PLATE TECTONICS

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On the enigmatic birth of the Pacific Plate within the Panthalassa Ocean

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The oceanic Pacific Plate started forming in Early Jurassic time within the vast Panthalassa Ocean that surrounded the supercontinent Pangea, and contains the oldest lithosphere that can directly constrain the geodynamic history of the circum-Pangean Earth. We show that the geometry of the oldest marine magnetic anomalies of the Pacific Plate attests to a unique plate kinematic event that sparked the plate's birth at virtually a point location, surrounded by the Izanagi, Farallon, and Phoenix Plates. We reconstruct the unstable triple junction that caused the plate reorganization, which led to the birth of the Pacific Plate, and present a model of the plate tectonic configuration that preconditioned this event. We show that a stable but migrating triple junction involving the gradual cessation of intraoceanic Panthalassa subduction culminated in the formation of an unstable transform-transform-transform triple junction. The consequent plate boundary reorganization resulted in the formation of a stable triangular three-ridge system from which the nascent Pacific Plate expanded. We link the birth of the Pacific Plate to the regional termination of intra-Panthalassa subduction. Remnants thereof have been identified in the deep lower mantle of which the locations may provide paleolongitudinal control on the absolute location of the early Pacific Plate. Our results constitute an essential step in unraveling the plate tectonic evolution of "Thalassa Incognita" that comprises the comprehensive Panthalassa Ocean surrounding Pangea.

INTRODUCTION

Oceanic spreading records are the primary source of data in making global plate reconstructions. Because the oldest sea floor currently present on the Earth dates back to ~200 million years ago (Ma), building models of plate tectonic before 200 Ma requires a different approach and relies on data from the continents. As a result, continent motion in global plate reconstructions for times before 200 Ma [for example, reconstructions of Stampfli and Borel (*1*) and Domeier and Torsvik (*2*)] is well constrained, but the now-subducted oceanic plates in those models are conceptual and inevitably speculative.

The Panthalassa Ocean (*3*) was the comprehensive oceanic domain surrounding the supercontinent Pangea in Late Paleozoic and Early Mesozoic times. This vast water mass must have been underlain by multiple oceanic tectonic plates, comparable to the Pacific Ocean today (*4*–*6*). Because the Panthalassa Ocean was completely surrounded by subduction zones, none of its plates was connected to a continent by an oceanic spreading record, and the majority of the plates have been lost to subduction. As a result, reconstructing Panthalassa's plate tectonic evolution has proved to be a challenge. However, attempting this reconstruction is worthwhile because the motion of Panthalassa's surface plates may provide the only direct kinematic constraint that we can obtain to assess the style of mantle dynamics in the presence of a supercontinent and particularly may help resolve how Pangea was formed and eventually broke up [for example, the study of Conrad *et al.* (*7*)]. The starting point for a Panthalassa reconstruction is a full kinematic restoration of the plates underlying the present-day Pacific Ocean, on the basis of their marine magnetic anomalies. The oldest lithosphere present in the Pacific domain is the oldest part of the Pacific Plate (the "Pacific triangle") and is of Early Jurassic age (*5*, *8*–*10*), setting the limit of this reconstruction at ~190 Ma. However, we show here that this piece of lithosphere also contains clues on the plate boundary configuration of the "pre-Pacific" plates of the Panthalassa Ocean and can take us an essential step further back in time.

