

# Tectonics

## RESEARCH ARTICLE

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### Key Points:

- Remnants of an accreted intra-oceanic arc are exposed in the accretionary complexes of Hokkaido, Japan
- We reconstruct this arc, which went extinct in an open ocean setting around 145 Ma, 45 Myr before accretion, likely due to ridge subduction
- The associated ~145 Ma plate reorganization is reflected in a change in magnetic anomaly orientation at the northwestern Pacific Plate

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# Reconstructing Jurassic-Cretaceous Intra-Oceanic Subduction Evolution in the Northwestern Panthalassa Ocean Using Ocean Plate Stratigraphy From Hokkaido, Japan

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**Abstract** Plate reconstructions of the Panthalassa Ocean typically portray a simple system of diverging plates surrounded by active margins, yet geological and seismic tomographic records demonstrate that intra-oceanic subduction existed. Here, we reconstruct the plate tectonic evolution of the pre-Cretaceous intra-oceanic Oku-Niikappu island arc, remnants of which are exposed on Hokkaido, Japan. This arc formed at a Jurassic subduction zone separating two oceanic plates: the Izanagi Plate and the here proposed ‘Izanami’ Plate. The Oku-Niikappu arc was previously shown to have gone extinct in an intra-oceanic setting, was subsequently (hyper)extended, and overlain by Berriasian cherts. The extinct arc remained on the Panthalassa ocean floor for ~45 Myr until its ~100 Ma accretion to Hokkaido, revealing an original position far from the continental margin and likely above the previously identified Telkhinia slabs. We show that arc extinction coincided with a northwestern Panthalassa plate reorganization recorded by a ~30° change in spreading direction, and that extinction and subsequent extension of the arc is straightforwardly explained by subduction of the Izanami-Pacific ridge followed by continued divergence between the Izanagi and Pacific plates. From our reconstruction, it follows that the outer zone of Japan, to which the accretionary complex in which the Oku-Niikappu Complex resides belongs, was separated from the inner zone by a back-arc basin during the Early to mid-Cretaceous. This study illustrates the value of accretionary orogens in the development of plate reconstructions of lost oceanic plates and ancient continental margins, particularly when combined with seismic tomographic and marine geophysical data sets.

## 1. Introduction

Because the plates underlying ocean basins that existed in deep geological time are mostly lost to subduction, reconstructing their tectonic evolution is difficult. For the Panthalassa Ocean that surrounded the supercontinent Pangea, marine magnetic anomalies preserved on the Pacific Plate reveal that this ocean must have hosted at least three plates that all shared spreading ridges with the growing Pacific Plate: the conceptual Phoenix Plate in the south, the Farallon Plate in the northeast, and the Izanagi Plate in the northwest (Larson & Chase, 1972; Nakanishi et al., 1992; Woods & Davies, 1982). In global plate tectonic reconstructions (e.g., Müller et al., 2016, 2019; Scotese, 2004; Seton et al., 2012), plates and plate motions in the Pacific domain are based on these marine magnetic anomalies, and these reconstructions portray the Panthalassa Ocean as a three-plate (Izanagi–Phoenix–Farallon) system with one central ridge-ridge-ridge triple junction before, and a four-plate (Izanagi–Phoenix–Farallon–Pacific) system after Early Jurassic birth of the Pacific Plate. In such reconstructions, it is assumed that the Izanagi, Phoenix, and Farallon plates existed since long before 190 Ma, and that they subducted gradually below the circum-Pacific margins (Müller et al., 2016, 2019; Scotese, 2004; Seton et al., 2012).

Depending on their characteristics (i.e., mechanical coupling between the subducting and overriding plate, sediment supply, presence/absence of fluids, etc.) subduction zones can be accretionary, neutral, or erosive, and subduction zones can switch between the two modes when these characteristics change (Le Pichon et al., 1993). Present-day subduction at the circum-Pacific margins is mainly erosive (Straub et al., 2020), but throughout their history, many circum-Pacific trenches have experienced episodes of subduction accretion, resulting in the formation of accretionary orogens. Such accretionary orogens generally consist of series of

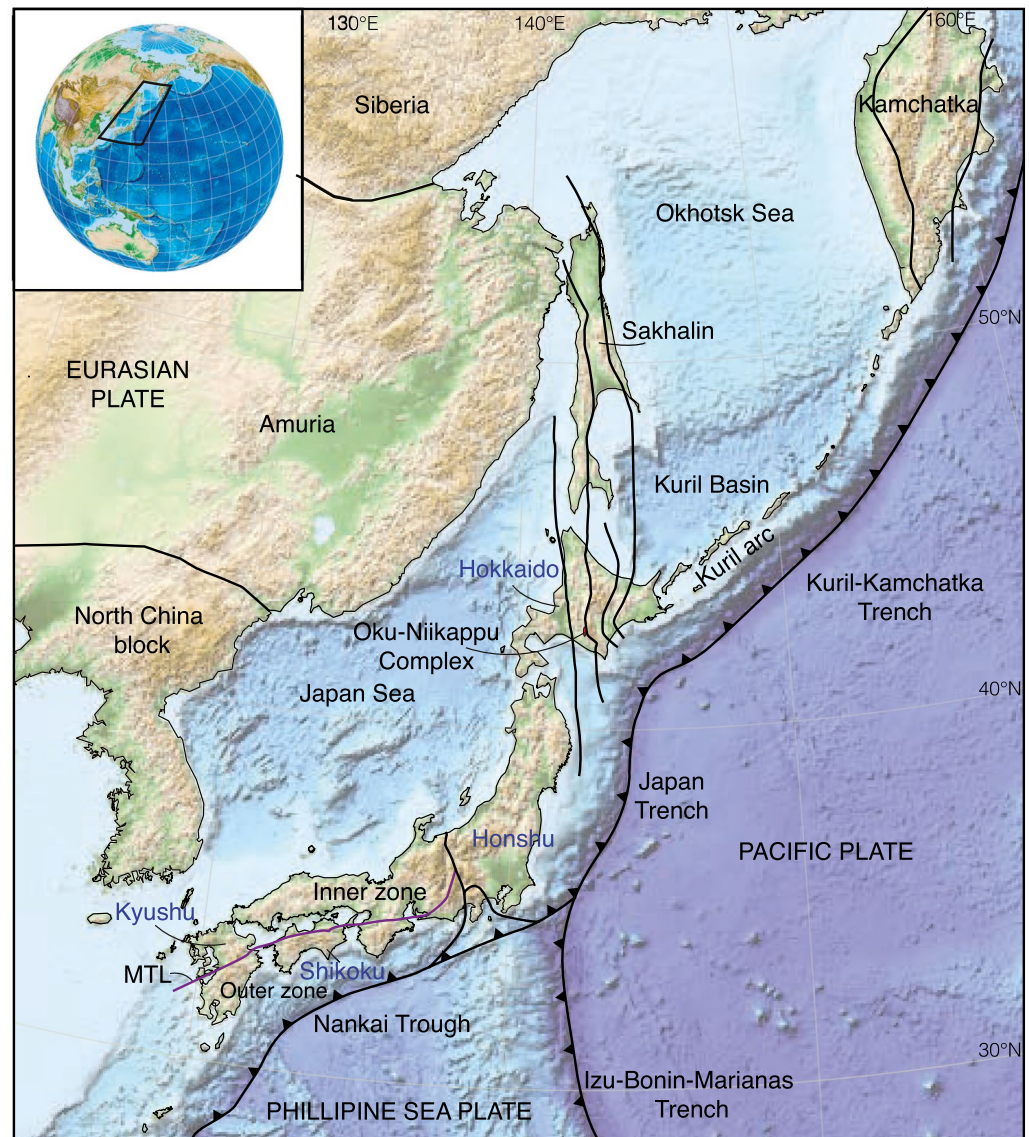
overall trenchward-younging complexes, and these complexes typically contain sequences or fragments of Ocean Plate Stratigraphy (OPS; Isozaki, 2000; Isozaki et al., 2010). OPS, originally formed and deposited on oceanic lithosphere, consist in its most complete form of mafic magmatic basement rocks, overlying oceanic sedimentary rocks (radiolarian cherts, limestones, pelagic and hemipelagic mudstones), and turbiditic and tuffaceous trench-fill deposits. Typically, age gaps between adjacent sequences of trench-fill deposits separate the accretionary rocks into distinct complexes (Isozaki et al., 1990). Analysis of OPS sequences provides key information on the history and motion of subducted plates: through geochemical analysis of the mafic basement, it is possible to identify whether the OPS formed at a mid-ocean ridge, an island arc, or a plume-related seamount or plateau. Furthermore, the age difference between the base of the OPS and the trench-fill deposits at the top reflects the minimum—and in the case of a MORB geochemical signature, true—age of the oceanic lithosphere at the time of subduction.

Although the record of subducted paleogeography preserved in accretionary complexes is highly incomplete both spatially and temporally, it is in many occasions the sole source of information on the tectonic history of former oceanic domains, and has been used in studies reconstructing plate motions of subducted oceanic plates, intra-oceanic arcs, or seamounts. For example, on the Siberian Kamchatcha Peninsula and the island of Karaginsky, a sequence of mafic (meta)volcanics, tuffs, volcanoclastics, cherts, and siliceous sedimentary rocks is exposed (Hourigan et al., 2009; Kirmasov et al., 2004; Konstantinovskaia, 2001). These rocks are interpreted as remnants of the Late Cretaceous–Paleogene intra-oceanic Olyutorsky arc, which originated at an intra-Panthalassa subduction zone (Konstantinovskaia, 2001; Shapiro & Solov'ev, 2009). This subduction zone was incorporated in tectonic reconstructions and linked to mantle structure by Domeier et al. (2017) and Vaes et al. (2019), and provides evidence that the plate kinematic evolution of the northwestern Panthalassa Ocean involved more than just a single Izanagi Plate subducting at the continental northeast Asian margin.

