Dynamics of the Ryukyu/Izu-Bonin-Marianas double subduction system

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ABSTRACT

Trench motions represent the surface expression of the interaction between subducting plates and the underlying mantle, but the inherent dynamics are not fully understood. One interesting case is the migration of the Izu-Bonin-Marianas trench (IBM) that accommodates the subduction of the Pacific beneath the Philippine Sea Plate (PSP), which is in turn subducting below the Eurasian plate along the Ryukyu trench. The history of the IBM trench is dominated by fast, episodic retreat from 40 to 15 Ma. However, around 10–5 Ma, the IBM trench reversed its motion from retreat to advance. The switch in trench motion occurred soon after the breakoff of the PSP slab along the Ryukyu trench and the onset of new subduction, and represents a fundamental change in the dynamics of the western Pacific subduction zones. Here, following the modelling study of Čížková and Bina (2015), which suggested a link between IBM trench advance and Ryukyu subduction, we run 2-D numerical experiments to test the influence of this newly formed Ryukyu slab on the IBM subduction zone. The results from our geodynamic model compare favourably with the reconstructed trend, indicating that the switch in trench motion along the IBM trench may indeed be related to the onset of a new subduction zone along the Ryukyu trench. Our analysis substantiates the idea that advancing trench motions in the western Pacific are due to the establishment of a double subduction system. Further analysis of such dynamics provides insights for the mechanisms controlling subducting plate and trench motions and mantle force transmission.

1. Introduction

Seafloor trenches represent the sites where oceanic lithosphere subducts into the mantle. However, motion of the trenches themselves is also an important component of the surface expression of mantle convection. Assuming negligible accretion or erosion at the trench, trench kinematics may be reconstructed by subtracting backarc deformation from upper plate motion (Dewey, 1980). Geologic reconstructions show that trenches are indeed not stationary features but migrate in space and time. Present-day migration patterns indicate that trenches migrate backward (trench rollback) or forward (advancing trench) with respect to the upper plate (Heuret and Lallemand, 2005).

The rate of trench migration depends on the absolute plate motion reference frame. The “correct” choice of reference frame is not always clear, and the way that trench migration is partitioned between advancing and retreating motion also depends on the reference frame (Fucenello et al., 2008; Schellart et al., 2008; Becker et al., 2015). However, in some systems like the northern Philippine Sea region, where two subduction systems exist in close proximity, the sense of motion of one trench relative to one another and the sense of motion of both trenches relative to the uppermost plate (stable Eurasia) is unambiguous. On the Eastern boundary of the Philippine Plate, the Izu-Bonin Trench is presently advancing toward Eurasia, and on the Western boundary, the Ryukyu Trench is retreating, and the two trenches are converging with time.

Several geological examples illustrate that trench migration is not constant over time and reconstructions of back-arc spreading histories show that the migration of trenches may be episodic and/or short lived (e.g., Taylor and Knerr, 1983). The Izu-Bonin-Marianas subduction zone is an excellent example of such a system, as geological reconstructions show that it has undergone a dramatic shift from treating to advancing trench motion between 5 and 10 Ma.

Many factors may influence the rate and direction of trench migration in single slab subduction systems. These include plate-mantle coupling (e.g., Bellahsen et al., 2005; Faccenna et al., 2009; Fucenello et al., 2008), slab interactions with the upper–lower mantle transition...
(Kincaid and Olson, 1987; Christensen, 1996), three-dimensional (3-D) plate geometry and plate width (Funicelli et al., 2003; Stegman et al., 2006; Schellart et al., 2007), plate kinematics (Heuret et al., 2007; Lallemand et al., 2008), overriding plate properties (Capitanio et al., 2010; Yamato et al., 2009), and mantle rheology (Holt and Becker, 2017). In multi-slab systems, such as that existing in the Philippine Sea Plate region, the interaction between proximal slabs can have a major impact on trench migration rates, as explored through geologic observations and dynamic subduction models applied to various subduction regions (Jagoutz et al., 2015; Kiraly et al., 2016; Holt et al., 2017). Double slab systems are interesting in their own right but also serve to explore the parameters controlling single slab and trench dynamics, motivating study of natural examples.

