The fate of subducted sediments: A case for backarc intrusion and underplating

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ABSTRACT

Subduction of oceanic and continental sediments into the mantle is fundamental to the geochemical evolution of Earth. Using thermal-mechanical models, we examine the dynamics of sediments that are subducted below continental lithosphere. Owing to their low density relative to the mantle, model sediments detach from the subducting plate at ~100 km depth. With ongoing subduction, a subhorizontal sediment plume develops and intrudes the continental lithosphere. This occurs for a wide range of sediment densities and rheologies, suggesting that sediment detachment may be important for regions where the subducted sediment thickness is larger than ~350 m. In these areas, a reservoir of sediments may be found in the shallow backarc mantle. In contrast to models of sediment transport to the deep mantle, the detachment model predicts chemical and mechanical interactions between the sediments and backarc mantle lithosphere and a shallow sediment source for arc and backarc magmas.

Keywords: subduction zones, numerical models, sediment transport, volcanic arcs.

INTRODUCTION

Subduction zones are key conduits by which eroded continental crust and oceanic sediments enter the mantle. Primary evidence for sediment subduction is the anomalously small accretionary complex at most subduction zones (von Huene and Scholl, 1991). Crustal material may also be added to the mantle through tectonic erosion of the overriding plate, as indicated by margin truncation and forearc subsidence (von Huene and Scholl, 1991; Clift and Vannucchi, 2004). While some subducted sediment may accrete at mid-crustal depths (von Huene and Scholl, 1991), there is now abundant evidence that a significant volume is carried into the mantle. Trace element and isotope signatures of volcanic arc magmas, including ^{10}Be and ^{207}Pb, require the involvement of subducted sediments (e.g., Morris et al., 1990; Plank and Langmuir, 1993; Elliott et al., 1997). At a number of subduction zones, a subducted sediment signature has also been identified in backarc magmas, primarily from Sr, Nd, Pb, and Th isotopes (e.g., Cousens et al., 1994; Ryan et al., 1995; Turner and Foden, 2001; Fretzdorff et al., 2002; Ishizuka et al., 2003).

Whereas sediment subduction to depths of arc magma genesis is well documented, the fate of sediments beyond this point is poorly constrained. Most conceptual models assume that sediments are transported to depth with the subducting plate and stored or convectively dispersed in the upper mantle (e.g., Weaver, 1991). Conversely, recent numerical and analog modeling studies indicate that buoyant material, including sediments, may separate from the subducting plate at shallow depths (e.g., Gerya and Yuen, 2003; Boutelier et al., 2004). Knowing the fate of subducted sediments is critical for understanding the chemical evolution of Earth, as sediment subduction is a fundamental mechanism of mantle refertilization. In this study, we use numerical models to investigate the dynamics of sediments that are carried to mantle depths at a subduction zone.

NUMERICAL MODEL FORMULATION

The two-dimensional, plane strain, upper mantle scale numerical models address the subduction of an old (>70 Ma) oceanic plate and sediments beneath continental lithosphere (Fig. 1; see also the GSA Data Repository[1]). Convergence between the two plates at 5 cm/yr is kinematically imposed along the oceanic model boundary. Within the model domain, the dynamics are driven by the far-field boundary conditions and by buoyancy forces associated with thermal and compositional density variations. The coupled thermal-mechanical evolution of the system is calculated using arbitrary Lagrangian-Eulerian finite element techniques. All materials have a viscous-plastic rheology and temperature-dependent density. Frictional-plastic deformation uses a Drucker-Prager yield criterion with strain softening. When the state of stress is below plastic yield, deformation is viscous with an effective viscosity based on laboratory-derived flow laws.

The 2 km sediment layer is designed to deliver a constant sediment flux to the subduction zone. The model sediment is interpreted to be dominantly terrigenous with a small pelagic component. To avoid the complexity of computing phase transformations, sediments have a density consistent with felsic continental crust at ultrahigh-pressure (UHP) conditions (>2.6 GPa) and flow viscously according to a wet quartzite dislocation creep flow law (see GSA Data Repository[1]).