Similarly, a relic of intra-oceanic subduction is identified in the accretionary complexes of Hokkaido, the northernmost island of Japan, albeit older (Jurassic–earliest Cretaceous) in age (Ueda & Miyashita, 2005). This relic, the Oku-Niikappu Complex (Figures 1 and 2) that accreted in mid-Cretaceous time (~100 Ma), consists of pre-Berriasian magmatic basement, Berriasian radiolarian cherts, and mid-Cretaceous trench fill deposits (Ueda & Miyashita, 2005). Geochemical analysis of the magmatic basement revealed an arc signature (Ueda & Miyashita, 2005), thereby providing evidence for intra-oceanic subduction in the oceanic domain facing the Jurassic Hokkaido trench. The complex tectonic history of the Hokkaido arc-trench system (including Jurassic forearc basin spreading) and the small modern dimensions of the Oku-Niikappu Complex notwithstanding, we here demonstrate that the Oku-Niikappu arc was a major player in the tectonic history of the Jurassic–Cretaceous northwestern Panthalassa Ocean.

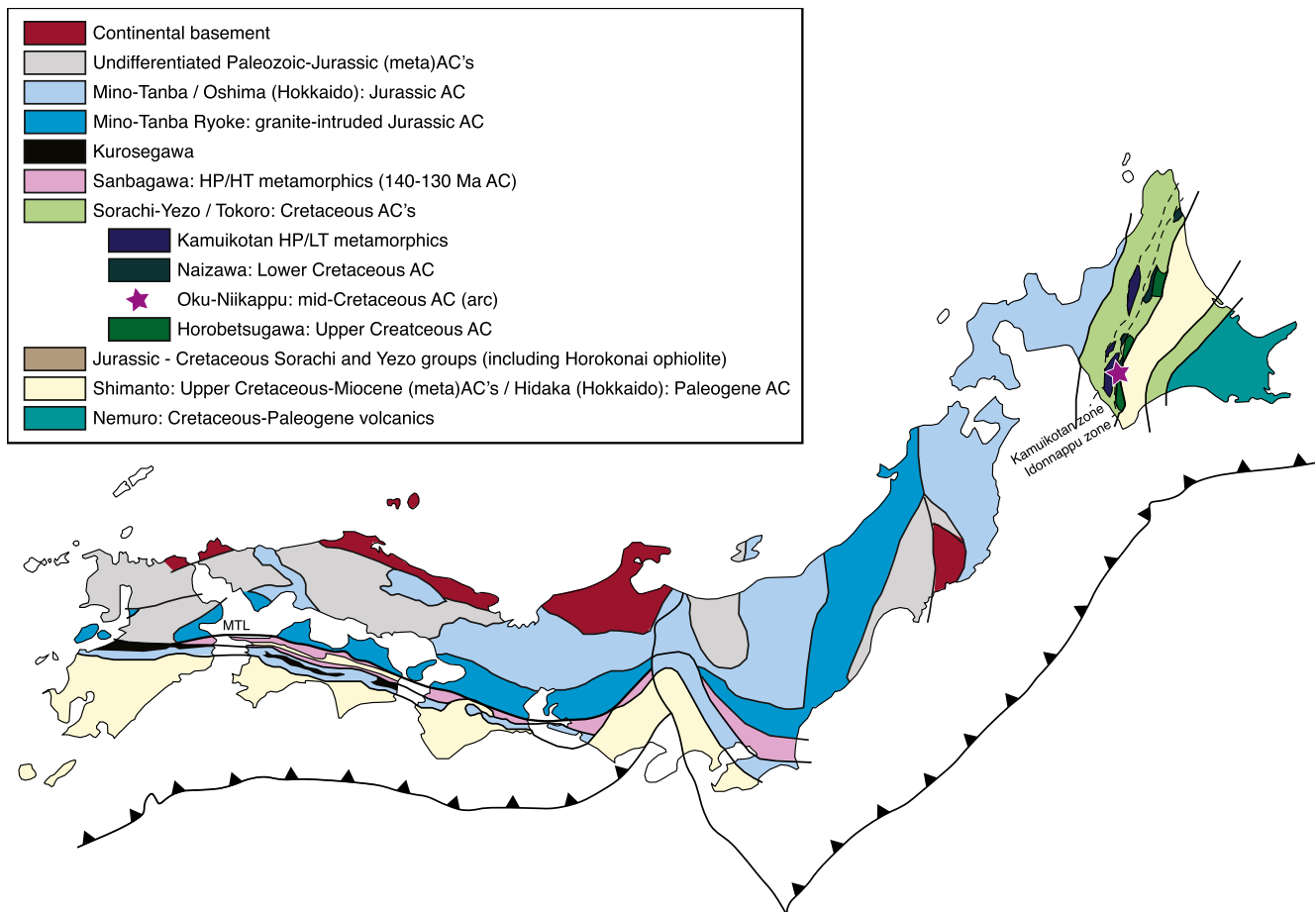
There are multiple other lines of evidence for Jurassic intra-Panthalassa subduction. First, age grids of marine magnetic anomaly based global reconstructions, such as those from Müller et al. (2016), underestimate the age of large parts of oceanic lithosphere in the Panthalassa Ocean when compared to OPS records. These age grids predict the age of oceanic lithosphere that subducted below the northeast Asian continental margin in Middle Jurassic time to be ~245–265 Ma, whereas the OPS sequence that accreted on Hokkaido in Middle Jurassic time contains Upper Carboniferous sediments, indicating that its ocean floor formed around or before 300 Ma. For such old ocean floor to be present along the northeast Asian margin, part of the conjugate oceanic lithosphere of the Pacific Plate must have been consumed by subduction, not only along the continental margin, but also elsewhere, at an intra-Panthalassa subduction zone.

Second, seismic tomographic images of the lower mantle below the Pacific Ocean have revealed wave speed anomalies, interpreted to result from intra-oceanic subduction in the Mesozoic central Panthalassa Ocean (van der Meer et al., 2012). van der Meer et al. (2012) interpreted a band of deep lower mantle seismic wave speed anomalies as slab remnants (the Telkhinia slabs), which they linked to the Oku-Niikappu arc, as well as to geological records of intra-oceanic subduction accreted in northeast Siberia. Their correlation suggests that intra-oceanic subduction occurred in one or multiple, roughly north-south oriented subduction systems stretching from ~60°N to equatorial latitudes close to the Jurassic–Early Cretaceous location of the Pacific Plate (Figure 3), thousands of kilometers east of the Eurasian margin, which is consistent with the ~45 Myr delay between Oku-Niikappu extinction and accretion in Hokkaido.



**Figure 1.** Tectonic map of Japan and the northeast Eurasian continent. MTL: Median Tectonic Line.

Third, marine magnetic anomalies on the Pacific ocean floor (Larson & Chase, 1972; Nakanishi et al., 1992; Woods & Davies, 1982) reveal a sharp,  $\sim 30^\circ$  change in Pacific-Izanagi spreading direction sometime between 146.6 and 137.9 Ma (Figure 4). This change indicates that a plate reorganization occurred within the northwestern Panthalassa Ocean around the time of termination of Oku-Niikappu intra-oceanic subduction. Collectively, these observations suggest that a Jurassic northwestern Panthalassa Ocean (the Izanagi domain) hosted at least one major intra-oceanic subduction system, and experienced a plate reorganization around 145 Ma. In this paper, we present a novel conceptual model of the subduction history of the Jurassic-Cretaceous northwestern Panthalassa Ocean, which is self-consistent and testable by future studies, and integrates the geological record of Hokkaido including evidence of intra-oceanic arc magmatism, seismic tomography, and the marine magnetic anomaly record of the Pacific Plate.



