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# Geodynamic regimes of intra-oceanic subduction: Implications for arc extension vs. shortening processes

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ABSTRACT

40% of the subduction margins of the Earth are intra-oceanic. They show significant variability in terms of extension and shortening. We investigated numerically the physical controls of these processes using a 2D petrological-thermo-mechanical intra-oceanic subduction model with spontaneous volcanic arc growth and deformation. We varied the fluid- and melt-related weakening, the ages of both the subduction slab and the overriding plate, the subducting plate velocities, and the cohesive strength of rocks. Three main geodynamic regimes were identified: retreating subduction with opening of a backarc basin, stable subduction, and advancing, compressive subduction. The main difference between these regimes is the degree of rheological coupling between plates, which is governed by the intensity of rheological weakening induced by fluids and melts. Retreating subduction regimes require plate decoupling, which results from strong weakening due to both fluids and melts. Spreading centers nucleate either in forearc or in intraarc regions. Episodic trench migration is often due to variations of plate coupling with time, which is caused by (fore) arc deformation. Stable subduction regime with little variation in the trench position forms at an intermediate plate coupling and shows a transient behavior from the retreating to advancing modes. The advancing subduction regime results from strong plate coupling. At the mature stage, this subduction mode is associated with both partial fragmentation and subduction of the previously serpentinized forearc region. Forearc subduction is typically associated with a magmatic pulse, which is caused by dehydration of subducted serpentinized forearc fragments. Our models demonstrate distinct differences in thermal and lithological structure of subduction zones formed in these different geodynamic regimes. Results compare well with variations observed in natural intra-oceanic arcs.



## 1. Introduction

Intra-oceanic subduction is a frequent plate tectonic process at the boundaries between converging oceanic plates. Intra-oceanic subduction zones (Fig. 1) comprise around 17,000 km, i.e. nearly 40%, of the subduction margins of the Earth (Leat and Larter, 2003). As a consequence, oceanic magmatic arcs are formed worldwide (Fig. 1) (Leat and Larter, 2003). Intra-oceanic subduction zones are sites of intense magmatic and seismic activity as well as metamorphic and tectonic processes shaping out arc compositions and structures. Despite their broad occurrence, intra-oceanic subduction zones and arcs are rather difficult to study since their major parts are principally below sea level, sometimes with only the tops of the largest volcanoes forming islands.

Intra-oceanic subduction zones show significant variability in terms of their structure and dynamics (Leat and Larter, 2003; Straub and Zellmer, 2012). Most of them currently function in *retreating* mode (trench moves backward, rollback) (Stern, 2002, 2011) while the overriding plates are affected by various forearc, intra-arc and backarc extension/spreading processes. For example, the Mariana- and Izu–Bonin-arc systems include temporal series of magmatic arcs and basins (Stern, 2002, 2011). An important variable is the location of the spreading center. It may split the arc into two distinct parts (*intraarc extension*) and may create a thin oceanic lithosphere in between; this is the case for the Mariana Trough between the active Mariana arc and the inactive West Mariana Ridge. These observations are consistent with the seismic images of the Izu–Bonin–Mariana-arc (Takahashi et al., 2008, 2009) showing the new lithosphere with different thickness and crustal compositions along-strike of the arc-system (Kodaira et al., 2008, 2010). Examples of currently *advancing* subduction zones (trench migrates in the direction of the subduction) are the intra-oceanic arc-systems of the Aleutian, and Solomon (Leat and Larter, 2003). It is, therefore, important to understand how and where arc extension vs. compression initiate and evolve.

Arc extension and compression remain a debated subject from both natural observations (Leat and Larter, 2003) and modeling

