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From oceanic plateaus to allochthonous terranes: Numerical modelling

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ABSTRACT

Large segments of the continental crust are known to have formed through the amalgamation of oceanic plateaus and continental fragments. However, mechanisms responsible for terrane accretion remain poorly understood. We have therefore analysed the interactions of oceanic plateaus with the leading edge of the continental margin using a thermomechanical–petrological model of an oceanic-continental subduction zone with spontaneously moving plates. This model includes partial melting of crustal and mantle lithologies and accounts for complex rheological behaviour including viscous creep and plastic yielding. Our results indicate that oceanic plateaus may either be lost by subduction or accreted onto continental margins. Complete subduction of oceanic plateaus is common in models with old (>40 Ma) oceanic lithosphere whereas models with younger lithosphere often result in terrane accretion. Three distinct modes of terrane accretion were identified depending on the rheological structure of the lower crust and oceanic cooling age: frontal plateau accretion, basal plateau accretion and underplating plateaus.

Complete plateau subduction is associated with a sharp uplift of the forearc region and the formation of a basin further landward, followed by topographic relaxation. All crustal material is lost by subduction and crustal growth is solely attributed to partial melting of the mantle.

Frontal plateau accretion leads to crustal thickening and the formation of thrust and fold belts, since oceanic plateaus are docked onto the continental margin. Strong deformation leads to slab break off, which eventually terminates subduction, shortly after the collisional stage has been reached. Crustal parts that have been sheared off during detachment melt at depth and modify the composition of the overlying continental crust.

Basal plateau accretion scrapes oceanic plateaus off the downgoing slab, enabling the outward migration of the subduction zone. New incoming oceanic crust underthrusts the fractured terrane and forms a new subduction zone behind the accreted terrane. Subsequently, hot asthenosphere rises into the newly formed subduction zone and allows for extensive partial melting of crustal rocks, located at the slab interface, and only minor parts of the former oceanic plateau remain unmodified.

Oceanic plateaus may also *underplate* the continental crust after being subducted to mantle depth. (U)HP terranes are formed with peak metamorphic temperatures of 400–700 °C prior to slab break off and subsequent exhumation. Rapid and coherent exhumation through the mantle along the former subduction zone at rates comparable to plate tectonic velocities is followed by somewhat slower rates at crustal levels, accompanied by crustal flow, structural reworking and syndeformational partial melting. Exhumation of these large crustal volumes leads to a sharp surface uplift.

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1. Introduction

The oceanic crust (which covers 60% of the Earth surface) is not homogenous, but contains significantly thicker crust than norm. About 10% of the present day's ocean floor is covered by anomalous thick crust typified by a high bathymetric relief, low upper crustal velocities, lack of clear magnetic lineations and steep margins (Nur and Ben-Avraham, 1982; Schubert and Sandwell, 1989). Although the origin of these oceanic rises remains controversial most of them are thought to represent extinct arcs or spreading ridges, detached continental fragments, volcanic piles or oceanic swells (e.g. Stein and Ben-Avraham, 2007 and references therein).

Regardless of their origin, these oceanic features may collide with continental margins to form collisional orogens and accreted terranes in places where oceanic lithosphere is recycled back into the mantle (Taylor, 1966; Ben-Avraham et al., 1981; Taylor and McLennan, 1985; Schubert and Sandwell, 1989). Hence, it has been argued that the rapid growth of some major segments of the continental crust is related to accretionary processes by which new material is added to the continental crust (e.g. Coney et al., 1980; Jones et al., 1982; Reymer and Schubert, 1986; Stein and Goldstein, 1996; Dobretsov et al., 2004). Large areas in western North America (Jones et al., 1977; Coney et al., 1980; Monger et al., 1982), Alaska (Jones and Silberling, 1986), and

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the Caribbean (Kerr et al., 1997; Kerr and Tarney, 2005) are believed to have formed through extensive accretion along its active margin. Schubert and Sandwell (1989) have estimated an upper bound to the continental crust addition rate by the accretion of all oceanic plateaus to be 3.7 km^3/year, which over a time span of 100 Ma would account for 5% of the total crustal volume of the continental crust.

The Ontong-Java Plateau in the southwestern Pacific is a present day example of an oceanic plateau that resists subduction and thus modifies subduction between the Pacific and Indian plate (Hughes and Turner, 1977; Mann and Taira, 2004). Despite the broad evidence that some plateaus may resist subduction to be accreted in form of collisional terranes others may be lost by subduction (Cloos, 1993), such as in the circum-Pacific where several oceanic plateaus are currently being consumed along with oceanic lithosphere (Rosenbaum and Mo, 2011). Among those are the Nazca (Pilger, 1981) and Juan Fernandez Ridges (von Huene et al., 1997) that are presently being subducted beneath South America. Geological and geochemical observations (Hilton et al., 1992) as well as analogue (Boutelier et al., 2003; Boutelier and Chemanda, 2011) and numerical experiments (Ranalli et al., 2000; van Hunen et al., 2002; Gerya et al., 2009) have supported the idea of deep subduction of crustal material. Thus significant amounts of continental crust may be recycled back into the mantle or be incorporated into active arcs with geochemical and tectonic implications that still need to be explored (e.g. McGeary et al., 1985; Hilton et al., 1992; Chopin, 2003; Rosenbaum and Mo, 2011).