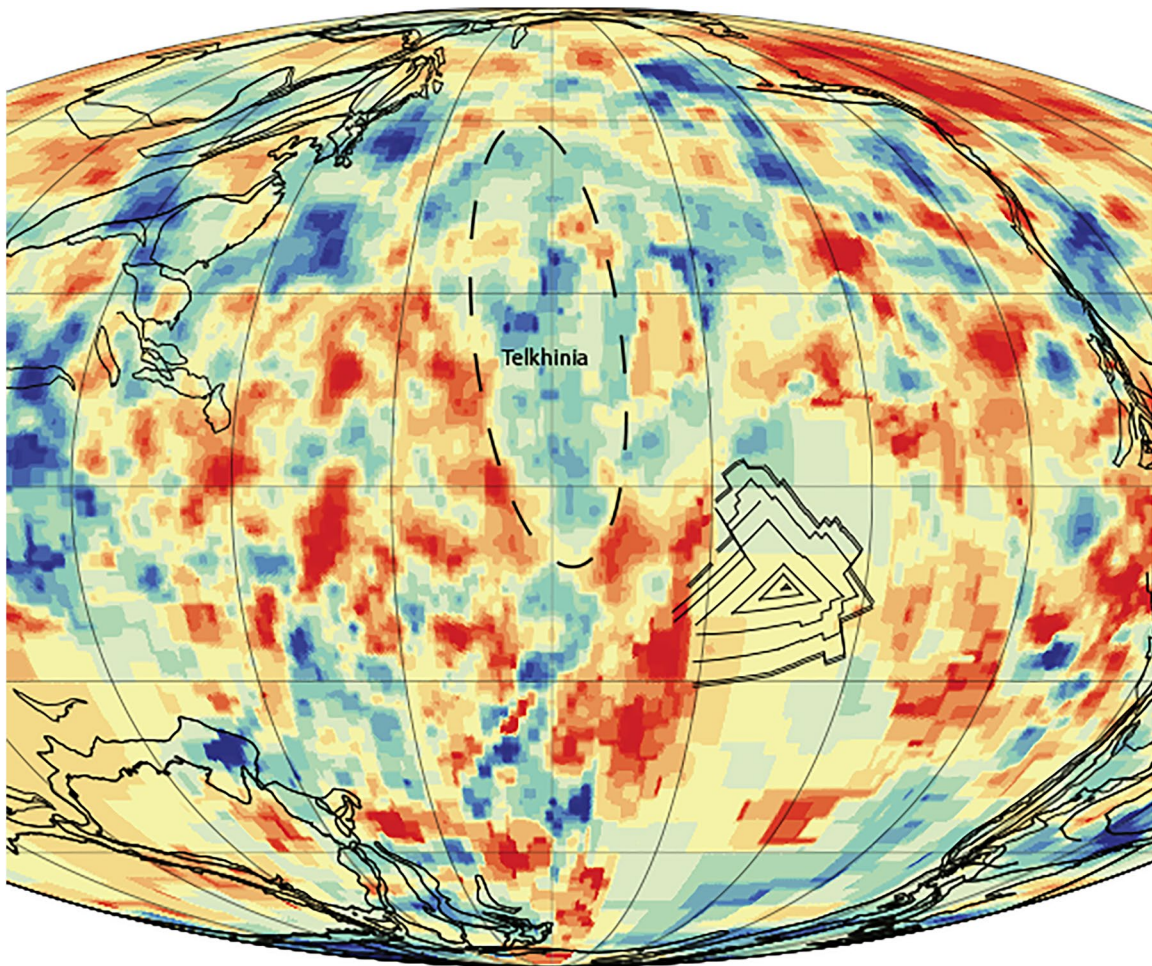
**Figure 2.** Simplified tectonic map of Japan. AC: accretionary complex. Note that although the Sanbagawa belt is shown in pink to emphasize its HP/HT (eclogite) metamorphism, the protolith is a 140–130 Ma AC, equivalent in time to the Naizawa complex on Hokkaido. Based on Isozaki et al. (2010) and Ueda (2016).

## 2. Geological Setting

### 2.1. Pacific–Izanagi Spreading Records

The oldest part of the Pacific Plate, located in the northwestern Pacific Ocean, contains marine magnetic anomalies and fracture zones in three orientations (Figure 4). The northeast trending “Japanese” lineations represent the record of spreading of the Pacific Plate relative to now-subducted lithosphere of the conceptual Izanagi Plate that existed in the northwestern Panthalassa Ocean. The preserved anomalies are correlated to ages between ~190 and ~100 Ma (Larson & Chase, 1972; Nakanishi et al., 1992; Woods & Davies, 1982). Spreading with the Izanagi Plate is thought to have continued longer, but post-100 Ma lithosphere of the Pacific Plate has already subducted below east Asia; the subduction of the Pacific–Izanagi ridge is thought to have occurred around 50 Ma (Seton et al., 2015; Wu & Wu, 2019).

In modern coordinates, fracture zone orientations indicate northwestward spreading relative to the Pacific Plate for the ~190–146.6 Ma interval, followed by an abrupt change toward north-northwestward motion (Figure 4). This change indicates a sudden reorganization of spreading direction and ridge orientation, sometime between 146.6 and 137.9 Ma. This change is not observed in the Hawaiian (eastern) or Phoenix (southern) lineations; the Hawaiian lineations, recording Pacific–Farallon spreading, do vary in orientation, but this variation is only present in younger lithosphere (137.9–100 Ma) and records a continuous rotation of the Pacific–Farallon spreading ridge rather than an abrupt plate motion change. The Phoenix lineations, recording Pacific–Phoenix spreading, are consistently oriented WSW–ENE and do not reflect a sudden Early Cretaceous change either. This indicates that the orientation change in the Japanese lineations is likely



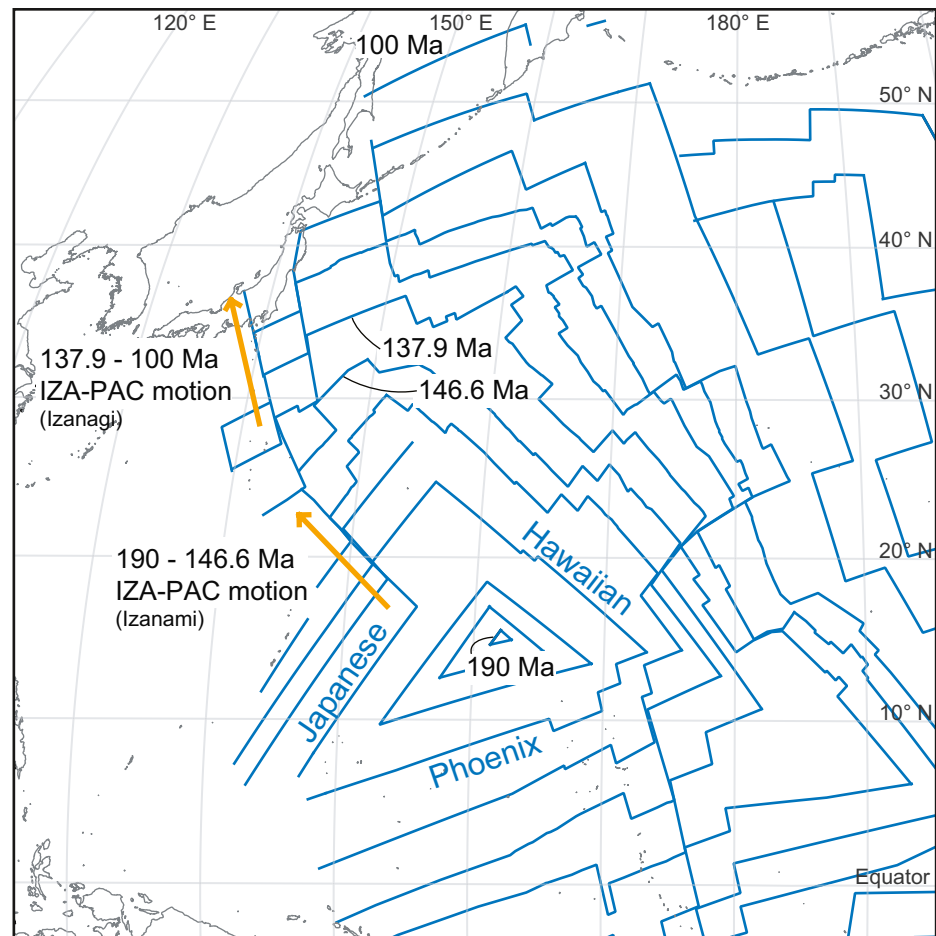
**Figure 3.** Seismic tomographic image from the UU-P07 model (Amaru, 2007). Depth slice of 2,110 km depth overlain by a tectonic reconstruction (at 145 Ma) of the Indo-Atlantic plate system (in the mantle reference frame of van der Meer et al., 2010), and the Pacific Plate (in the mantle reference frame of Torsvik et al., 2019). Centered at the 180° meridian.

caused by a plate reorganization in the northwestern Panthalassa Ocean that did not significantly affect the motion of the Pacific Plate relative to the Phoenix or Farallon plates. So far, this plate reorganization remains unexplained.

## 2.2. Seismic Tomography

Van der Meer et al. (2012) identified a band of seismic wave speed anomalies in the lower mantle below the central Pacific Ocean that they interpreted as subducted lithosphere, and named the Telkhinia slabs (Figure 3). This result has later been corroborated by seismic observations of Ma et al. (2016). During subduction, slabs may migrate considerably relative to the mantle through roll-back or slab dragging (Schellart, 2017; van de Lagemaat et al., 2018), but after slab break-off, they tend to sink near-vertically (Domeier et al., 2016) at overall lower mantle sinking rates on the order of 1–1.5 cm/yr (van der Meer et al., 2010, 2018). Using the assumption that slabs demarcate the location of former subduction zones after their break-off, tomography has in recent years become a tool to determine the absolute position of the global plate circuit (van der Meer et al., 2010), and to identify the paleo-location of former subduction zones whose geological records have been significantly displaced (Clennett et al., 2020; Domeier et al., 2017; Parsons et al., 2020; Shephard et al., 2013; Sigloch & Mihalynuk, 2013; Vaes et al., 2019; van der Meer et al., 2012; Wu et al., 2016).

