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Slab interactions in 3-D subduction settings: The Philippine Sea Plate region

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ABSTRACT

The importance of slab–slab interactions is manifested in the kinematics and geometry of the Philippine Sea Plate and western Pacific subduction zones, and such interactions offer a dynamic basis for the first-order observations in this complex subduction setting. The westward subduction of the Pacific Sea Plate changes, along-strike, from single slab subduction beneath Japan, to a double-subduction setting where Pacific subduction beneath the Philippine Sea Plate occurs in tandem with westward subduction of the Philippine Sea Plate beneath Eurasia. Our 3-D numerical models show that there are fundamental differences between single slab systems and double slab systems where both subduction systems have the same vergence. We find that the observed kinematics and slab geometry of the Pacific–Philippine subduction can be understood by considering an along-strike transition from single to double subduction, and is largely independent from the detailed geometry of the Philippine Sea Plate. Important first order features include the relatively shallow slab dip, retreating/stationary trenches, and rapid subduction for single slab systems (Pacific Plate subducting under Japan), and front slabs within a double slab system (Philippine Sea Plate subducting at Ryukyu). In contrast, steep to overturned slab dips, advancing trench motion, and slower subduction occurs for rear slabs in a double slab setting (Pacific subducting at the Izu–Bonin–Mariana). This happens because of a relative build-up of pressure in the asthenosphere beneath the Philippine Sea Plate, where the asthenosphere is constrained between the converging Ryukyu and Izu–Bonin–Mariana slabs. When weak back-arc regions are included, slab–slab convergence rates slow and the middle (Philippine) plate extends, which leads to reduced pressure build up and reduced slab–slab coupling. Models without back-arcs, or with back-arc viscosities that are reduced by a factor of five, produce kinematics compatible with present-day observations.

1. Introduction

The Philippine Sea Plate is bounded to the west and east by west-dipping subduction zones (Fig. 1). It is the primary modern example of a plate bounded by two subducting slabs with the same polarity and thus presents the opportunity to interrogate subduction dynamics through slab–slab interactions. The two slabs can interact with each other via forces transmitted through the intervening plate and also through viscous forces exerted by subduction-induced mantle flow (e.g., Jagoutz et al., 2015). Understanding how such systems operate therefore has wide-ranging implications for the forces operating at subduction zones, and can be approached by utilizing dynamic modeling in conjunction with observations of subduction zone kinematics.

Holt et al. (2017) used 3-D numerical models to show that two proximal slabs with parallel trenches and the same subduction polarity exhibit strikingly different behavior from one another (Fig. 2). The slab that dips away from the middle plate ("front slab") has, for example, a low dip angle and a retreating trench. The slab that dips beneath the middle plate ("rear slab") has a high dip angle and a trench that advances. A number of 2-D numerical modeling studies have also shed light on the diversity of subduction kinematics that can be attributed to this configuration of double subduction (Mishin et al., 2008; Čížková and Bina, 2015; Faccenna et al., 2017).

We build upon these studies by considering subduction geometries that are applicable to the highly 3-D setting surrounding the Philippine Sea Plate. In this region of the western Pacific, the subduction segments exhibit strong kinematic variability both along-

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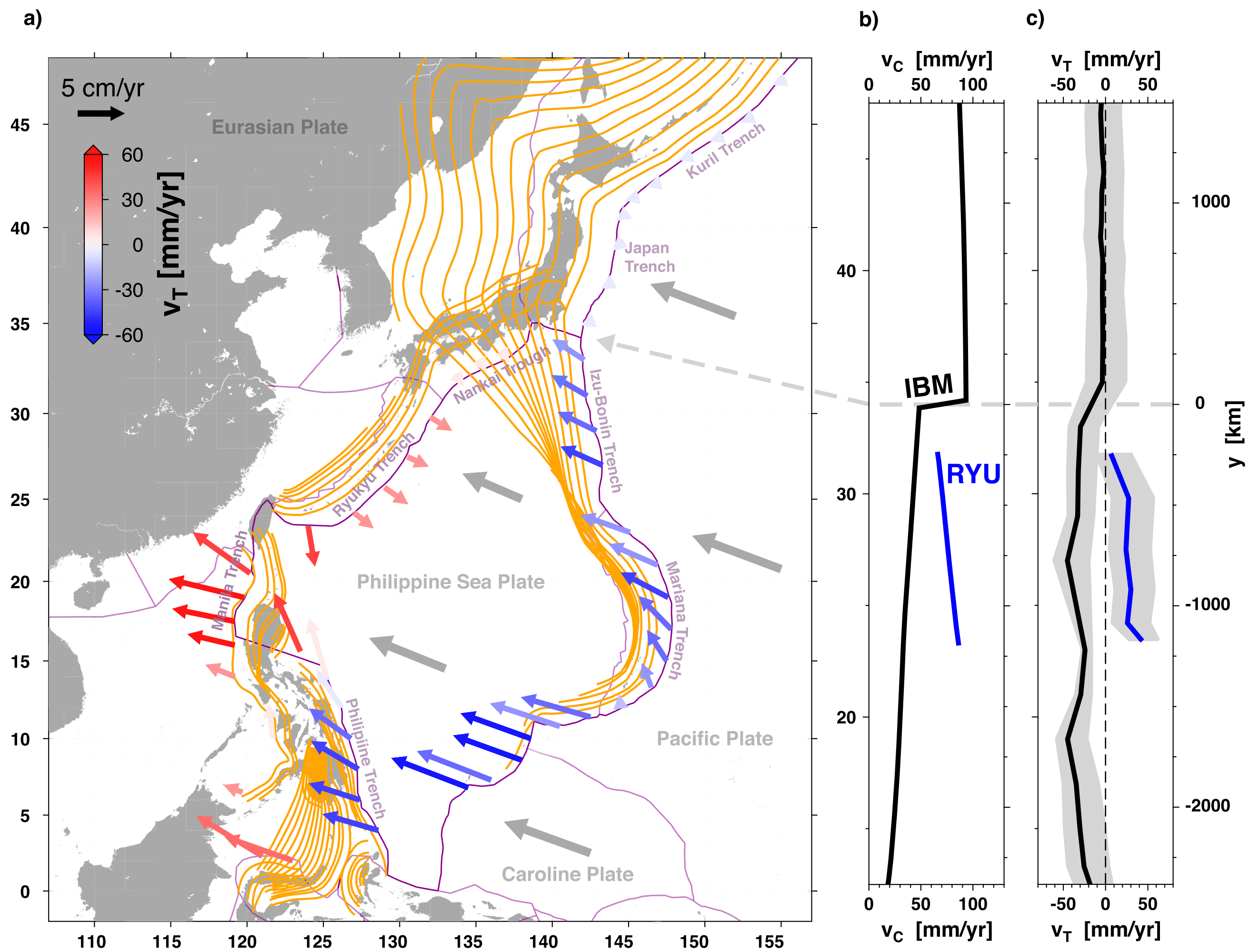