Recently, Čížková and Bina (2015) used 2-D subduction models to suggest that the advancing motion of the Izu-Bonin-Mariana Trench, which accommodates west-dipping subduction along the eastern boundary of the Philippine Sea Plate, can be attributed to the presence of a second west-dipping subduction zone located along the western boundary of the Philippine Sea Plate (the Ryukyu Trench). Here, we focus on the temporal evolution of this two-slab subduction system, particularly the mechanism by which a retreating Izu-Bonin-Mariana Trench can transition to an advancing mode of trench migration. Therefore, we examine how the coupled evolution of these two slabs is reflected in the rate and direction of Izu-Bonin-Mariana Trench migration.

We begin with a tectonic reconstruction of the Izu-Bonin-Mariana system during the last 20 Ma followed by numerical tests that capture the first order dynamics of double subduction. An important aspect of this study is our exploration of the switch from trench retreat to advancement along the Izu-Bonin-Mariana system, and its dependence on subduction along the Ryukyu Trench.

2. Evolution of the Izu-Bonin system

2.1. Observed geometry and kinematics

The Izu-Bonin-Marianas (IBM) and Ryukyu trenches accommodate west-dipping subduction along the eastern and western margins of the Philippine Sea Plate (PSP), respectively. The geometry of these subducting plates at depth has been illuminated by several studies of seismic tomography and seismicity (e.g. van der Hilst et al., 1991; van der Hilst and Seno, 1993; Bijwaard et al., 1998; Fukao et al., 2001; Miller et al., 2006; Li et al., 2008; Fukao and Obayashi, 2013). Along the northeast margin of the PSP, the Izu–Bonin slab is characterized by a 50° to 70° west-dipping Wadati–Benioff zone, which flattens into the transition zone as indicated by a long, high velocity anomaly that sits just above the 660-km discontinuity. Northward, below Japan, the slab shallows to a dip of about 30° whereas, southward, below the Mariana Trench, the slab becomes nearly vertical, and even overturns locally (Fig. 1). The Ryukyu Trench is currently retreating eastward, producing back-arc extension in the Okinawa Trough. The IBM Trench presently advances to the west (Fig. 1). This kinematics pattern is present in the reference frame that fixes Eurasia, which represents the upper plate of the subduction system, and in the other reference frames commonly adopted (Funicelli et al., 2008; Di Giuseppe et al., 2009). The magnitude of trench motion depends on the reference frame; higher values of advance for the IBM Trench and lower values of retreat for the Ryukyu Trench are obtained using a Pacific hotspot reference frame such as H3S (~6 cm/yr and ~1 cm/yr, respectively; Gripp and Gordon, 2002), relative to a No-net-rotation (NNR) reference frame (~2 cm/yr and ~6 cm/yr respectively; DeMets et al., 2010) or to spreading-aligned absolute reference frame (Fig. 1, ~4 cm/yr and ~2 cm/yr, respectively; Becker et al., 2015). Accordingly, the subduction velocity at Ryukyu Trench, which depends upon the IBM and Ryukyu Trench velocity, varies from ~7 cm/yr in H3S (Gripp and Gordon, 2002), ~2 cm/yr in NNR (DeMets et al., 2010) or to ~4 cm/yr spreading-aligned absolute reference frame (Fig. 1, Becker et al., 2015).

The tectonic evolution of the region is here summarized using a schematic reconstruction (Fig. 2) and a table listing the main tectonic events (Table 1). The Philippine Sea Plate is surrounded by subduction zones, and has been formed by sea-floor and back-arc spreading along at least three different axes (Figs. 1, 2). The first and the oldest portion of the plate, the West Philippine Basin, formed during the Eocene from 54 to 30 Ma (Deschamps and Lallemand, 2002 and reference therein; Fig. 2a; Table 1). At ~30 Ma, spreading moved to form the Shikoku and Parece-Vela basins, and spreading occurred until ~15 Ma (Chamot-Rooke et al., 1987; Okino et al., 1994, 1998; Sdrolias et al., 2004). Three spreading stages have been detected in the Shikoku and Parece-Vela basins as the spreading direction changed from E–W to NE–SW at ~20 Ma (Okino et al., 1994, 1998; Sdrolias et al., 2004). The half spreading rate ranged from 2 to 3 cm/yr to 5–6 cm/yr and was accompanied by a total of trench retreat of ~1000 km along the northern portion of the Izu-Bonin trench. The third extensional episode, which continues today, occurred behind the Mariana Trough, which began rifting at ~7 Ma (Hussong and Uyeda, 1981; Fryer, 1995; Stern et al., 2003; Kato et al., 2003; Martinez et al., 1995).