The Telkhinia slabs range in depth from ~1,600 km down to the base of the mantle, suggesting a subduction age of Triassic to Early Cretaceous (van der Meer et al., 2012, 2018). Van der Meer et al. (2012) correlated not

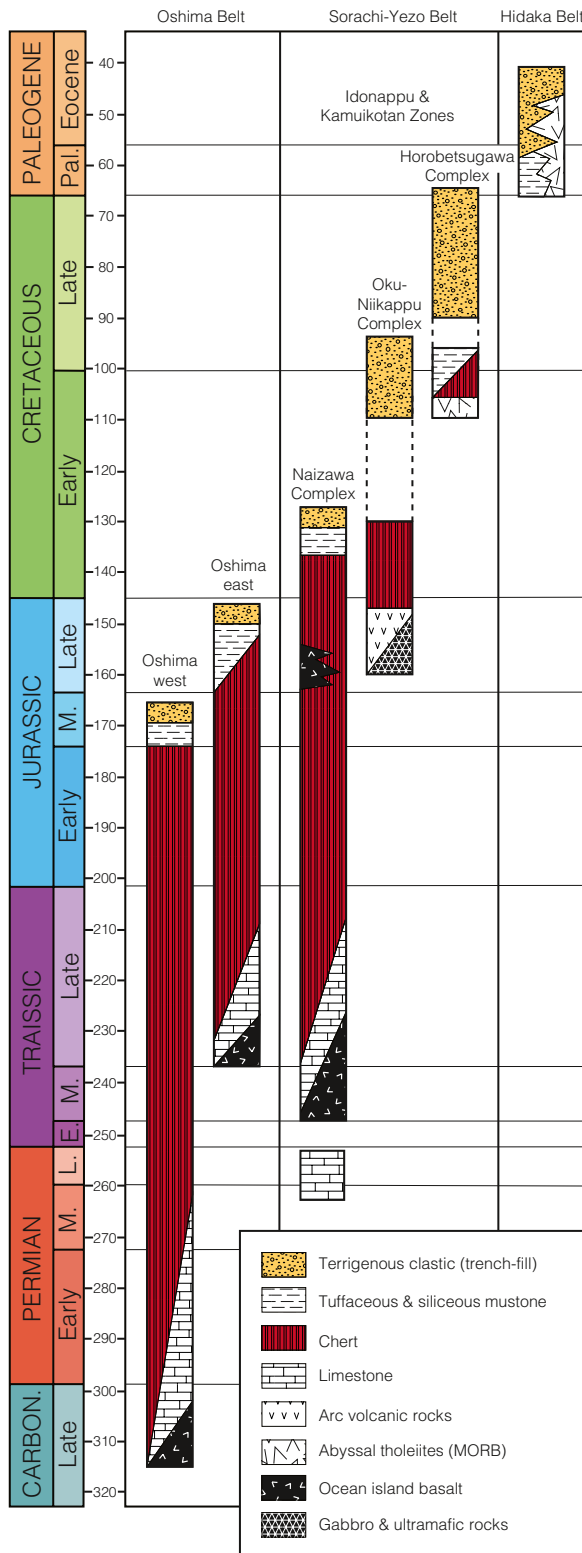


**Figure 4.** Isochrons (from Wright et al., 2016) of the Pacific Plate based on marine magnetic anomalies.

only the Oku-Niikappu Complex to Telkhinia subduction, but also intra-oceanic arc remnants exposed in the Russian northeast (the Kolyma–Omolon and Anadyr–Koryak terranes Nokleberg, 2000; Stone et al., 2003). However, these arc remnants are considerable older (Triassic–Jurassic), and accreted earlier (Late Jurassic–Early Cretaceous for Kolyma–Omolon, and Early middle Cretaceous for Anadyr–Koryak; van der Meer et al. (2012) and references therein). A direct connection between these intra-oceanic arc remnants and the Oku-Niikappu arc is not excluded, but we focus this analysis on the Oku-Niikappu Complex only.

### 2.3. Accretionary Orogen of Hokkaido

Hokkaido is divided into the ~N–S trending Oshima, Sorachi-Yezo, Hidaka, Tokoro, and Nemuro tectonostratigraphic belts (Figure 2), containing accretionary complexes, intruded and overlain by magmatic and sedimentary arc and fore-arc assemblages (Kiminami, 1992; Ueda, 2016). The western Oshima belt continues on Honshu in the south and the Jurassic–Paleogene western three belts continue on the Russian island of Sakhalin (Figures 1 and 2). The accretionary complexes of the western three belts are interpreted to have formed due to (north)westward subduction of Panthalassa lithosphere below the North China block (Ueda, 2016). In contrast, the Late Cretaceous–Paleogene eastern two belts (Tokoro and Nemuro, Figure 2) consist of thrust slices with opposite vergence and contain clastic rocks richer in basic to intermediate volcanic rocks and only minor continent-derived silicic materials (Kiminami & Kontani, 1983). These belts are therefore considered to have been formed in a distinct subduction system (Ueda, 2016), see also (Vaes et al., 2019). This eastern arc-trench system developed north and east of Hokkaido and was juxtaposed against western Hokkaido in Miocene time during opening of the Kuril back-arc basin (Arita et al., 1986; Kimura, 1986; Kimura & Tamaki, 1985). In this study, we focus on the history of subduction between the



**Figure 5.** Simplified stratigraphic columns of the Ocean Plate Stratigraphy (OPS) sequences of the Oshima, Sorachi-Yezo, and Hidaka belts. Modified from Ueda (2016).

Panthalassa plates and the North China block, and thus focus on the stratigraphy of the Oshima, Sorachi-Yezo and Hidaka belts.

The Oshima belt consists of Middle Jurassic–lowermost Cretaceous terrigenous clastic sedimentary sequences incorporating Upper Carboniferous–Lower Jurassic pelagic chert, limestone and oceanic island basalt, overlain and intruded by Lower Cretaceous arc-related plutonic, volcanic, and sedimentary rocks (Ishiga & Ishiyama, 1987; Kawamura, 1986; Minato & Rowett, 1967; Minoura & Kato, 1978; Tajika et al., 1984; Ueda, 2016; Yoshida & Aoki, 1972). The clastic sequences are interpreted as accretionary complexes and these complexes are characterized by the occurrence of both stacked thrust sheets of coherent OPS sequences of cherts and clastic rocks, and block-in-matrix mélangé facies. The trenchfill clastics consist of mudstones and sandstones rich in quartz and feldspars, and detrital zircon ages of ~1.8 and 2.5 Ga indicate a continental source (Kawamura et al., 2000). Kawamura et al. (2000) subdivided the Oshima accretionary complexes into an older western belt (Oshima–West), characterized by Carboniferous–Permian limestone and chert and Middle Jurassic clastic trench-fill deposits, and a younger eastern belt (Oshima–East) containing Triassic limestone and chert and Upper Jurassic trench-fill (Figures 2 and 5, Table 1). These two belts represent the oldest two OPS sequences of Hokkaido. No MORB has been identified (only OIB), which means that the age of the original magmatic basement of both these OPS sequences is of unknown age, but at least the age of the oldest (Carboniferous and Triassic, respectively) identified pelagic sedimentary rocks.

The Sorachi-Yezo belt, located east and positioned structurally below the Oshima belt, contains a series of Cretaceous accretionary complexes overthrust by the Jurassic Horokanai ophiolite and its conformable Sorachi and Yezo Groups sedimentary cover. The Horokanai ophiolite contains a succession of serpentinized peridotite, gabbro, amphibolite, MORB-like basalt, and Upper Jurassic cherty and tuffaceous siliceous sedimentary rocks (Asahina & Komatsu, 1979; Ishizuka, 1980, 1985). The Sorachi and Yezo Groups, conformably overlying the ophiolite, comprise a coherent sequence of pillow and massive basalts (lower Sorachi Group, which is the upper basaltic section of the Horokanai ophiolite), Upper Jurassic–middle Lower Cretaceous chert, siliceous mudstone, felsic tuff and volcanic sandstone, and conglomerate (upper Sorachi Group), and Lower–Upper Cretaceous terrigenous clastic rocks (Yezo Group; Ando, 2003; Niida & Kito, 1986; Takashima et al., 2001, 2004). These sedimentary sequences are interpreted as either back-arc (Jolivet et al., 1988) or more commonly, as fore-arc basin fill deposited on oceanic crust that was proximal and connected to the continental margin (Kiminami et al., 1985; Niida & Kito, 1986; Wallis et al., 2020).

The underlying accretionary complex rocks are exposed in the high-pressure, low-temperature (HP–LT) Kamuikotan and non-metamorphosed Idonappu zones, the former interpreted as the deeper-subducted equivalent of the latter (Iwasaki et al., 1995; Ueda, 2016; Ueda et al., 2000, 2001; Figure 2). The metamorphic rocks of the Kamuikotan Zone are exposed as tectonic windows in the cores of antiforms and contain both coherent masses of schist and low-grade meta-clastic rocks, and blocks in serpentinite mélanges (Sakakibara & Ota, 1994). The Idonappu Zone is subdivided into the western Naizawa Complex containing OIBs,