Despite its implications to crustal growth and/or loss, mechanisms responsible for terrane accretion or its deep subduction remain poorly understood. Previous analytical studies have concentrated on the buoyancy of the oceanic lithosphere and bathymetric rises (Cloos, 1993), while analogue (e.g. Boutelier et al., 2003) and early numerical studies have focused on the rheological strength of these features (Ellis et al., 1999). Ellis et al. (1999) have shown that continental fragments of low crustal strength may be deformed and folded within the subduction channel as they approach the continental margin. However, these models concentrated on the upper crustal section and did not take the sublithospheric mantle into account that will significantly affect the dynamics involved in terrane accretion. Subsequent studies have mainly focused on the consequences of plateau subduction/accretion upon the slab and overriding plate. It has been demonstrated in terms of geodynamic models, that oceanic plateaus might alter trench behaviour leading to flat subduction, slab break off, trench advance and trench retreat (van Hunen et al., 2002; Gerya et al., 2009; Mason et al., 2010). Three-dimensional numerical experiments on the influence of a buoyant oceanic plateau on subduction zones show that oceanic plateaus may spread laterally along the trench during collision, if the plateau itself has a sufficiently low density (Mason et al., 2010). Most recently, Tetreault and Buiter (2012) have presented a detailed numerical study on accretion of various crustal units. Their study emphasizes that lithospheric buoyancy alone does not prevent subduction during constant convergence and that a weak detachment layer is necessary in order to accrete crustal units onto the overriding plate. The depth of this detachment layer controls the amount of accreted crust and may lead to crustal underplating or collisional accretion. However, this recent study has employed a constant prescribed subduction velocity and has moreover neglected slab dehydration and melting processes. According to recent results on subduction zones of Sizova et al. (2012) a prescribed convergence velocity and the neglect of fluid- and melt-related weakening effects may inhibit the development of several important collisional processes, such as slab breakoff, vertical crustal extrusion, large scale stacking, shallow crustal delamination and relamination, and eduction of the continental plate. Geodynamic models on collisional orogens that have employed spontaneously moving plates demonstrate that crustal delamination and accretion processes are critically controlled by the rheology of the lower crust and age of the subducting slab (Duretz et al., 2011, 2012; Sizova et al., 2012, Ueda et al., 2012). The latter parameter has not yet been explored in relation to terrane accretion processes.

In this present work we aim to extend previous terrane accretion models and explore geodynamic regimes with implications to magmatic activity using spontaneously moving plates. We have undertaken a detailed study of 2-D petrological–thermomechanical numerical experiments to (i) characterise the variability of accretion processes, and (ii) investigate possible effects of melting of subducted crustal units upon magmatic addition rates associated with terrane accretion. Our parametric study is primary focussed on influences of two major parameters which control crustal accretion in collisional zones: (1) the age of the subducting oceanic plate and (2) the rheology of the lower continental crust.

2. Model Setup

The numerical model simulates forced subduction of an oceanic plate beneath a continental margin on a lithospheric to upper mantle cross-section (4000 km by 1400 km) Fig. 1. The rectangular grid with $1361*351$ nodal points is non-uniform and contains a (1000 km wide) high-resolution area of 1 km$*$1 km in the centre of the domain. The rest of the model remains at a lower resolution (10$*$10 km).

The oceanic crust contains an oceanic plateau that moves with the oceanic lithosphere as it migrates towards a fixed continent, fated to collide with the continental margin. The oceanic crust is composed of 2 km of hydrothermally altered basalt, underlain by 5 km of gabbroic rocks that cover 2500 km horizontally. The continental crust is felsic and has a total thickness of 30 km, composed of 15 km upper and 15 km lower crust that extend over 1500 km. The total thickness of the continental crust corresponds to extended continental crust of Western Europe and Western North America and was adopted according to Christensen and Mooney (1995). Since the composition and thickness of oceanic plateaus are not known in detail we have chosen a simplified description and assume the crustal structure to be similar to continental crust. Schubert and Sandwell (1989) have calculated the average crustal thickness of oceanic and continental plateaus, to vary between ~10 and 20 km based on global topographic data analysis. Sandwell and MacKenzie (1989) on the other hand, estimated that continental plateaus with a relief greater than 4.2 km have roots that extend to 25–35 km depths, while oceanic plateaus have a lower relief and thus shallower roots (15–25 km). For the sake of simplicity we have chosen a total crustal thickness of 20 km, subdivided into upper and lower crust of 10 km each, which cover 100 km horizontally. Both the asthenosphere and the upper mantle are composed of anhydrous peridotite and are defined by the temperature profile. The rheological parameters used in the experiments are summarized in Table S1 (Supplement). All mechanical boundary conditions are free slip only the lower boundary is permeable satisfying an external free slip boundary condition (Gorczyk et al., 2007; Ueda et al., 2008). To allow for topographic build up of the lithosphere, the top surface of the lithosphere is treated as an internal free surface (Schmeling et al., 2008) by using a top layer (of 20–22 km thickness) with low viscosity (10^{18} Pas) and low density (1 kg/m^3 for air, 1000 kg/m^3 for sea water).

The initial temperature field of the oceanic plate is defined by its oceanic geotherm (Turcotte and Schubert, 2002) for a specific lithospheric cooling age that was varied from 20 Ma to 80 Ma. Embedded into oceanic crust, the oceanic plateau is assumed to have the same thermal structure as the oceanic lithosphere. The initial temperature field of the continental plate increases linearly from 0 °C at the surface to 1344 °C at the lithosphere asthenosphere boundary (140 km depth). For the asthenospheric mantle (> 140 km) a thermal gradient of 0.5 $°C\ km^{-1}$ is used.

An internally prescribed velocity field within the convergence condition region enables spontaneous slab bending of the oceanic crust. During the first 6 Ma the oceanic plate is pushed toward a fixed continental plate with a constant velocity, reproducing an active

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