The evolution of the subduction system is complex due to initiation and cessation of subduction in some places and northward migration of the Ryukyu-Izu Bonin triple junction. Subduction of the Pacific plate at the IBM Trench began at ~54 Ma (Cosca et al., 1998; Ishizuka et al., 2008, 2011; Deschamps and Lallemand, 2002; Ishizuka et al., 2011; Lallemand, 2016). Because of the northward migration of the Ryukyu-IBM triple junction, subduction in the northern side of the Ryukyu was first produced by the Pacific and later progressively replaced by the PSP (Fig. 2b). The subduction of the PSP was interrupted by the entrance at trench of the northern extent of the Gagua Ridge which is a paleo-transform plate boundary separating a Cretaceous deep lithosphere (Huatung Basin; Deschamps et al., 2000) from the shallow Eocene lithosphere (West Philippine Basin). Following Lallemand et al. (2001) this transform fault should have entered at trench producing an episode of slab break-off (Lallemand et al., 2001; Fig. 2c; Table 1). Following slab break-off, subduction of the Philippine Sea Plate was reinitiated along the Ryukyu Trench, resulting in the modern Ryukyu subduction system (Lallemand, 2016). As discussed in Section 2.2, the timing of slab break off can be reconstructed by the length of the present-day Ryukyu slab and should have occurred around ~10 Ma. Just after this episode of slab break-off, a fundamental change in kinematics of trench motion occurred around 5–8 Ma. Prior to this time, the IBM Trench underwent (eastward) trench retreat, but afterwards changed direction and began to advance westward (Carlson and Melia, 1984). The total magnitude of the IBM Trench advance is ~70 km, from ~10 Ma to the present day (Seno and Maruyama, 1984). Paleomagnetic data also provide constraints on the timing of both clockwise rotation and on the northward drift of the PSP (Hall et al., 1995), indicating trench advance over the last 5 Myr (Hall, 2002). Le Pichon and Huchon (1987) estimated that at 3 Ma the triple junction between Ryukyu, Izu, and Japan was located to the west of the present-day position by ~30 km, moving 30 km eastward, hence advancing, since that time.

The switch in the direction of trench migration, from retreating to advancing, represents a fundamental change in the dynamics of the western Pacific subduction zones (Seno and Maruyama, 1984; van der Hilst and Seno, 1993). It has been associated with a re-organization of major tectonic boundaries along the western margin of the Pacific margin and is probably associated with an increase in the speed of the Pacific Plate (Faccenna et al., 2012).

2.2. Reconstruction of the northern Philippine Sea Plate region

To better visualize the evolution of the subduction, we reconstruct the Ryukyu, Izu-Bonin system along a section at a latitude of 28° N,
Fig. 1. Present-day plate kinematic setting of the western Pacific, showing the subducting slab contours at 50 km depth intervals (RUM model of Gudmundsson and Sambridge, 1998), plate and trench velocities (plate: gray vectors, MORVEL-NRR56, Argus et al., 2011, colored: trench motions from Heuret and Lallemand, 2005), both in the spreading-aligned absolute reference frame of Becker et al. (2015). Also shown is the seafloor age from Müller et al. (2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Simplified tectonic evolution of the region in five steps from 20 Ma onward (modified from Deschamps and Lallemand, 2002; plate motion from Seton et al., 2012). The double dashed line indicates the Gagua Ridge (Fig. 2e–f from Lallemand, 2016), the single dashed line the position of the of active spreading centre and the single dashed line indicates the trace of the cross section of Fig. 3. The arrow indicates the motion of the plate from Seton et al. (2012).
adopting the plate velocity model of Sdrolias and Müller (2006), and tectonic setting based mainly on the reconstruction of Deschamps and Lallemant (2002). This reconstruction is simplified and intended to give a schematic representation of the evolution and interaction of the Izu-Bonin and Ryukyu slabs, and therefore does not include the three-dimensional complexity of the subduction setting (Wu et al., 2016). The Izu-Bonin and Ryukyu slabs, and therefore does not include the three-dimensional complexity of the subduction setting (Wu et al., 2016).

