1998; Tatsumi and Eggins, 1995), whereas residual slab materials continue descending and ultimately influence the chemical composition of the deep mantle. Portions of ancient slabs may subsequently form discrete source materials for intraplate basaltic magmatism (e.g., Bebout, 2013; Hofmann, 1997), thereby completing the crustal recycling process that begins at subduction zones.

Understanding subduction zone processes has been the focus of intensive research effort over the last few decades, much of which is summarised in review articles based on the nature of fluid phases liberated from subducted slabs (Hermann et al., 2006; Manning, 2004; Scambelluri and Philippot, 2001; Schmidt and Poli, 2003) or the nature of metamorphic/metasomatic processing of slab materials during subduction (Bebout, 2007, 2013). This paper presents a status update of research on subduction zones with a view to development of a holistic model for chemical cycling from the subducting slab to the arc crust. To set the scene, we first present a short review of historical progress of research in the field, and then we outline the major inputs and outputs of subduction zones. The focus of the paper examines the physical and chemical processing of subducted slabs and the nature of slab-derived fluid phases, as constrained from studies of natural high pressure (HP) and ultra-high pressure (UHP) metamorphic rocks, experiments, numerical simulations and geophysical studies. We cannot comprehensively review the entire, ever-growing scientific literature on these topics; rather, we focus on what we regard to be the most important finding and ideas in the field, with hope that this approach will stimulate new research directions that will further expand and refine our understanding of subduction-zone processes.

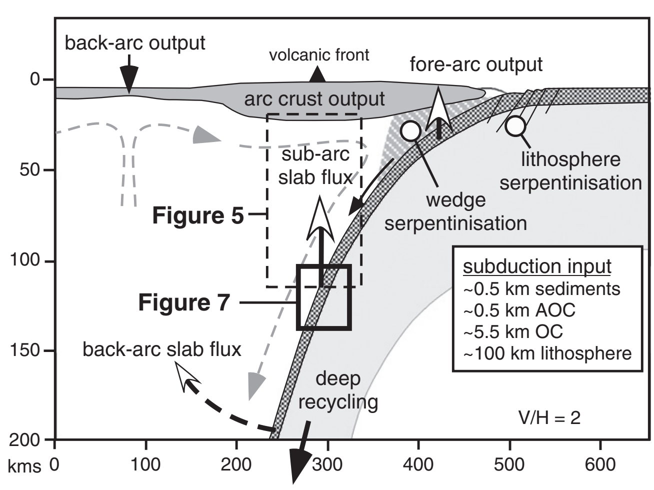

Fig. 1. Cartoon cross section of an intra-oceanic subduction system showing major slab inputs, fore-arc, arc and back-arc outputs, and potential sites of serpentinite formation. AOC = altered oceanic crust, OC = oceanic crust.

2. A brief historical overview

The landmark achievement of the Asilomar Penrose Conference in 1969 was the synthesis of the modern plate tectonic model (Dickinson, 1970). This new theory unified data and observations on seafloor spreading, continental drift, ophiolite emplacement, orogenic blueschist/eclogite belts, accretionary complexes, and the global distribution of seismicity and arc volcanism. Importantly, the new model incorporated the concept of plate subduction on the global scale and recognised Wadati–Benioff seismic zones extending beneath volcanic arcs as the physical expression of the subducting lithosphere descending into the mantle (Dickinson, 1970; Isacks et al., 1968). Although the spatial association between volcanic arcs and the downgoing plate was clear, understanding their genetic relationship presented a scientific challenge that, in many respects, persists to the present day. The burgeoning of high pressure experimental petrology in late 1960s and early 1970s allowed researchers to investigate previously unobtainable deep Earth conditions and processes. Experimentalists initially proposed partial melting of mafic eclogite as the direct source of 'calc-alkaline' series arc magmas (Green and Ringwood, 1968; see also Marsh and Carmichael, 1974). However, this model was inconsistent with the relatively cold geothermal gradients of subduction zones as indicated from geophysical modelling (Oxburgh and Turcotte, 1971) and thermobarometric studies of blueschist belts (Ernst, 1973), and a mismatch between the compositions of arc magmas and experimentally-derived high-pressure melts of subducted lithologies (Stern and Wyllie, 1973). The apparent paradox of arc magma generation in relatively cold mantle environments was resolved through the recognition that subducting plates contain significant volatiles (particularly H_2O), which could be released by metamorphic devolatilisation reactions during subduction (Ringwood, 1974; Wyllie, 1973). The liberated fluids then flux melting of the slab or overlying mantle wedge to produce arc magmas (e.g., Kushiro, 1973).