The Pacific triangle is located just east of the Marianas Trench (Fig. 1) and contains magnetic anomalies in three orientations: the northeast-trending Japanese, northwest-trending Hawaiian, and east-trending Phoenix lineations (*11*). The geometry of the triangle that is formed by these sets of anomalies (Fig. 1) implies that the Pacific Plate (PAC) grew as a result of ocean spreading at three ridges that must have separated the Pacific Plate from three conceptual preexisting oceanic plates. These plates are known as the Izanagi (IZA), Farallon (FAR), and Phoenix (PHO) Plates to the northwest, northeast, and south, respectively. Except for some relics of the Farallon Plate, these plates have been lost to subduction. Mirroring the Japanese, Hawaiian, and Phoenix lineations at conceptual ridges with Izanagi, Farallon, and Phoenix allows for reconstructing a plate boundary evolution of the nascent stages of the Pacific Plate in the Early Jurassic, showing that the Pacific Plate originated virtually at a point. This is a very unusual tectonic event because all other modern plates formed as a result of breakup of a predecessor by rifting and subsequent mid-ocean ridge formation within the continental or oceanic lithosphere. For example, the African Plate became a separate plate as a result of the breakup of Pangea, whereby the current plate obtained its final plate boundary by the formation of the South Atlantic mid-ocean ridge upon the separation of Africa from South America (*12*, *13*). This not only holds true for plates containing continental crust, but also for purely oceanic plates. For example, the oceanic Juan de Fuca, Cocos, and Nazca Plates of the eastern Pacific region formed as a result of the breakup of the former Farallon Plate (*14*, *15*). Thus, all of these plates contain or contained crust that is older than the formation of at least one of its plate boundaries. However, the center of the Pacific triangle contains crust that is no older than the formation of the ridges that created it. This point of birth of the Pacific Plate represents the triple junction between the Farallon, Izanagi, and Phoenix Plates (*4*) and is generally portrayed as a ridge-ridge-ridge (RRR) triple junction, at which the Pacific microplate formed ~190 Ma as a result of

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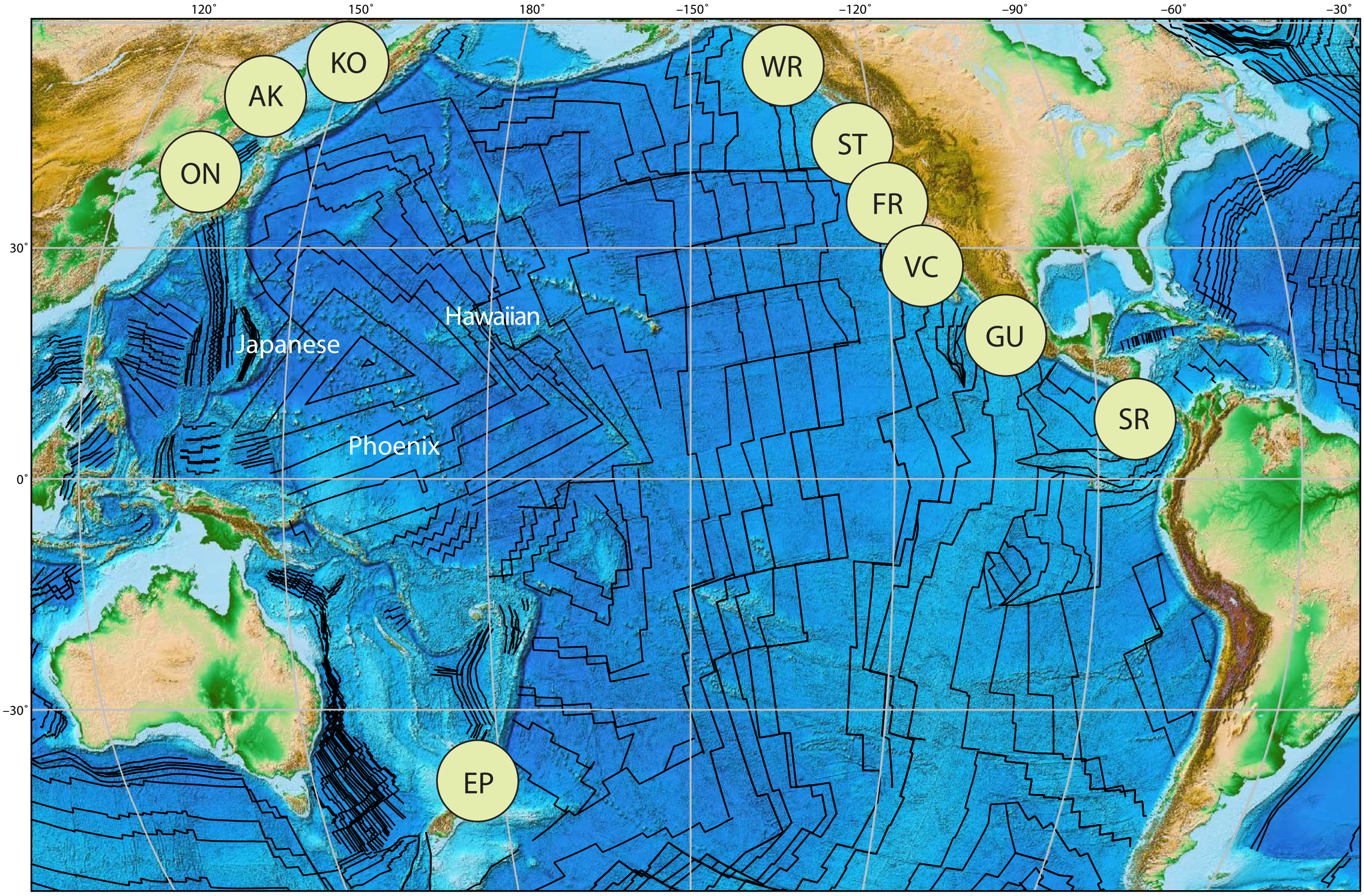