NUMERICAL MODEL RESULTS

Figure 2 shows the evolution of the reference model ($\Delta\rho = \rho_{mantle} - \rho_{sed} = 550$ kg/m^3 at 800 °C). Initially, sediments accrete in the trench region, but with continued convergence, sediments begin to bypass the accretionary complex. By 24 m.y., a well-developed subduction channel has formed in which sediments are carried to ~100 km depth. As sediments enter the mantle below the continental lithosphere, they detach from the subducting plate in a Rayleigh-Taylor-like instability, owing to their positive buoyancy relative to the surrounding mantle. The detached sediments first accumulate in the mantle wedge corner. Later (>36 m.y.), the detached sediments are expelled laterally, forming a horizontal plume of material that intrudes the continental mantle lithosphere. Intrusion occurs where lithosphere strength is decreased owing to high temperatures, and thus lithosphere can be displaced by the buoyant sediments. In addition to injecting sediments into the shallow backarc, this process mechanically perturbs the lowermost continental lithosphere, causing it to delaminate and sink because it is cool and dense.

[1]GSA Data Repository item 2007275, supplementary information on the numerical modeling approach, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

CONTROLS ON SEDIMENT DYNAMICS

The behavior of subducted sediments depends on the competing effects of sediment buoyancy and viscous entrainment by the subducting plate. Where buoyancy exceeds entrainment, sediments detach from the subducting plate. Sediment buoyancy scales with the density difference between sediments and mantle, while entrainment depends on sediment rheology. We have therefore carried out a series of numerical experiments to constrain sediment dynamics as a function of density and rheology (Fig. 3).

At UHP conditions, both sediment density and rheology are poorly known. Density can be increased by composition (e.g., increased pelagic sediment or mafic mineral content) and UHP phase changes. Effective viscosity can be decreased by compositional changes (e.g., higher carbonate or volatile/water content), metamorphism, and partial melting. Conversely, drier, more mafic materials or materials with a nonnegligible activation volume for creep (assumed to be negligible in the reference model) will increase the viscosity. Given the uncertainties, the effects of variations in density and rheology were studied by considering sediment densities of 2800–3300 kg/m^3 and by scaling the reference wet quartzite effective viscosity by a factor f, where 0.1 < f < 50.

The results (Fig. 3) demonstrate two regimes (detachment and subduction) where sediments either detach or remain attached to the subducting plate. For sediments with a rheology of wet quartzite or weaker (f ≤ 1), sediment density provides the primary control, and detachment occurs when $\Delta\rho \geq 100$ kg/m^3. At smaller $\Delta\rho$ or as sediment viscosity increases (particularly for f ≥ 5), entrainment by the subducting plate