Fig. 1. Subduction kinematics in the Philippine Sea Plate region: a) Trench migration velocities in an absolute, spreading-aligned reference frame (Becker et al., 2015), relative plate motion vectors from MORVEL (DeMets et al., 2010) relative to Eurasia fixed, and RUM slab contours (Gudmundsson and Sambridge, 1998). Panel b) shows along-strike profiles of the magnitudes of the individual trench convergence rates at the Ryukyu (Philippine Sea Plate relative to Yangtze Plate) and Japan–Izu–Bonin–Mariana (Pacific Plate relative to Okhotsk and Philippine Sea plates) trenches (MORVEL). Panel c) shows the trench migration rates, V_T, at the subduction zones either side of the Philippine Sea Plate (black: Japan–Izu–Bonin–Mariana, "IBM", blue: Ryukyu, "RYU"). Negative and positive V_T corresponds to trench advance and retreat, respectively. In panel c), the solid lines are trench motions in the spreading-aligned reference frame. The upper (more positive) bound of the gray shading shows trench motions in a no-net-rotation (NNR) reference frame, and the lower bound shows motions in the hotspot (HS3) reference frame (Gripp and Gordon, 2002). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

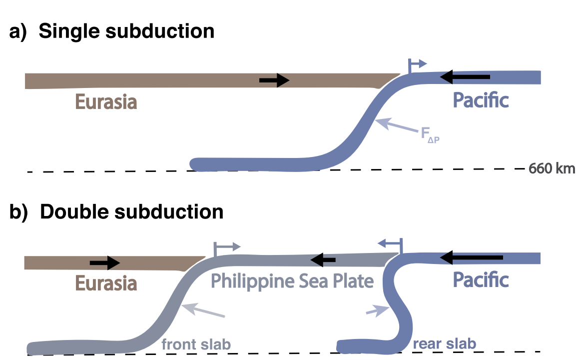

Fig. 2. Schematic illustration of the plate kinematics observed in the 3-D models of Holt et al. (2017): a) A "single subduction" model, and b) a "double subduction" model. Black arrows: plate velocities; dark colored arrows: trench migration velocities; light colored arrows: the force due to the across-slab asthenospheric pressure difference, ΔP.

strike and either side of the plate. We use observations from the Philippine Sea Plate and surrounding regions, coupled with 3-D dynamic modeling, to better constrain the forces and processes that operate around the margins of the Philippine Sea Plate, and those which dictate the along-strike change in behavior of the Pacific slab adjacent and north of the Philippine Sea Plate.

2. Tectonic overview

We first present a summary of the geometry and plate kinematics of the Philippine Sea Plate with a focus on the present-day. For an overview of the evolution of the Philippine Sea Plate since its inception (~55 Ma) we point the reader to the recent review of Lallemand (2016).

The Philippine Sea Plate is a relatively small plate (~2500 × 3250 km) consisting of oceanic lithosphere and sandwiched between the Pacific and Eurasia to the east and west and bounded, in a complex fashion, by the Sunda, Indo-Australian and Caroline plates to the south. Along its eastern margin, the Philippine Sea Plate overrides the Pacific Plate at the Izu–Bonin and Mariana trenches (Fig. 1). Along most of it western margin (Philippine, Ryukyu and Nankai boundaries), the Philippine Sea Plate subducts beneath a range of small-to-intermediate plates bordering the Eurasian Plate. In order to focus on the large-scale geodynamics, we group these plates together as the "Eurasian Plate" in our idealized models. The distance between the Ryukyu and Izu–