Fig. 1. Isochrons of the Pacific Plate based on marine magnetic anomaly data, including the Japanese, Hawaiian, and Phoenix sets (*5*) and accretionary intra-Panthalassa subduction complexes. KO, Kolyma-Omolon; AK, Anadyr-Koryak; ON, Oku-Niikappu; EP, New Zealand's Eastern Province; WR, Wrangellia; ST, Stikinia; FR, Franciscan accretionary complex; VC, Vizcaíno-Cedros region of Baja California; GU, Guerrero; SR, Santa Rosa accretionary complex.

the triple junction falling apart into three new RRR triple junctions (*5*, *16*). However, an RRR triple junction is stable (*14*, *17*, *18*), and there is no reason for this triple junction to spontaneously fall apart. Present-day RRR triple junctions (for example, in the South Atlantic, Indian, and Pacific Oceans) have been stable for tens of millions of years, or even more than 100 million years (My) (*5*, *9*). Oceanic plate boundary reorganization is instead expected when existing plate boundaries are obstructed (for example, by collision) or cease to exist (for example, because of ridge subduction), or when an unstable triple junction forms (*18*). With the Pacific Plate originating from a triple junction, we therefore explore how it may have originated from an unstable triple junction between the Izanagi, Farallon, and Phoenix Plates, and discuss how reconstructing this is relevant for deciphering the plate tectonic evolution of the Panthalassa Ocean.

RESULTS

The orientations of the Pacific triangle magnetic anomalies allow construction of the relative motions between IZA-PAC, FAR-PAC, and PHO-PAC, and, indirectly, of IZA-FAR-PHO motions. The relative motion diagram (Fig. 2) shows that, since 190 Ma, IZA-FAR, FAR-PHO, and PHO-IZA were diverging; thus, their plate boundaries, as well as the triple junction at which the Pacific Plate was born, must have consisted of a combination of only ridges (R) or transform faults (F). The orientation of these ridges and transform faults can be inferred from the relative motion diagram (Fig. 2). RRR, RRF, and RFF triple junctions are all stable, and these three can alternate through time (*19*, *20*). However, the fourth option, an FFF triple junction, is unstable and has the property of opening a triangular "gap" in its center immediately after its formation (Fig. 3B). Consequently, ridges form at which new oceanic crust is accreted, which then fills this gap, and a new plate is born at this now-stable plate boundary configuration (Fig. 3C). This plate system predicts the ridges and their geometry that generated the Jurassic triangular magnetic anomalies of the Pacific Plate observed on the sea floor.

By definition, an unstable triple junction can only exist temporarily (*14*) as a transitional plate boundary configuration between one stable situation and the next. The nature of the IZA-FAR-PHO triple junction before the birth of the Pacific Plate can be constructed using the basic rules of plate tectonics, assuming no change in relative plate motion in the IZA-FAR-PHO system before and after the birth of the Pacific Plate occurred. To end up in the unstable FFF triple junction, two plate boundaries must have been transform faults that remained unchanged, whereas the third plate boundary must have been kinked, resulting in a transform