The timing of the slab break-off occurred at a depth of 100 km the amount of post-break-off subduction is 300 km. The present day Ryukyu subduction rate is around ~4–5 cm/yr as it is the IBM Trench advancing rate. However, during the last 10 Ma, the IBM Trench advance rate was lower than the present day one (~4–5 cm/yr), as it switched from retreat to advance, in the order of 2–3 cm/yr. Correspondingly, also the average Ryukyu subduction was lower than the present-day and of the same order. We may then estimate that timing of slab break off occurred around ~10–12 Ma.

A relevant question regarding the dynamics of the PSP system concerns the switch from trench retreat to trench advance of the IBM Trench and its relationship with the Ryukyu Trench. A range of models have been proposed. Van der Hilst and Seno (1993) suggested that the overall clockwise rotation of the Izu Bonin-Mariana Trench is related to the on-going penetration of the Mariana slab into the lower mantle. These authors proposed that the recent advance of the Izu-Bonin-Mariana Trench could be related to the northward propagation of this process, and that trench advance is about to initiate along the northern Mariana Trench. However, the reason why the on-going penetration of the Mariana slab into the lower mantle, and the on-going penetration of the Mariana slab into the lower mantle.

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#### Table 1

slab break off and onset of modern Ryukyu subduction (Fig. 2c, d), by a few million years. We use numerical models of the single and double subduction process to investigate the feasibility of a double subduction induced switch in the trench motion direction. We additionally investigate the mechanical controls on both the onset time of the switch, and the eventual magnitude of the trench advance velocity.

3. Model set up

We use dynamically consistent (i.e., no external forces/velocities imposed) thermo-mechanical numerical models to examine whether the initiation of an additional subduction zone can induce a transition from a retreating trench to an advancing trench. Our approach is to run a standard single subduction zone mode, in which the slab represents that of the Izu-Bonin, to a time-step at which mature subduction is established (for the Pacific slab at ~10 Ma), and then insert an additional subduction zone corresponding to modern Ryukyu. We then compare the subsequent trench evolution of IBM in the single slab model (i.e., without the model modification), with a model that contains an added subduction zone (i.e., the modified model). We use the finite-element code CitcomCU (Moresi and Gurnis, 1996; Zhong, 2006) to model subduction in a Cartesian domain. CitcomCU solves the equations governing convection in an incompressible viscous fluid with negligible inertia (Boussinesq and infinite Prandtl number approximations).

The domain size is 10,560 km (x) × 1320 km (z) × 13.2 km (y, i.e. the computations are pseudo-2-D), and all boundaries are free slip. Finite element dimensions vary from 6 km in the refined, plate boundary region to 14.5 km elsewhere. The refined region extends from x = 4225 km to x = 7400 km, for depths shallower than 400 km. We parameterize the 660 km phase transition with a factor of 50 viscosity increase, compatible with geoid observations (e.g. Hager, 1984; Mitrovica and Forte, 2004), but omit buoyancy effects and additional phase transitions. Both the subducting and overriding lithospheric plates have initial lengths of 4000 km, and are initially placed at a horizontal distance of 1280 km away from the side boundaries.

For the single slab model, we use a model setup similar to that presented in Holt et al. (2015), their Fig. 1, but with a high viscosity lower mantle (see Table 2 for all model parameters). In order to focus on first-order slab-slab interactions, we use a simplified subduction setup, both mechanically and rheologically. We consider an initially constant temperature (1573 K) and therefore constant viscosity (10^{20} Pa s) sub-lithospheric mantle. Thermally, we impose constant temperature (273 K) on the upper, surface boundary, and zero heat flux on the base and side boundaries.