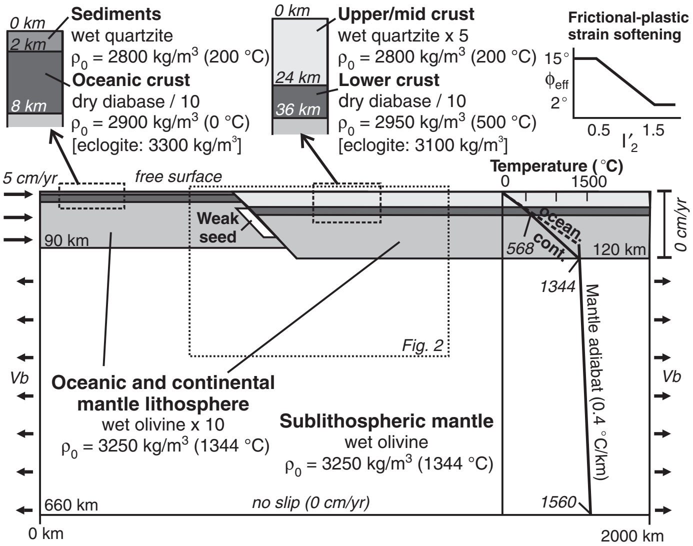

Figure 1. Initial design of the two-dimensional model. Oceanic lithosphere is introduced through the left boundary at 5 cm/yr, and a small sublithospheric mantle outflux (*Vb*) maintains mass balance. Frictional-plastic deformation with strain softening follows a Drucker-Prager yield criterion, with an effective internal friction angle (ϕ_{eff}) that decreases with cumulative strain (I'_2) (upper right). Viscous deformation is based on laboratory-derived flow laws for wet quartzite, dry diabase, and wet olivine. All materials have a temperature-dependent density with thermal expansion coefficient 3×10^{-5} K^{-1} and reference density (ρ_0) at the temperature indicated. The oceanic crust and lower continental crust undergo a phase change to eclogite at high pressures and temperatures. The top and basal boundaries are 0 and 1560 °C respectively, incoming oceanic lithosphere enters with an oceanic geotherm, and all other boundaries are insulating. The initial laterally averaged continental and oceanic geotherms are shown. See GSA Data Repository [see footnote 1] for more information and larger figure.