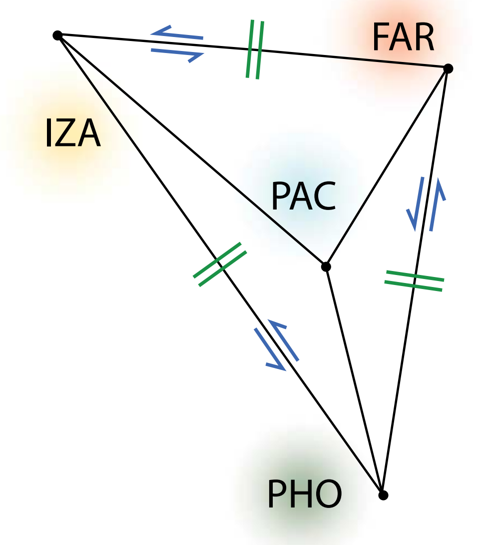

Fig. 2. Relative motion diagram of the PAC-IZA-FAR-PHO plate system. The sense of motion of transform segments (in blue) and the orientation of ridges (in green) of the conceptual IZA-FAR, FAR-PHO, and PHO-IZA plate boundaries.

plate boundary on one side of the kink and an oblique subduction zone [trench (T)] on the other (Fig. 3A). The resulting transform-transform-trench (FFT) triple junction is stable but migrates along the trench toward the kink. During triple junction migration, the length of the subduction zone segment reduces diachronously, and when the triple junction arrives at the kink, an unstable FFF triple junction is generated at which the Pacific Plate starts forming (*18*). On the basis of the marine magnetic anomaly data of the Pacific triangle, it is impossible to determine which plate boundary contained the subduction segment and which plate was in the overriding plate position. As a result, three different but geometrically similar plate boundary configurations are possible. Figure 3A shows the scenario in which the Farallon Plate is subducted below the Izanagi Plate, resulting in a subduction segment that is oriented north-northwest–south-southeast.

DISCUSSION

Current plate motion models of the Pacific Plate [for example, the model of Wright *et al.* (*6*)] show that it can be incorporated into the global plate circuit until 83 Ma. This age marks the onset of spreading in the Antarctic-Pacific ridge, and the record of this spreading allows for constraining the motion of the Pacific Plate relative to the global plate circuit in great detail. Before 83 Ma, the Pacific Plate and the oceanic plates from which it was separated by spreading ridges were entirely surrounded by subduction zones, isolating it from the global plate circuit. The best available constraint on Pacific Plate motion before 83 Ma is provided by a fixed hotspot reference frame for the Pacific Plate (*21*), which goes back to 145 Ma. This hotspot frame provides the position of the Pacific Plate with respect to the mantle. There is currently no control on either relative (to the global plate circuit) or absolute Pacific Plate motion before this time.

Our reconstruction infers an essential role for subduction and subduction termination in the formation of the unstable triple junction that sparked the birth of the Pacific Plate. Remnants of such Early Jurassic subduction can be found with deep-earth seismology. Seismic tomography (*22*–*26*) and seismic waveform analysis (*27*, *28*) of deep mantle structure below the present Pacific Ocean show two major high-velocity anomaly zones that have been interpreted as remnants of slabs belonging to two large-scale intra-Panthalassa subduction systems that are oriented north-northwest–south-southeast: a central system ("Telkhinia" subduction system) and a "fringing" subduction system, closer to the present American continents (*29*, *30*). The depth of these anomalies suggests that intra-oceanic subduction occurred during and before the time window in which the Pacific Plate originated. Furthermore, the modern circum-Pacific accretionary prisms of Japan, Siberia, New Zealand, and western North and Central America contain accretionary subduction complexes (Fig. 1), including Lower to Middle Mesozoic ocean floor rocks that are scraped off downgoing Panthalassa plates, as well as intraoceanic volcanic arcs that went extinct up to tens of millions of years before accretion into the fold-thrust belts where they currently reside (*29*–*32*). The arc remnants of the North American margin have previously been linked to the fringing subduction system (*29*, *30*), whereas the remnants of the northwest Pacific appear to have traveled farther and are related to the Telkhinia subduction system (*29*).

Our reconstruction links the birth of the Pacific Plate to the termination of an intra-Panthalassa subduction system, which may correlate either to the Telkhinia or to the fringing subduction system. Figure 4 shows the motion path of the Pacific Plate relative to the mantle in 5-My steps. The motion path is based on the model of Wright *et al.* (*6*), placed in a slab-fitted mantle reference frame (*33*) for 0 to 83 Ma (in black), and in the Pacific hotspot WK08-A model (*21*) for 83 to 140 Ma (in gray). The motion path shows an unrealistic jump between 85 and 80 Ma, illustrating the uncertainties in both the slab and fixed Pacific hotspot frames, but the trend in both frames shows an overall westward motion since 140 Ma. Figure 4 also shows the position of the continents at 190 Ma (*34*) and a 2480-km depth tomography slice from the UU-P07 tomographic model (*23*), interpreted to show slabs that subducted in the Early Jurassic (*29*).