The initial thickness of the subducting and overriding plates is 89 km and 59 km, respectively, and these plates are initially isothermal. These lithospheric thicknesses were chosen to provide depth-integrated buoyancies, B, equivalent to those expected for the average ages of the subducting Pacific (80 Ma age gives B = 6.1 × 10^8 kg/m^2) and Philippine Sea plates (35 Ma age yields B = 4.0 × 10^8 kg/m^2).

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**Table 2**

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computed using a half-space cooling model. The initial lithosphere-asthenosphere temperature contrast is set to 1300 K. To generate the negative buoyancies stated above, we therefore use a thermal expansivity of \(1.59 \times 10^{-5} \text{K}^{-1}\) and a reference mantle density of 3300 kg/m\(^3\).

We adopt a lithospheric rheology similar to that described in Holt et al. (2015), where the effective viscosity is composed of the harmonic mean of a Newtonian and a plastic component. The Newtonian component of the lithospheric viscosity is controlled by a maximum viscosity cut-off and is factor 500 more viscous than the asthenosphere. For the plastic component, we use a Byerlee type yield stress, \(\tau_{\text{yield}} = \lambda(a \sigma_L + b)\), where \(a\) is the coefficient of friction (0.6), \(b\) is the cohesion (60 MPa), \(\sigma_L\) is the lithostatic pressure (= \(\rho_0 g z\)), and \(\lambda\) is a “pore pressure” pre-factor (0.15). This pre-factor value is broadly consistent with that used in previous studies (e.g. Enns et al., 2005: 0.1; Di Giuseppe et al., 2008: 0.08), and is low enough to trigger plastic weakening in the bending region, yet high enough to avoid slab break-off. In Supplementary material, we also examine the trench motion systematics produced by models with either a purely viscous rheology or a visco-plastic rheology with a reduced yield stress, \(\lambda = 0.1\) (Fig. S1).

To decouple the two plates, we insert a 15 km thick crustal layer within the subducting plate, which has a constant viscosity of \(5 \times 10^{19} \text{Pa s}\) (e.g. Holt et al., 2015). As the decoupling layer strength has been shown to exert a strong control on slab dynamics (e.g., Čížková and Bina, 2013), we have tested that stronger and weaker layers do not change the first order systematics (Fig. S2). To initiate subduction, we allow the subducting plate to extend below the overriding plate to a depth \(z_{\text{init}}\) of 150 km, with an initial radius of curvature \(R_{\text{init}}\) of 150 km (Fig. 4).

In our reference model, we choose a model time of 5.4 Myr to insert Ryukyu (at a distance of 1500 km from IBM), which corresponds to the instance when the slab first impinges on the strong lower mantle (cf. Fig. 4b, c). Such a mature model subduction stage is chosen following our reconstruction (Figs. 2, 3). The Ryukyu subduction zone is added to the model viscosity and density fields as a proto-slab with the same curvature as that used to initiate IBM subduction (i.e. \(R_{\text{init}} = z_{\text{init}} = 150\) km), but reduced subducting plate thickness corresponding to the younger PSP. In addition, a weak crustal, decoupling layer is added onto the middle plate, extending from the new notch to a distance of \(\approx 50\) km to the right of the mature trench. This decouples the Ryukyu slab from the leftmost, Eurasian, plate. At the time-step at which Ryukyu is inserted, there is a discontinuity in the model evolution and so the trench velocity is taken to be the mean average between the single slab model, and the modified model with an additional, incipient subduction zone.