**Table 1**  
*Lithologies and Ages of the Ocean Plate Stratigraphy Sequences Depicted in Figure 5*

	<b>Oshima</b>	<b>Naizawa</b>	<b>Oku-Niikappu</b>	<b>Horobetsugawa</b>	<b>Hidaka</b>
<b>Sandstone</b>	Sandstone of unknown age	Middle Lower Cretaceous terrigenous sandstone (Kato et al., 1986; Igo et al., 1987; Tumanda & Sashida, 1987; Kato & Iwata, 1989; Tumanda, 1989; Kiyokawa, 1992; Hori & Sakakibara, 1994; Ueda et al., 2001)	Siliciclastic sandstone (Ueda & Miyashita, 2005)	Upper Cretaceous - lowermost Paleocene sandstone (Kiyokawa, 1992; Ueda et al., 2001; Nanayama et al., 2019)	Paleocene-Eocene terrigenous turbiditic sandstone and mudstone (Watanabe & Iwata, 1985; Kiminami et al., 1990a; Tajika & Iwata, 1990; Tajika, 1992; Nanayama, 1992; Nanayama et al., 2018)
<b>Mudstone</b>	Middle Jurassic to Upper Jurassic-lowermost Cretaceous mudstone; age from radiolarians and conodonts (Tajika et al., 1984; Ishiga & Ishiyama, 1987)	Middle Lower Cretaceous hemipelagic mudstone; age from radiolarians (Kato et al., 1986; Igo et al., 1987; Tumanda & Sashida, 1987; Kato & Iwata, 1989; Tumanda, 1989; Kiyokawa, 1992; Hori & Sakakibara, 1994; Ueda et al., 2001)	Albian-Cenomanian black mudstone; age from radiolarians (Kiyokawa, 1992; Kawamura et al., 2001; Ueda & Miyashita, 2005)	Albian-Cenomanian red mudstone; age from radiolarians (Kiyokawa, 1992; Ueda et al., 2001)	Paleocene-Eocene hemipelagic mudstone; age from radiolarians (Watanabe & Iwata, 1985; Kiminami et al., 1990a; Tajika & Iwata, 1990; Tajika, 1992)
<b>Chert</b>	Upper Carboniferous or Lower Permian to Lower Jurassic chert; age from radiolarians and conodonts (Tajika et al., 1984; Ishiga & Ishiyama, 1987). Oshima west: Carboniferous-Permian to Lower Jurassic, Oshima-east: Triassic - Jurassic (Kawamura et al., 2000)	Upper Triassic - lowermost Cretaceous chert; age from radiolarians (Kato et al., 1986; Igo et al., 1987; Kato & Iwata, 1989; Kiyokawa, 1992; Hori & Sakakibara, 1994; Sakakibara et al., 1997; Ueda et al., 2001)	Lower Cretaceous (Berriasian - Valanginian) chert; age from radiolarians (Ueda & Miyashita, 2005)	Albian-Cenomanian chert; age from radiolarians (Kiyokawa, 1992; Ueda et al., 2001)	
<b>Limestone</b>	Upper Carboniferous, Permian and Upper Triassic limestone; age from corals, algae, fusulinids and conodonts (Minato & Rowett, 1967; Sakagami et al., 1969; Yoshida & Aoki, 1972; Minoura & Kato, 1978). Oshima-west: Carboniferous-Permian, Oshima-east: Triassic (Kawamura et al., 2000)	Permian - Triassic limestone (Igo et al., 1974; Hashimoto et al., 1975; Ishizaki, 1979; Sakagami & Sakai, 1979; Kato et al., 1986)			
<b>Magmatic basement</b>	Basaltic lava and breccia (oceanic-island affinity) of unknown age (Kawamura et al., 1986)	Ocean island basalts of unknown age (Nakano & Komatsu, 1979; Kimura et al., 1994; Sakakibara et al., 1999)	Andisitic, boninitic and MORB-like dykes and pillow lavas of unknown age. Andisitic and boninitic rocks: island-arc affinity. (Ueda & Miyashita, 2005)	Mid-Cretaceous(?) MOR basalt (Ueda et al., 2000)	Paleocene-Eocene MOR basalt and dolerite; formation is coeval with deposition of turbiditic sandstones (Kiminami, 1999; Mariko, 1984; Miyashita & Katsushima, 1986; Mariko & Kato, 1994; Miyashita & Yoshida, 1994; Miyashita & Kiminami, 1999; Nakayama (2003)



Permian-lowermost Cretaceous limestones, cherts, and Lower Cretaceous trench-fill deposits (Hashimoto et al., 1975; Igo et al., 1987; Kato & Iwata, 1989; Kato et al., 1986; Kiyokawa, 1992; Peyrotty et al., 2020; Sakagami & Sakai, 1979; Sakakibara et al., 1997; Ueda et al., 2001), the central Oku-Niikappu Complex, and the eastern Horobetsugawa Complex containing mid-Cretaceous MORB-basalts, chert, red pelagic mudstones, and Upper Cretaceous–lowermost Paleocene trench-fill deposits (Kiyokawa, 1992; Nanayama et al., 2019; Ueda et al., 2000, 2001), representing three OPS sequences (Figure 5, Table 1).

The Oku-Niikappu Complex, identified by Ueda and Miyashita (2005), consists of (a) massive and foliated serpentinite; (b) sheeted dykes of andesitic, boninitic, and MORB-like character; (c) pillow basalts, conglomerates (containing clasts of volcanic rocks and serpentinite) and Berriasian red bedded chert; and (d) Albian-Cenomanian mudstone and siliciclastic sandstone (Ueda, 2003; Ueda & Miyashita, 2003, 2005). Geochemical analysis on the volcanic rocks including the boninitic dykes yielded chemical characteristics suggesting an island arc origin (Ueda & Miyashita, 2005). Therefore, the Oku-Niikappu complex is interpreted as a Jurassic intra-oceanic arc, which went extinct in a pelagic setting, far away from a continental margin (Ueda & Miyashita, 2005). Notably, arc extinction was associated with extension (forming the MORB-like dykes), exhumation of serpentinitized peridotite along detachment faults, erosion, and deposition of conglomerates (Ueda & Miyashita, 2005). Subsequent tectonic quiescence and subsidence led to the deposition of cherts, and finally, ~45 Myr after arc extinction, these cherts were overlain by trench-fill deposits, and the complex accreted to the Hokkaido margin (Ueda & Miyashita, 2005). Importantly, during and after the ~145 Ma extinction of the Oku-Niikappu arc and deposition of radiolarian cherts, Sorachi-Yezo forearc sedimentation was ongoing, further indicating that these represent two separate arc-trench systems; the former located in an open-ocean setting, the latter at a marginal basin.

The Hidaka belt, structurally located below the Sorachi-Yezo belt, consists of Upper Cretaceous to Paleocene-Eocene hemipelagic mudstones and Paleocene-Eocene terrigenous turbiditic sandstone, MORB-chemistry dolerite and basalt, incorporating Permian-mid-Cretaceous blocks of limestone and chert (Endo & Hashimoto, 1955; Iwata & Tajika, 1989; Kiminami et al., 1990; Mariko & Kato, 1994; Miyashita & Katsushima, 1986; Miyashita & Yoshida, 1994; Tajika & Iwata, 1990; Watanabe & Iwata, 1985). These latter older rocks, as well as the Upper Cretaceous mudstones are considered to be reworked mélangé blocks derived from the Idonnappu Zone in the west (Tajika & Iwata, 1990). Structures in the Paleocene-Eocene mudstones and dolerites and basalts (inter-pillow mudstone, silicified baked margins of mudstones in contact with dolerites, and mudstone fragments as xenoliths in the dolerites) indicate that eruption and intrusion of the magmatic rocks was syn-sedimentary (Kiminami, 1999; Mariko, 1984; Miyashita & Katsushima, 1986; Nakayama, 2003; Figure 5, Table 1). Therefore, these magmatic rocks are interpreted to have formed due to seafloor spreading adjacent to the continent, that is, just prior to subduction of the ridge (Miyashita & Katsushima, 1986).

#### 2.4. Hokkaido in Context of the Wider Japanese Accretionary Orogen

The Japanese islands became separated from the continental North China block by Oligo-Miocene Sea of Japan back-arc basin opening (Jolivet et al., 1994; Martin, 2011; Otofujii et al., 1985; Figure 1). Similar to the western belts of Hokkaido, the islands of Honshu, Shikoku and Kyushu farther to the south contain trenchward-younging accretionary complexes, but are intersected by the Median Tectonic Line (MTL, Figures 1 and 2). The MTL is a major E-W striking, northward dipping (~35°) fault that is, currently accommodating right-lateral strike-slip motion in the order of 5–10 mm/yr (Okada, 1973; Sugiyama, 2012), interpreted as strain partitioning in the overriding plate due to obliquely subduction of the Pacific Plate at the Nankai Trough (Okada, 1973; Sato et al., 2015; Sugiyama, 2012; Figure 1). However, this right-lateral motion was established only recently; before 0.8 Ma, the MTL accommodated (oblique) thrusting (Sato et al., 2015). The MTL juxtaposes an outer (southern) zone against an inner (northern) zone. The westernmost belt of Hokkaido, the Oshima belt, is interpreted to correlate to the inner zone; the Sorachi-Yezo and Hidaka belts to the outer zone (Ishiga & Ishiyama, 1987; Isozaki et al., 2010; Ueda, 2016). The inner zone of southwestern Japan consists of Paleozoic-Jurassic HT metamorphic (granite-intruded) and non-metamorphic accretionary complexes of the Ryoke, Mino-Tanba and other belts (Banno & Sakai, 1989; Takasu et al., 1994; Figure 2). The outer zone consists of the Cretaceous HP/HT metamorphic Sanbagawa belt, the Chichibu belt, which

is a composite belt comprising pre-Jurassic and Jurassic accretionary complexes and Paleozoic basement, and Late Cretaceous-Miocene metamorphic and non-metamorphic accretionary complexes of the Shimanoto belt (Aoki et al., 2008, 2009; Isozaki & Itaya, 1991; Isozaki et al., 2010; Okamoto et al., 2004; Tsutsumi et al., 2009; Figure 2). The Sanbagawa belt is a ~140–130 Ma accretionary complex metamorphosed to eclogite (ultra-high pressure) conditions at either ~120 or ~89–88 Ma, and is in direct contact with the Ryoke belt of the inner zone through the MTL (Aoki et al., 2009; Okamoto et al., 2004; Sato et al., 2015; Tsutsumi et al., 2009; Wallis & Endo, 2010). It contains internal structures parallel to the MTL fault surface (Sato et al., 2015), indicating that the MTL served as the subduction interface along which the Sanbagawa belt subducted during the Early or Late Cretaceous, and likely, also along which it was subsequently exhumed (Aoki et al., 2009; Banno, 2004; Isozaki et al., 2010; Itaya et al., 2011; Okamoto et al., 2004; Ota et al., 2004; Sato et al., 2015). The most northerly unit of the Sanbagawa belt, the Iratsu eclogite body, represents a deeply subducted accreted arc (Utsunomiya et al., 2011). A Late Cretaceous (~84–68 Ma) sinistral pull-apart basin (the Izumi Group) is present along the MTL (Figure 2) suggesting that during the second half of the Late Cretaceous, the MTL accommodated oblique extensional motion (Ichikawa et al., 1979, 1981; Miyata, 1990; Noda & Sato, 2018; Noda & Toshimitsu, 2009).