Using a maximum absolute plate motion velocity of 10 cm/year as reasonable upper bound (*35*), the 190-Ma position of the Pacific Plate should lie within a circle with a radius of 5000 km centered around its 140-Ma position (Fig. 4). Both the fringing and the Telkhinia subduction systems are present within the limits of this circle, and therefore, deep mantle anomalies of both could be linked to the reconstructed subduction segment. A comparison of alternative tomographic models (*24*–*26*) with the UU-P07 model (Supplementary Materials) shows that the anomalies related to the fringing subduction system are a common feature in all four models. The equatorial part of this system, located within the dotted black line in Fig. 4, was previously detected in seismological (*36*–*38*) and tomographic (*39*) studies and was named the Trans-Americas slab by van der Meer *et al.* (*33*). The Telkhinia system, a prominent positive anomaly in the UU-P07 model, is less evident in the other tomographic models. However, the other models do show a weakly positive or subdued negative anomaly, interpreted to reflect the effect of a sinking slab into the anomalously hot Pacific large low shear wave velocity province (*29*).

If the Pacific Plate started forming as a result of cessation of a part of the fringing subduction system, the absolute Pacific Plate motion would have been more or less continuously westward since 190 Ma. The second scenario, whereby the Pacific Plate originated at the Telkhinia

Fig. 3. Three-step evolution of the FAR-PHO-IZA plate system and birth of the Pacific Plate. (**A**) Pre–190 Ma. (**B**) Approximately 190 Ma. (**C**) Post–190 Ma.