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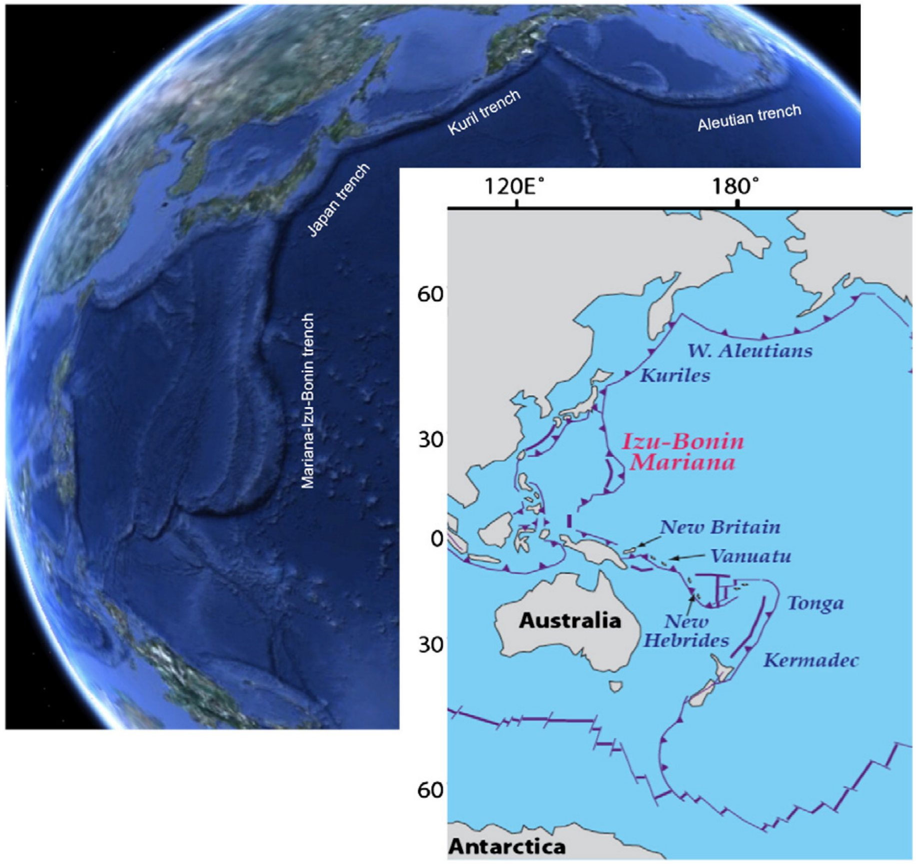


**Fig. 1.** Overview of major modern intra-oceanic subduction zones (based on Google Earth, Tatsumi and Stern, 2006).

(Arcay et al., 2005; Billen, 2008; Nikolaeva et al., 2008) points of view. Recent studies of intra-oceanic arcs focused on rheological variations (Arcay et al., 2005; Billen, 2008; Nikolaeva et al., 2008), plate motions (Sdrolias and Muller, 2006; Arcay et al., 2008; Clark et al., 2008), crustal growth (Kodaira et al., 2007; Takahashi et al., 2007, 2008; Lallemand et al., 2008; Nikolaeva et al., 2008; Zhu et al., 2009, 2011) and spatial and temporal evolutions (Miller et al., 2006). Several authors (Gerya et al., 2002; Arcay et al., 2005, 2008; Gorczyk et al., 2006) proposed that weakening and extension of the overriding plate are controlled by hydration/serpentinization reactions triggered by aqueous fluid released from the slab. Arcay et al. (2008) investigated the influences of subducting and overriding plate velocities on arc tectonic regimes and concluded that upper plate retreat (vs. advance) increases extension (vs. compression) in the arc lithosphere. Their modeling confirmed the statistical kinematic relationship that describes the transition from extensional to compressional stresses in the arc lithosphere (Lallemand et al., 2008). Arcay et al. (2008) also showed that the arc deformation mode is time-dependent on scales of millions to few tens of million years. Clark et al. (2008) investigated numerically the episodic behavior in trench motion and backarc tectonics based on simplified 3D models with freely subducting slabs. They defined three types of episodicity and found evidence of these in nature.

Shortening of intra-oceanic arcs received relatively little attention in terms of modeling. Boutelier et al. (2003) investigated with analog models different stages of arc and forearc subduction those that likely played important roles in collisional mountain belts such as the Himalayas and Tibet (Boutelier and Chemenda (2011) and references therein). These authors, in particular, argued that without the existence of a backarc (i.e. no thin and weak lithosphere in the rear of the arc), the overriding plate fails in the arc area. This may lead to forearc block subduction. So far, no numerical modeling has successfully complemented these analog models. Only recently, Gerya and Meilick (2011) demonstrated numerically that in case of oceanic–continental (i.e. active margin) subduction geodynamic transition from arc compression to extension should be critically determined by the magnitude of rheological weakening induced by fluids and melts. These results are, however, not directly applicable to intra-oceanic subduction because of major differences in the overriding plate origin, composition and structure.

In this paper we aim to investigate numerically which physical parameters control the transition from compression to extension in intra-oceanic subduction. We performed systematic numerical experiments with a new 2D high-resolution petrological-thermo-mechanical subduction model including spontaneous intra-oceanic arc development and deformation. The results are analyzed with respect to fluid and melt weakening effects, cohesive strength of rocks, subducting plate velocity and plate ages. We classify three major intra-oceanic subduction regimes and present their implications for arc extension and compression, forearc subduction and trench migration.

## 2. Numerical model description

Our modeling approach is comparable to that of (Sizova et al., 2010) and Gerya and Meilick (2011) who presented numerical details not provided here. The model is based on the 2D thermo-mechanical I2ELVIS code (Gerya and Yuen, 2003a, 2003b, 2007) based on finite differences and marker-in-cell method.

### 2.1. Model design

The 2D numerical model (Fig. 2) simulates subduction of an oceanic plate beneath another oceanic plate. The model starts with subduction initiation and spans a period equivalent to about 40 Ma.