The Chichibu belt of the outer zone plays a crucial role in the interpretation of the tectonic history of southwest Japan, as it forms an anomaly to the overall trenchward-younging character of the belts. Its Paleozoic basement belt (the Kurosegawa belt, Figure 2) contains clastic rocks with a continental affinity (Aitchison et al., 1991; Hada et al., 2001), and is located between the North and South Chichibu belts, consisting of pre-Jurassic and Jurassic accretionary complexes, respectively. The duplication of (pre-)Jurassic accretionary complexes in the inner and outer zones and the apparent out-of-sequence (Early Cretaceous) timing of thrusting along the MTL was explained by Isozaki and Itaya (1991) by interpreting the Chichibu belt as a klippe of inner zone material, with the North and South Chichibu belts being equivalents of the Mino-Tanba accretionary complex. This interpretation followed geophysical analyses of lower crustal structure, showing that the accretionary complexes of the outer zone underthrust the inner zone complexes, reaching far beyond the surface transect of the MTL (Isozaki, 1988; Isozaki & Itaya, 1991; Ito et al., 2009; Sato et al., 2005). In this interpretation, the Chichibu belt is not part of the basement of the outer zone, and all accretionary complexes of southwest Japan are formed in sequence.

However, paleontological studies have shown that the Chichibu belt contains Triassic–Jurassic Tethyan (i.e., low-latitude) faunal assemblages (Hallam, 1986; Hayami, 1984; Kobayashi & Tamura, 1984; Matsumoto, 1978), whereas the inner zone contains a Permian assemblage of boreal (high-latitude) fauna similar to South Primorye, Far East Russia (Hayami, 1961; Kobayashi & Tamura, 1984; Sato, 1962; Tazawa, 2001). This faunal contrast suggests that during Permian times, the inner zone was already located adjacent to the North China continental margin in its pre-Sea of Japan opening position, whereas until at least Jurassic time, the outer zone was located  $>10^\circ$  farther south (Hallam, 1986; Hayami, 1984; Kobayashi & Tamura, 1984; Matsumoto, 1978). Furthermore, sediment provenance and paleomagnetic studies on Paleozoic–Early Cretaceous rocks of the Chichibu belt have illustrated an origin adjacent to South China Block (e.g., Aoki et al., 2015; Hara et al., 2018; Ikeda et al., 2016; Uno et al., 2011). To explain these observations, tectonic models were put forward in which the Cretaceous MTL accommodated large ( $>1,000$  km) left-lateral strike-slip motion, moving the outer zone along the Asian continental margin toward its modern position (Sakashima et al., 2003; Taira et al., 1983; Yamakita & Otoh, 2000; Yao, 2000).

However, both tectonic models (the Cretaceous MTL as in-sequence thrust between two accretionary complexes, or the MTL as major sinistral strike-slip fault) do not satisfy all geological constraints. Despite the presence of the Izumi Group pull-apart basin, a primarily strike-slip character for the MTL is not in line with its  $35^\circ$  north-dipping character, nor with the eclogite conditions in the Sanbagawa belt containing MTL-parallel internal structures. An origin as in-sequence accretionary complex thrust (i.e., paleotrench) does not explain the faunal differences between the inner and outer zones. Moreover, Charvet (2013) challenged the idea that the ultrahigh-pressure conditions of the eclogite nappe of the Sanbagawa belt, typically only found in continental collisional settings, are resultant from oceanic subduction. Instead, he explained the metamorphic conditions by interpreting the Kurosegawa belt as an accreted microcontinental fragment, reworked as a klippe during the latest Cretaceous. This third interpretation is in line with the characteristics

of the Sanbagawa belt, the north-dipping nature of the MTL and may explain the faunal and zircon provenance differences between the inner and outer zones.

### 3. Reconstructing Latest Jurassic-Earliest Cretaceous Subduction Termination in the Northwestern Panthalassa Ocean

#### 3.1. Possible Positions of the Oku-Niikappu Intra-Oceanic Trench, and Plate Kinematic Consequences

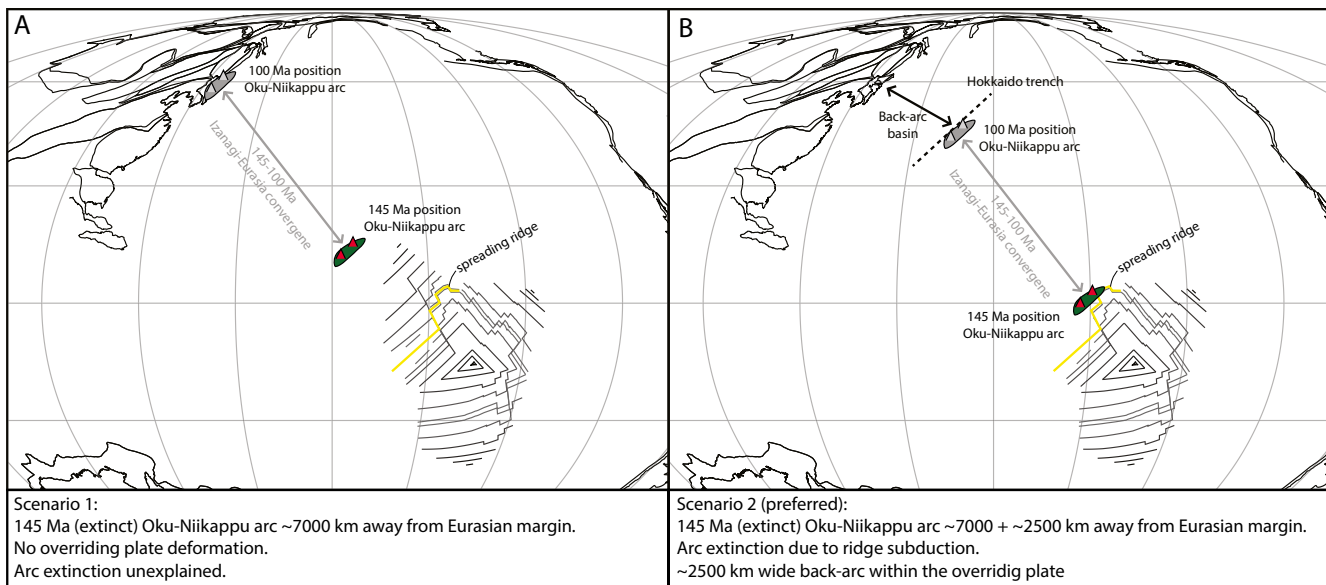
We here develop a plate tectonic reconstruction of the northwestern Panthalassa Ocean including the Oku-Niikappu intra-oceanic subduction zone. The main challenge herein is determining the position of the Oku-Niikappu arc at the time of extinction (~145 Ma), and before. A first essential constraint on this position is the delay between arc extinction at ~145 Ma, and arc accretion as OPS in the accretionary prism that is, presently exposed on Hokkaido at 100 Ma. There is no evidence for additional Early Cretaceous intra-oceanic plate boundaries between the extinct Oku-Niikappu arc and the Pacific-Izanagi ridge, and therefore, the post-145 Ma extinct Oku-Niikappu arc is expected to have been part of, and moved with, the Izanagi Plate. As a result, the distance between the 145 Ma position of the Oku-Niikappu arc and the Eurasian margin was at least equal to the amount of Izanagi-Eurasia convergence that occurred between 145 and 100 Ma (Figure 6a). To estimate this distance, we reconstruct Izanagi Plate motions based on the marine magnetic anomaly record of the Pacific Plate, and connect Izanagi Plate motions to motion of the Eurasian Plate using the Pacific hotspot frame of Torsvik et al. (2019) for the Panthalassa plate system and the slab-fitted frame of van der Meer et al. (2010) for the Indo-Atlantic plate system (including Eurasia), following Boschman et al. (2019). With this combined reconstruction, we estimate ~7,000 km of convergence between the (extinct) Oku-Niikappu arc and the northeast Asian margin. If the Hokkaido subduction zone at which the Oku-Niikappu remnant arc accreted at 100 Ma was located along the northeast Asian margin (e.g., in its pre-Sea of Japan opening position), the 145 Ma Oku-Niikappu arc would be located ~7,000 km southeast of the Hokkaido margin, at low latitude (~12°N, in the Torsvik et al. (2019) mantle reference frame; Figure 6a). This position matches well with the southern, low-latitude part of the Telkhinia slabs (Figure 3) inferred by van der Meer et al. (2012) to be related to Oku-Niikappu subduction, or lower mantle anomalies just east of these, below the Marquesas Islands.