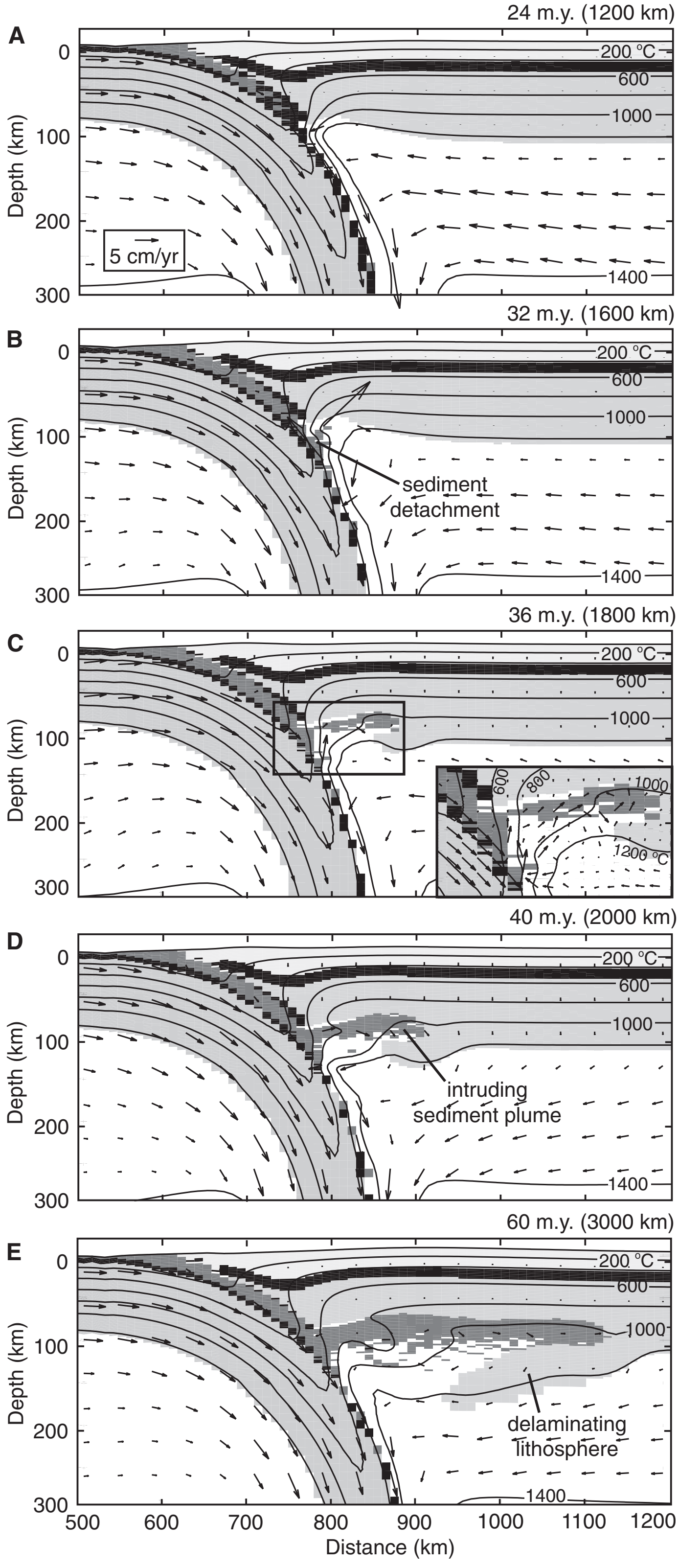

Figure 2. Evolution of the reference model ($\Delta\rho = \rho_{mantle} - \rho_{sed}$ = 550 kg/m^3). The elapsed time and total convergence since the start of the model (subduction initiation) are given at the top right. Gray scales are materials defined on Eulerian elements and correspond to those in Figure 1 (black denotes eclogitized oceanic crust). Medium gray is subducted sediment and detached sediment plume.

dominates, and sediments are subducted to depth. These estimates can be regarded as upper bounds because natural detachment in the form of three-dimensional instabilities may be more efficient (i.e., occur at smaller Δρ and larger f) than predicted by the two-dimensional models.

At many subduction zones, the sediment thickness entering the trench is less than the 2 km used in the models (Clift and Vannucchi, 2004). We cannot accurately resolve very thin sediment layers in the models and therefore provide a first-order estimate of the effect of thickness by scaling the above results assuming that the ratio of buoyancy to entrainment forces is proportional to the detaching material volume. The critical length scale is sediment thickness, as variations in the downdip length of the detaching unit have a similar effect on buoyancy and entrainment forces. The results (Fig. 3) indicate that sediments with a wet quartzite rheology and UHP density of ~2800 kg/m^3 will detach if they are >350 m thick.

Sediment behavior is influenced by a number of other factors. For a subduction rate greater than 5 cm/yr, the magnitude of entrainment will in general increase, and a greater buoyancy (i.e., larger Δρ or volume) would be required for detachment. Sediment dynamics also depend on the mantle properties above the subducting plate. In the models, sediment detachment occurs as sediments enter the sublithospheric mantle because shallower detachment is prevented by the high viscosity of the cool, strong continental lithosphere. If the overriding lithosphere were thinner (e.g., oceanic lithosphere or hotter continental lithosphere), sediment detachment would occur at a shallower depth. Furthermore, hydration of the mantle wedge by water released from the subducting plate may reduce mantle viscosity and enhance sediment detachment. However, mantle hydration sufficient to form serpentinized mantle also decreases the mantle density by 100–300 kg/m^3 (e.g., Gerya and Yuen, 2003), thereby reducing the propensity for detachment. Mantle hydration may also result in small-scale flow, including the formation of mantle plumes that upwell from the subducting plate at 50–200 km depth, which would likely assist in sediment detachment (Gerya and Yuen, 2003; Gerya and Stockhert, 2006; Gorczyk et al., 2006).