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4. Modelling results

In the reference single slab model, with a visco-plastic rheology (Fig. 4b), the subducting plate enters the mantle through a combination of subducting plate motion and trench retreat, as is typically observed in similar dynamic subduction models (e.g. Enns et al., 2005; Stegman et al., 2006). In the reference frame of the model side boundaries, the subducting plate velocity increases to a maximum rate of 102 mm/yr before the slab impinges on the lower mantle. Simultaneously, the trench retreats rapidly, increasing from an initial rate of ~30 mm/yr to a maximum of ~80 mm/yr (Fig. 5). As the slab interacts with the high viscosity lower mantle, the slab is folded and finally flattens while penetrating into the lower mantle slowly. This lower mantle interaction causes a reduction in both the plate and trench velocities. The subducting velocity reduces to ~60 mm/yr, and the trench retreat velocity gradually reduces throughout the subsequent duration of the model, by ~2.7 mm/yr per Myr.

In the model within which we insert an additional slab (Fig. 4c), the style of trench motion is very different (Fig. 5). The additional slab (Ryukyu), which itself exhibits rapid trench retreat (mean trench velocity, \(V_t = 118 \text{ mm/yr}\)), exerts a strong influence on the behavior on the mature, rear slab (IBM). When the additional notch is initially inserted, the Izu-Bonin slab remains in the retreating regime. However, as the Ryukyu slab subducts progressively deeper into the asthenosphere, and the two slabs become closer together, the amount of slab pull acting on the middle plate (PSP) increases and the IBM slab switches from a retreating to an advancing mode. This switch occurs ~6 Myr after Ryukyu subduction initiation, and our modelled Izu-Bonin slab advances at rates of up to 23.2 mm/yr (Fig. 5). Because trench retreat tends to reduce, and advance tends to increase slab dip (e.g., Christensen, 1996), we observe near vertical rear-slab dips, in the models containing an additional slab (Fig. 4c).

In addition to inducing a switch from a retreating to an advancing trench, the initiation of the second subduction zone increases the subduction velocity of the rear plate (Pacific), in the reference frame of the model box (Fig. S3). For equivalent time periods (after the rear slab has reached the lower mantle), the mean rear plate velocity is ~58 mm/yr in the single slab model, and increases to ~72 mm/yr in the model with an additional, inserted subduction zone.

In Supplementary material, we show that the trench motion systematics observed for the reference model are unchanged by the specific rheology assumed for the lithospheric plates. For lithospheric plates with both a viscous rheology and a reduced yield stress (\(\lambda = 0.1\)), we also observe a switch from a retreating to an advancing Pacific subduction induced by Ryukyu subduction (Fig. S1). Motivated by the inherent uncertainty regarding the appropriate viscosity for parameterizing the crustal, decoupling layer (e.g., Androvichová et al., 2013), we also show that the first order trench motion trends are unchanged in models which employ either a stronger \(\eta_{\text{crust}} = 2\eta_{\text{mantle}}\) or a weaker \(\eta_{\text{crust}} = 0.1\eta_{\text{mantle}}\) crustal layer to decouple the plates (Fig. S2).

Because the PSP plate is highly 3-D, with variable trench-perpendicular distance between the two slabs/trenches as a function of along-strike location, we have conducted additional tests to examine the effect of inserting Ryukyu subduction at a range of initial, horizontal distances from the Pacific subduction zone (\(\Delta x = 1250, 1500, 1750, 2250 \text{ km}\)), appropriate for the PSP geometry. The largest trench-trench distance of 2250 km is approximately equivalent to the widest portion of the Pacific plate double slab system, from the centre of the Marianas Trench to the centre of the Ryukyu Trench. Fig. 6a shows the evolution of trench motion velocities for these four double slab cases. For each case, as the inserted subducting slab becomes more mature, and the two trenches become closer together (primarily due to Ryukyu Trench rollback), the trench retreat rate of the modelled IBM Trench reduces until it begins to advance. Increasing initial slab separation increases the time it takes for the trenches to become a certain distance apart, and so delays the time at which a shift from trench retreat to trench advance occurs. Going from an initial trench separation of 1250 km to an initial trench separation of 2250 km, this trench motion transition time is delayed by ~8 Myr. However, we do ultimately observe a switch from Pacific Trench retreat to advance for all of the initial trench separations. Similarly, we find that an acceleration of the modelled Pacific Plate (relative to the plate velocity observed in the single slab models) occurs for all of the initial trench separations (Fig. S3).