If the Oku-Niikappu arc had at 145 Ma instead been located closer to the Eurasian continental margin (in a marginal basin setting), then 145–100 Ma Izanagi-Eurasia convergence was larger than Oku-Niikappu-Eurasia convergence. This excess convergence would require an additional subduction zone between the extinct Oku-Niikappu complex and the Izanagi Plate, for which there is no evidence. We therefore deem a tectonic scenario in which the 145 Ma Oku-Niikappu arc was located closer than 7,000 km to the Eurasian margin highly unlikely. Alternatively, if the Oku-Niikappu arc was located further toward the southeast, the Hokkaido subduction zone at which it accreted at 100 Ma was not located along the North China margin but must have been in an intra-oceanic position, separated from the continental margin by a basin that closed after 100 Ma (Figure 6b). This latter scenario is further explored and discussed below.

#### 3.2. Explaining Oku-Niikappu Arc Extinction

As evidenced by the Berriasian radiolarian cherts directly overlying the magmatic basement of Oku-Niikappu, the Oku-Niikappu arc went extinct in a pelagic, deep-marine setting, far away from a continental margin. Cessation of subduction is often accomplished by clogging a subduction zone with buoyant crustal material such as a continental fragment, an arc, or a large igneous province (e.g., Tetreault & Buitert, 2012). This is typically accompanied by accretion of rocks from the indenter to the upper plate (Cawood et al., 2009), and by upper plate shortening (Cloos, 1993), which in intra-oceanic settings then typically leads to subduction polarity reversal (Burke, 1988; Domeier et al., 2017; Stern, 2004; Vaes et al., 2019; von Hagke et al., 2016). The geology of the Oku-Niikappu Complex contains no evidence for any of these events, but instead, reveals that when subduction ceased around 145 Ma, the arc became extended to a point that lithospheric mantle rocks were exhumed to the surface.

Cessation of subduction may alternatively be the result of arrival of a spreading ridge in the subduction zone. During ridge subduction, a three-plate system changes into a two-plate system upon full subduction



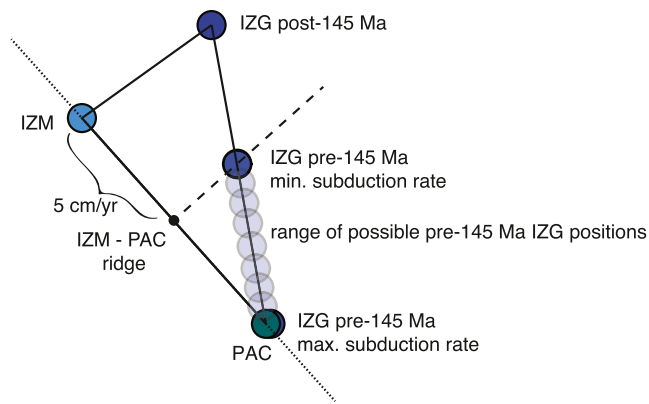
**Figure 6.** Exploration of possible 145 Ma locations of the Oku-Niikappu arc, whereby the Oku-Niikappu arc was part of the Izanagi Plate since its 145 Ma extinction. (a) following a simplest-case reconstruction approach (not preferred) in which the Hokkaido trench was located in its pre-Sea of Japan opening position at the northeast Asian continental margin. A 145 Ma position further to the northwest (closer to the Eurasian margin) is not possible without inferring an additional intra-Panthalassa subduction zone, for which there is no evidence. (b) A position further to the southeast explains cessation of subduction due to ridge subduction, and predicts a mid-Cretaceous marginal basin at the northeast Asian continental margin (see also Figure 8).

of the central plate that was spreading relative to one, and subducting below the other plate. The nature of the plate boundary between the two remaining plates depends on their relative motion, yielding three options for the resulting plate configuration: either (a) the two remaining plates converge, and subduction continues (e.g., subduction of the Izanagi-Pacific ridge below Japan was followed by subduction of the Pacific Plate Seton et al., 2015); (b) relative motion between the two remaining plates is parallel to the former trench, and a transform plate boundary forms (e.g., subduction of the Pacific-Farallon ridge below western North America resulted in formation of the San Andreas fault Atwater, 1970); or (c) the two remaining plates diverge, and a new ridge forms at the former subduction zone where the intervening plate disappeared. Importantly, the spreading direction at this new ridge may (and in almost all cases will) differ in rate and direction from the subducted ridge. Just after ridge subduction, the extinct magmatic arc is located adjacent to the new spreading ridge and may be affected by the change from convergence to divergence. As spreading continues, the extinct arc migrates away from the ridge as part of the newly formed oceanic lithosphere toward a tectonically quiet, pelagic environment.

In the 145 Ma simplest-case scenario shown in Figure 6a, the Oku-Niikappu arc is located ~7,000 km away from the nearest continental margin, in line with the pelagic environment in which the Berriasian cherts were deposited after arc extinction. However, this scenario does not provide an explanation for cessation of subduction. We propose that cessation of Oku-Niikappu intra-oceanic subduction was caused by subduction of the Pacific spreading ridge. This requires placing Oku-Niikappu 2,500 km to the southeast, at the ridge (Figure 6b), and explains cessation of subduction without collision, shortening, or a polarity reversal, and with the observed extension of the arc immediately after extinction signaling the transition from subduction to spreading. Furthermore, it explains the plate reorganization in the northwestern Panthalassa Ocean related to the change in spreading direction between 146.6 and 137.9 Ma.

### 3.3. Constraints on Panthalassa Plate Motions

We propose the following plate kinematic scenario: since initiation of intra-oceanic Oku-Niikappu subduction, the northwestern Panthalassa Ocean hosted at least three plates: Pacific (PAC), Izanagi (IZG), and a



**Figure 7.** Velocity diagram including the Pacific (PAC), Izanami (IZM), and Izanagi (IZG) plates. The orientations of the Pacific-Izanami and Pacific-Izanagi lines are derived from fracture zone orientations (Figure 4). Plate motion rates (spreading and subduction rates) described in text and illustrated in Figure 8 are as measured along the dashed line.

third that we here name Izanami (IZM). The Oku-Niikappu intra-oceanic subduction zone separated Izanagi (in the west) from Izanami (in the east), and a spreading ridge separated Izanami from Pacific (Figures 7 and 8). The 190–146.6 Ma anomalies on the Pacific Plate thus formed due to spreading between Pacific and Izanami. Upon arrival of the Izanami-Pacific ridge at the Oku-Niikappu trench, Izanami was entirely subducted, and the system transformed into a two-plate system containing a single spreading ridge (Izanagi-Pacific; Figures 7 and 8). The change in spreading orientation between 146.6 and 137.9 Ma shows that Izanagi-Pacific divergence was not parallel to Izanami-Pacific divergence, but occurred at a  $\sim 30^\circ$  angle.

Marine magnetic anomalies provide estimates of pre-146.6 Ma Izanami-Pacific and post-137.9 Ma Izanagi-Pacific plate motion rates and directions. Using these, an estimate of pre- $\sim 145$  Ma Izanami-Izanagi subduction rates (and therefore indirectly, Izanagi-Pacific divergence rates) can be calculated from pre-145 Ma Izanami-Pacific half-spreading rates. In a 2D cross-section parallel to Izanami-Pacific spreading (Figure 7), pre-145 Ma half spreading rates were  $\sim 5$  cm/yr. The lower limit of subduction rates (in the same 2D cross-section) is determined by the requirement for convergence between the Oku-Niikappu trench and the Pacific-Izanami ridge. If subduction rates were lower than or equal to half spreading rates, the trench-ridge distance would increase,

or be stationary, and the Izanami-Pacific ridge would not have arrived at the Oku-Niikappu trench. To accommodate trench-ridge convergence resulting in ridge subduction, subduction rates must have exceeded half-spreading rates ( $> 5$  cm/yr, Figure 7). The upper limit of subduction rates, on the other hand, is constrained by the required divergence between Pacific and Izanagi. If subduction rates were higher than or equal to full-spreading rates, there would not be net divergence between Izanagi and Pacific, and ridge arrival at the trench would not have led to Izanagi-Pacific spreading, but to ongoing subduction. To accommodate net Izanagi-Pacific divergence, subduction rates must have been lower than full-spreading rates ( $< 10$  cm/yr). From this, it follows that Izanagi-Pacific divergence rates were between 0 and  $\sim 5$  cm/yr (Figure 7).

Had relative plate motion remained unchanged during ridge subduction, full-spreading rates would have dropped from 10 cm/yr to anywhere between 0–5 cm/yr. However, the spacing between the post-137.9 Ma anomalies indicates that in fact spreading rates slightly increased (from  $\sim 10$  cm/yr for 190–146.6 Ma to  $\sim 11$ –12 cm/yr for 137.9–110 Ma). This means that cessation of Oku-Niikappu subduction was followed by a rapid acceleration of Izanagi-Pacific divergence, and by inference, Izanagi subduction below the Hokkaido trench. Although a geodynamic explanation of the plate acceleration following cessation of Oku-Niikappu subduction is beyond the scope of the present paper, we note that, when placed in the Pacific fixed hotspot frame of Torsvik et al. (2019), the Oku-Niikappu trench and the associated subducting slab advanced westwards relative to the mantle. The transition at the southeastern plate boundary of Izanagi from subduction to spreading released a resisting force against westward plate motion and replaced it by a driving force (ridge push). We tentatively suggest that this transition in forcing may explain, and is in any case consistent with, this acceleration.