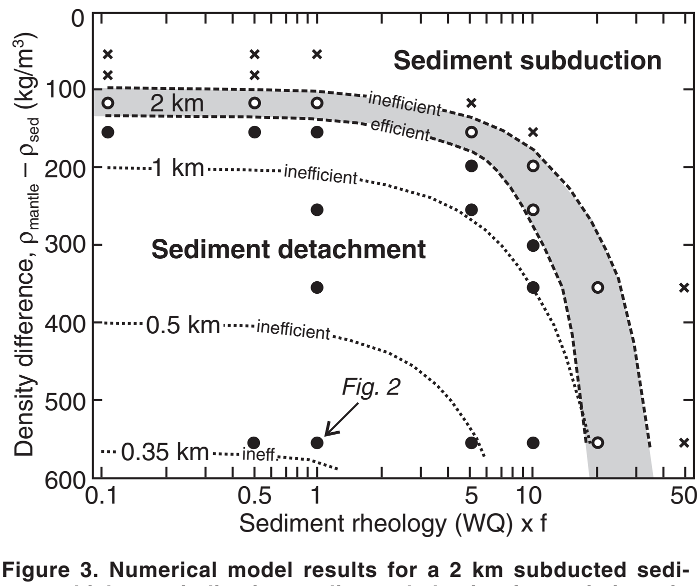

Figure 3. Numerical model results for a 2 km subducted sediment thickness indicating sediment behavior for variations in sediment density and rheology (as a multiple of the reference wet quartzite [WQ] effective viscosity). Solid circles are models with efficient sediment detachment from the subducting plate. Crosses show models where sediments are subducted to depth. Between the two regimes, detachment is inefficient (open circles) and occurs over a wide depth range, resulting in sediment accumulation in the mantle wedge corner and reduced backarc intrusion. Dotted lines are the approximate boundaries between the sediment detachment and subduction regimes for variations in sediment thickness.

IMPLICATIONS FOR SUBDUCTION PROCESSES AND MANTLE COMPOSITION

The two end-member behaviors of subducted sediment (Fig. 4) provide a framework for the associated implications for subduction zone structure, geochemistry and rheology, and the larger-scale problem of mantle refertilization. In the standard sediment subduction model (Fig. 4A), sediments remain on top of the subducting plate. Volcanic arc magma geochemistry indicates that sediments are added to the magma source as a melt, on the basis of efficient recycling of Th, Be, and Rb (Elliott et al., 1997; Johnson and Plank, 1999). This constraint has been used to infer the temperature of the subducting plate surface below the arc, i.e., this temperature must exceed the sediment wet solidus (≥750 °C) (Johnson and Plank, 1999; Schmidt et al., 2004). Through sediment melting, incompatible elements are transported into the arc magma source region. The remaining sediments are carried deeper, where further melting introduces a siliceous melt to the mantle wedge. Geochemical evidence of a sediment-sourced melt contribution in backarc magmas thus requires upward transport of the sediment signature across the mantle wedge from slab depths of 200–300 km. Residual sediment not incorporated into arc

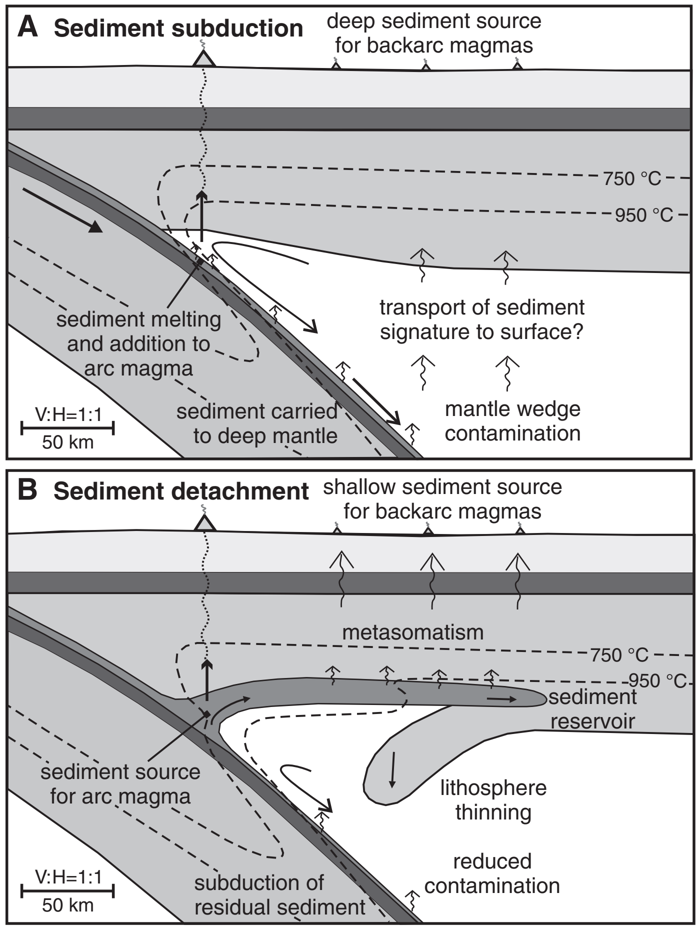

Figure 4. End-member models for subducted sediment dynamics and implications. A: Sediment subduction. Sediments remain attached to the subducting plate and are carried to depth. B: Sediment detachment. Sediments buoyantly detach from the subducting plate and intrude the overriding plate lithosphere considered here to be continental and not extending. The thickness of sediments intruding the lithosphere is based on model results (Fig. 2) but may be thinner and less uniform in natural examples. Backarc magmas for a non-extensional backarc may record sediment-related metasomatism of the lithosphere. In the case of backarc spreading, sediments may be entrained in flow toward the spreading center, giving an enhanced sediment signal in backarc magmas.