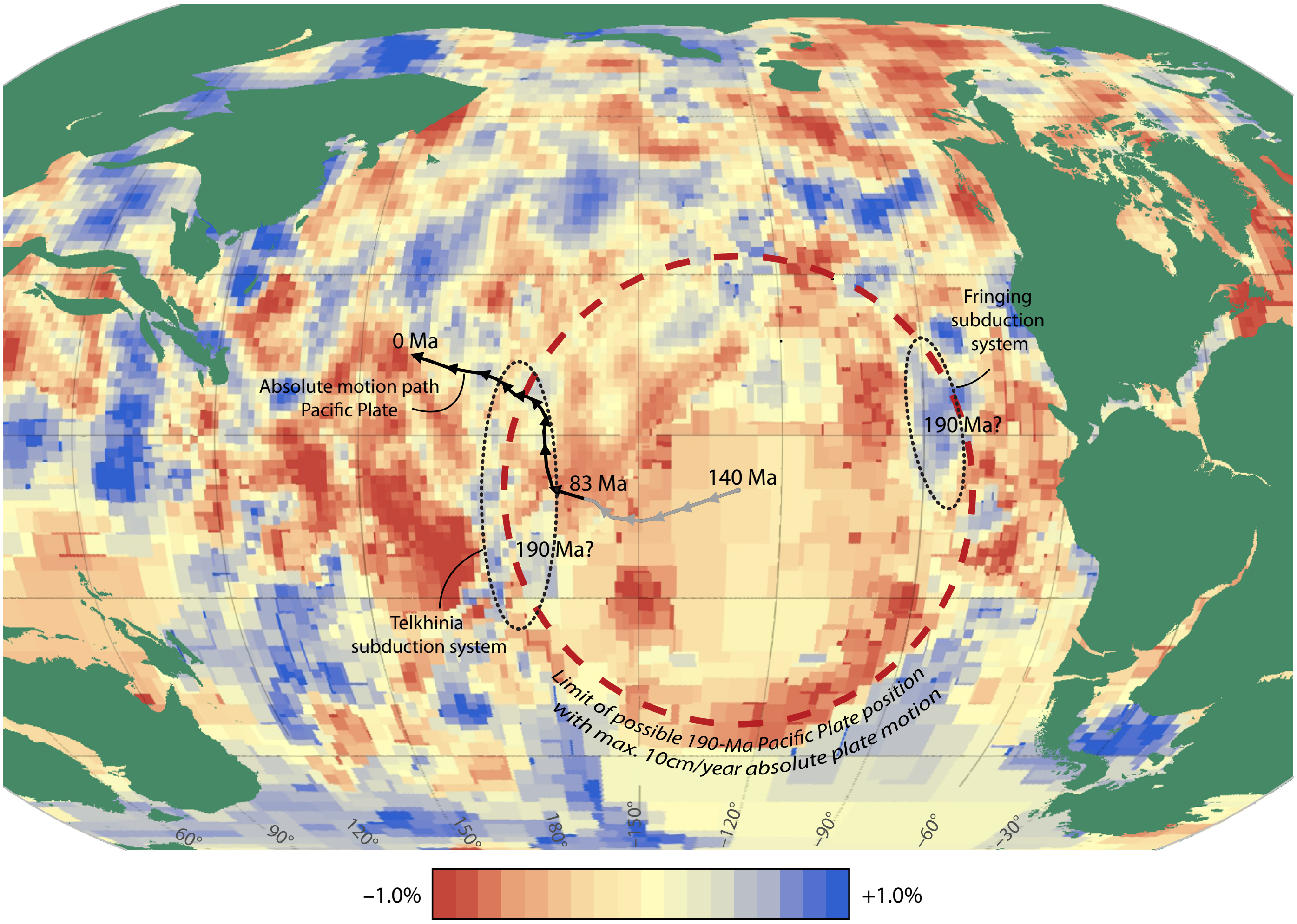

Fig. 4. Absolute plate motion path of the Pacific Plate. The black line is based on the model of Wright *et al.* (*6*), incorporated in a mantle reference frame (*33*); the gray line is based on the fixed Pacific hotspot frame from Wessel and Kroenke (*21*). Red and blue background colors represent the 2480-km depth slice of the UU-P07 tomographic model.

subduction system, would require an abrupt absolute plate motion change around 140 Ma. Although not impossible, this second scenario depends on a less simple tectonic model and is therefore not favored. To further discriminate between the two possible scenarios, relative motions of the Panthalassa plates with respect to the surrounding continents, or absolute plate motion rates of the Izanagi and Farallon Plates, play an essential role. To investigate those, paleolatitudinal motions can be inferred from paleomagnetic and faunal analysis on the Panthalassa rocks in the geological records of the circum-Pacific margins [for example, records of Tarduno *et al.* (*40*), Oda and Suzuki (*41*), and Kodama *et al.* (*42*)], and paleolongitudinal motion can be inferred from linking paleolatitudinally constrained intraoceanic volcanic arcs to deep mantle structure (*18*, *19*).

CONCLUSION

Our analysis shows that it is possible to develop a data-informed plate model of the IZA-FAR-PHO system before the birth of the Pacific Plate using the philosophies and techniques from the early days of plate tectonic reconstructions (*4*, *18*). Including the Izanagi, Farallon, and Phoenix Plates into a global plate reconstruction requires control on absolute plate motions, which can be inferred from combining this surface model with seismology. The analysis presented here provides a key to unlocking the plate kinematic history of the plates that once occupied the "Thalassa Incognita," which comprises the comprehensive Panthalassa Ocean surrounding Pangea.

MATERIALS AND METHODS

Our reconstruction of relative motions between the Pacific, Farallon, Izanagi, and Phoenix Plates was inferred from isochrons (*6*), on the basis of marine magnetic anomaly data. The absolute motion path of the Pacific Plate (tracking the center of the Pacific triangle) was plotted in the context of a global plate reconstruction (*34*), using the GPlates plate reconstruction software [www.gplates.org; (*43*)]. The global reconstruction was placed in a slab-fitted mantle reference frame (*33*); for the time period between 140 and 83 Ma, the Pacific Plate was placed in a Pacific fixed hotspot frame (*21*), Figures 1 and 4 were produced using GPlates.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/2/7/e1600022/DC1

movie S1. Comparison of the UU-P07 (*23*), S40RTS (*24*), SEMUCB-WM1 (*25*), and TX2015 (*26*) tomography models for the Panthalassa region at 1500- to 2840-km depth.

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