As the precise morphology of the Pacific slab at the time of Ryukyu slab break-off and re-initiation is not known, we also examine models within which Ryukyu subduction is initiated at different stages in the evolution of Pacific subduction. Fig. 6b shows the effect of initiating Ryukyu subduction at a time significantly before the Pacific slab tip reaches the lower mantle (model time \(\approx 2.2\) Myr), and a time after the slab tip has had significant interaction with the lower mantle (time \(\approx 7.4\) Myr), i.e. before and after the reference case shown in Figs. 4 and 5. Initiating subduction at a later stage in the Pacific subduction does not modify the trench motion systematics. However, initiating Ryukyu subduction before the Pacific slab touches the lower mantle causes the magnitude of the double slab effect on trench motion to be reduced (Fig. 6b). While Ryukyu subduction still causes both a drastic reduction in the trench retreat rate and eventual switch to trench advance, the switch is substantially delayed and the attained trench advance is at a reduced maximum rate of 12 mm/yr (Fig. 6b). In general, an important result of all of the tests described is that, despite at what trench-trench distance or relative time Ryukyu is inserted to the system (Fig. 6), the switch from a retreating to an advancing IBM Trench occurs only after the tip of the IBM slab is sufficiently supported by the stronger lower mantle.

5. Discussion and conclusions

The Izu-Bonin area is a key region for studying the dynamics of trench migration. Číšková and Bina (2015) first analyzed the influence of a double subduction system on trench migration and applied that to the present-day Izu-Bonin-Marians setting in order to explain the advancing motion of the Izu-Bonin. Here, we combine a geological reconstruction of the region and idealized numerical models to explain why, between 10 and 5 Ma, trench motion here changes from retreating to advancing. Our tectonic reconstruction and numerical modelling suggest that the change in trench motion is related to initiation of the most recent phase of subduction along the Ryukyu Trench. In our reconstruction, this latest phase of subduction follows a period of slab break off that occurred after subduction of the Gagua Ridge. At any one point, passage of the triple junction between the paleo Ryukyu and Izu Bonin trenches is followed by ridge subduction, slab break off and, finally, re-initiation of modern Ryukyu subduction.

For an idealized model geometry, our numerical models demonstrate the ability of an incipient subduction zone (Ryukyu) to exert forces strong enough to change a nearby mature subducting slab (Izu-Bonin) from a retreating to an advancing trench mode. This occurs because the newly initiated subduction boundary causes subduction of the overriding plate of the Izu-Bonin system. Slab pull from the frontal, Ryukyu slab is transmitted through the plate separating the Philippine Sea and Pacific plates, producing a horizontal force which acts to pull the rear trench (IBM) toward the front trench (Ryukyu), producing advance of the IBM Trench. At a slab depth of 660 km, our modelled Ryukyu slab has an available slab pull force of ~25 Tm/m and we find that this is sufficient to ultimately trigger a transition in the trench motion direction of the mature IBM Trench. Upon initiation of Ryukyu subduction in our reference model (Fig. 4c), it takes ~6 Myr for the trench to start to advance. This delay occurs because the Ryukyu subduction must be mature enough to be able to transmit a large slab pull force (proportional to slab depth), and the slab pull of the rear IBM slab must be strongly supported by the stronger lower mantle. This modelled delay time is broadly consistent with the reconstructed time delay.
between spreading ridge subduction and Izu-Bonin Trench advance.

We also examine the effect of both the initial trench-trench distance (as this is highly variable for the present Philippine plate geometry) and the stage of IBM subduction at which Ryukyu subduction is initiated (Fig. 6). For a range of initial trench separations up to 2250 km (the maximum present day Ryukyu-Izu Bonin separation), all models exhibit a switch to Izu-Bonin trench advance. However, the time lag between the initiation of Ryukyu subduction and the switch to IBM trench advance is greater for larger initial trench separations. Because the middle Philippine Sea Plate is gradually consumed during subduction, the slabs become closer through time, and so the effectiveness of Ryukyu slab pull transmission through the middle Philippine Sea Plate increases. This time lag for larger initial trench-trench distances can therefore be understood by considering that the two slabs/trenches must be at or below a threshold distance apart (~600 km for our model setup) for the required force transmission. In other words, it is the time delay at which the trench motion switch occurs that is a strong function of the initial slab separation, rather than whether advancing trench motion ultimately occurs.