or backarc magmas continues downward with the subducting plate and is a putative source of chemical enrichment for the deep mantle.

The opposite model holds that sediments detach from the subducting plate at shallow mantle depths (Fig. 4B). By implication, the depth at which sediment is melted prior to addition to the arc magma source could be shallower than the subducting plate surface. This relaxes the constraint that the plate surface exceed 750 °C because melting occurs higher in the hotter mantle wedge. As oceanic basalt and sediments have similar wet solidus temperatures, a cooler slab surface could explain the lack of evidence for melting of subducted oceanic crust, except under unusual circumstances (e.g., George et al., 2005). A cooler thermal structure also has significant consequences for the stability of hydrous phases within the subducting plate, dehydration melting, and hydration of the backarc mantle. In addition, sediment detachment may contribute to cooling of the mantle wedge corner through advection of cool sediments and by inhibiting the flux of hot sublithospheric mantle into the corner.

Most subducted sediment detaches at shallow depths, producing a reservoir of crustal material and oceanic sediments in the shallow backarc mantle, which may be seismically detectable. Remaining sediment would be carried to depth and act as a diminished source for mantle fertilization. Sediment intrusion into the backarc lithosphere will mechanically and chemically affect the shallow backarc. Intruded sediments act as a destabilizing agent by perturbing the lithosphere and by introducing a rheologically weak layer within the lithosphere (Fig. 2). This causes gravitationally driven lithosphere removal, resulting in thinned mantle lithosphere. Breakdown and melting of the sediments also metasomatize the backarc lithosphere. Under hydrous conditions, pelitic sediments melt at ~750 °C, whereas if backarc conditions were dry, sediment melting would be associated with phengite breakdown at 950 °C (Schmidt et al., 2004). As shown in Figures 2 and 4, this temperature is predicted to occur more than 100 km behind the volcanic arc. Sediment breakdown will release water and incompatible elements to the overlying backarc lithosphere, where ensuing melting would carry this signature to the surface. Furthermore, as sediments are a source of potassium and incompatible elements, ultrapotassic magmatism, including lamproites (e.g., Nelson, 1992), may be associated with shallow backarc sediment intrusion. If the model prediction of a shallow backarc sediment reservoir is correct, an important question is whether sediments can pass through the high-temperature volcanic arc region into the backarc without undergoing wholesale melting and incompatible element loss.

Backarc magma geochemistry at numerous subduction zones indicates the involvement of subducted sediments, requiring that at least some sediments bypass the volcanic arc (e.g., Cousens et al., 1994; Ryan et al., 1995), but the origin depth of the sediment signature is currently not well constrained. Future studies on the backarc magma sediment source, as well as seismic tomography data and compositional studies of backarc mantle xenoliths, are needed to differentiate between the two end-member models.

CONCLUSIONS

Numerical models indicate that, contrary to most conceptual models, buoyant subducted sediments may detach from the subducting plate at ~100 km depth and either intrude or underplate the backarc lithosphere. Sediment detachment occurs for a broad range of conditions, and the resulting horizontal sediment plume intrudes several hundred kilometers laterally, thereby mechanically destabilizing and thinning the lithosphere (Fig. 4). This behavior predicts (1) reduced sediment refertilization of the deep mantle in comparison with the standard subduction model, and (2) a potential source of compositional enrichment of the shallow mantle, which may lead to backarc hydration and metasomatism, explaining surface magmatism that contains a sedimentary signature in its source.

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