We find that Ryukyu subduction initiated at an earlier stage of Pacific Plate subduction ($t = 2.2$ Myr) induces a switch from a retreating to an advancing IBM Trench at a much later time of $\approx 20$ Myr after subduction initiation (Fig. 6b). However, Ryukyu subduction that is initiated during, or after, slab folding atop the stronger lower mantle results in strong advance of the Izu-Bonin Trench 5–7 Myr after subduction is initiated (Fig. 6b). This short delay is consistent that inferred from our tectonic reconstruction, and a mature/deep Pacific slab geometry is also consistent Ryukyu re-initiation at ~10 Ma (given an Izu-Bonin-Marianas initiation at ~50 Ma and average convergence rate of > 50 mm/yr). In the model in which Ryukyu is inserted at an earlier stage, we find that the IBM slab tip impinges on the lower mantle viscosity increase with an increased dip angle (due to a reduced trench retreat rate after Ryukyu insertion), which causes significant slab folding at depth (e.g., Christensen, 1996). This slab folding is apparent as an oscillation in the trench migration rate evolution (Fig. 6b), and appears to result in the time delay of the switch between IBM Trench retreat and advance. In addition to the model requirement that the IBM slab is in contact with the strong lower mantle, this further implies that a switch from a retreating to an advancing trench is not solely a function of transmitted slab pull, but also strongly depends on other factors influencing the IBM force balance such as slab interaction with a higher viscosity lower mantle or a phase transition.

While our 2-D model is able to produce the first order Izu-Bonin Trench motion trends, we suggest that the three-dimensional geometry of the system may significantly complicate the evolution. As the numerical models are 2-D, mantle flow through the lower mantle is required to accommodate the motion of the two slabs toward each other as the middle plate is subducted. However, in a 3-D setting, toroidal flow around slab edges may be a more energetically favourable way of evacuating asthenosphere from this central region, and this variability in mantle flow style may influence the plate kinematics (e.g., Schellart, 2004). Indeed, single slab subduction models have demonstrated that 3-D mantle flow can play a large role in dictating plate kinematics with, for example, narrower plates tending to produce more rapid rates of trench retreat (e.g., Stegman et al., 2006; Schellart et al., 2007). While similar 3-D effects are likely important in a Philippine Plate style geometry, particularly at the northern terminus of the Ryukyu/Nankai slab, the complex slab geometry of this region (e.g., highly variable trench separation) complicates the direct application of these studies.

While we therefore choose to focus on the less computationally demanding 2-D models, previous work has shown that the same first order plate kinematics are present in a 3-D double slab model, in which rollback-driven mantle flow is almost exclusively toroidal (cf. Fig. 5b in Holt et al., 2017). In the 3-D models, as the two trenches/slabs converge, there is an increase in both the extensional stress in the middle plate and the mantle pressure between the two slabs. These first order patterns are also present in our 2-D models (e.g. Fig. S4), albeit with somewhat different stress magnitudes owing to the differing model setups (including 2-D vs. 3-D geometry). Therefore, even in our simplified 2-D picture, the trench motions obtained by the geodynamic model can, to first order, be compared favourably with the reconstructed trend. Our analysis substantiates the idea that advancing trench motions in the western Pacific are due to the establishment of a double subduction system. Further joint analysis of geological constraints and geodynamic models of subduction may elucidate the dynamics of both isolated and regionally interacting slab systems.
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Appendix A. Supplementary data

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References

Androvichová, A., Čížková, H., van den Berg, A.P., 2013. The effects of rheological de-
Holt, A.F., Becker, T.W., 2017. The effect of a power-law mantle viscoelasticity on trench re-
Holt, A.F., Buffet, B.A., Becker, T.W., 2015. Overriding plate thickness control on sub-
Huchon, P., Barrier, E., de Bremaecker, J.C., Angelier, J., 1986. Collision and stress tra-