#### 4. Discussion: Juxtaposition of the Inner and Outer Zones of Japan

The reconstruction of Oku-Niikappu subduction evolution presented above enables testing the contrasting tectonic scenarios proposed for the Cretaceous juxtaposition of the inner and outer zones of Japan along the Median Tectonic Line. In the tectonic model in which the MTL is interpreted to have accommodated left-lateral margin-parallel strike-slip motion, the Oku-Niikappu remnant arc would travel from its place of extinction in the central Panthalassa Ocean toward the continental margin of the South China Block, where it would have arrived at 100 Ma. Alternatively, in the tectonic model in which the inner and outer

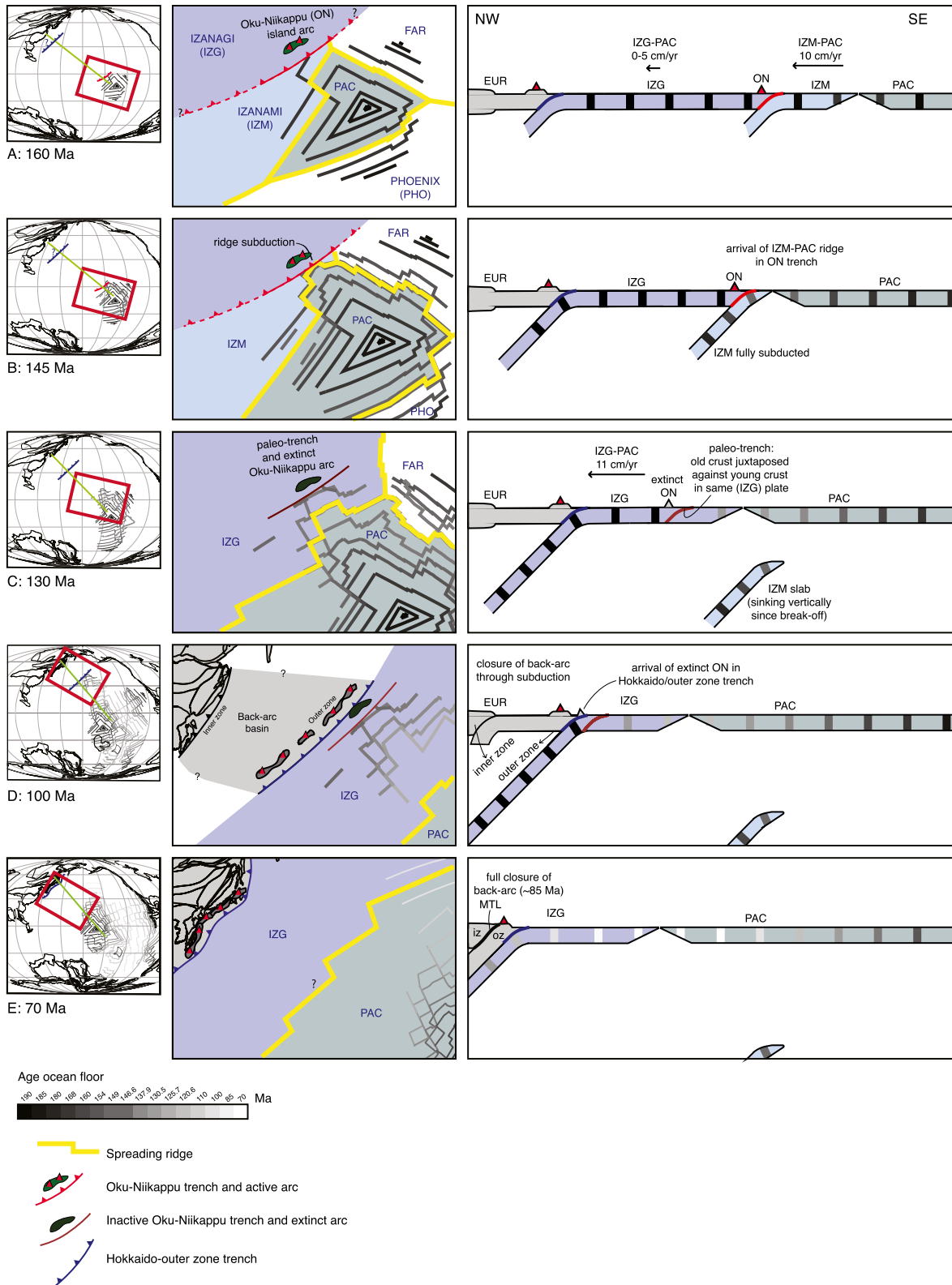


Figure 8.

zones are inferred to consist of a continuous sequence of accretionary complexes, the Oku-Niikappu arc is expected to travel toward accretion in a more northerly position along the continental margin, and in the third, micro-continental fragment model, the Oku-Niikappu arc is expected to travel toward a more easterly, outboard location. If our Oku-Niikappu reconstruction, in which arc extinction is linked to subduction of the Izanami-Pacific ridge, is correct, the Oku-Niikappu arc was located  $\sim 2,500$  km southeast of the continental margin of northeast Asia during 100 Ma accretion (Figure 8d). We note that uncertainties in absolute mantle reference frames are large (in the order of  $\sim 1,000$  km, see for example Boschman et al., 2019), but not large enough to explain the  $\sim 2,500$  km distance between the northeast Asian margin and the location of accretion of the Oku-Niikappu arc at 100 Ma. This implies that the outer zone was far outboard of continental Asia in the mid-Cretaceous. Our reconstruction of Oku-Niikappu intra-oceanic subduction thereby provides additional, independent evidence for separate tectonic histories of the inner and outer zone accretionary orogens of Japan. We propose that the outer zone rifted away from the continental margin of the South China block through opening of a marginal back-arc basin, whereby the Kurosegawa belt represents a sliver of rifted continental basement, and the protolith of the Iratsu eclogite body (part of the Sanbagawa belt), the arc. At  $\sim 100$  Ma, the (then already 45 Myr extinct) Oku-Niikappu arc accreted in this outboard subduction system, when the marginal basin was  $\sim 2,500$  km wide. During the first half of the Late Cretaceous, the back-arc basin closed through subduction, juxtaposing the outer and inner zones in their modern configuration and burying the northern margin of the outer zone to eclogite-facies depths, creating the metamorphic Sanbagawa belt. This proposed back-arc model (Figure 8) is consistent with the young estimate ( $\sim 85$  Ma) of peak metamorphism in the Sanbagawa eclogites and rapid exhumation shortly thereafter (e.g., Charvet, 2013; Wallis et al., 2009) and explains the South China derivation of the outer zone, its Tethyan fauna, the continental basement of the Kurosegawa belt, underthrusting of the outer zone below the inner zone, and the arc signature of the Iratsu eclogite body. The reconstructed “fringing-arc” system which rifted away from a continental margin and re-accreted later is not exceptional or unique in the Panthalassa realm. Other examples are found in the deformed circum-Pacific continental margins of for example, Mexico (the Guerrero arc and Arperos back-arc basin Boschman, Garza, et al., 2018, Boschman, van Hinsbergen, et al., 2018; Martini et al., 2011) or western Canada (the Wrangellia superterrane Nokleberg, 2000). The timing of opening of the proposed back-arc basin, as well as its lateral extent, is yet to be determined. The outer zone belts and correlates are currently restricted to Japan and Sakhalin, indicating that the mid-Cretaceous back-arc may have been of a size similar to the modern Japan Sea back-arc basin.

In this study, we integrate evidence for intra-oceanic subduction in the Jurassic-Cretaceous Panthalassa Ocean from the accretionary record of Hokkaido including the remnant arc Oku-Niikappu Complex, lower mantle seismic anomalies, and the marine magnetic anomaly record of the Pacific Plate. Inherent to reconstructing subducted oceanic plates and because of the incompleteness of the accretionary record of Japan and low tomographic resolution for the mantle above  $\sim 1,500$  km below the northwestern Pacific, uncertainties remain, both in the location of the outer zone-Hokkaido subduction system and the Oku-Niikappu subduction system. However, the presented plate reconstruction is self-consistent and in line with all currently available constraints. Paleomagnetic analysis on the Oku-Niikappu Complex, aimed at determining the Jurassic-Cretaceous paleolatitude of the (remnant) arc, paleomagnetic and sediment provenance analyses on the outer zone, and increased tomographic resolution will provide tests for the here presented plate reconstruction and may provide further insight in the tectonic evolution of the Mesozoic northeast Asian continental margin and the northwestern Panthalassa Ocean.

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**Figure 8.** Reconstruction of Izanami, Izanagi, and Pacific plate motion, Oku-Niikappu subduction (a) and extinction (b), and accretion of the Oku-Niikappu remnant arc in the outer zone trench separated from the northeast Asian continental margin by a  $\sim 2,500$  km wide back-arc (e). The orientation and length of the Oku-Niikappu subduction zone are speculative. Panels on the left are in the mantle reference frame of Torsvik et al. (2019), except for 160 Ma for which there is no mantle reference available, and in which the Pacific Plate is stationary compared to its 150 Ma position. Our reconstruction assumes an Izanami-Izanagi subduction rate of 7.5 cm/yr (within the permitted range of 5–10 cm/yr, see Figure 7) and extrapolates the relative post-145 Ma Izanagi-Pacific motion direction for earlier times, assuming that the orientation of Pacific-Izanagi motion did not change during ridge subduction.

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## 5. Conclusions

Marine magnetic anomalies from the Pacific Plate reveal that the Panthalassa Ocean hosted at least three plates that all shared spreading ridges with the Pacific Plate: the conceptual Phoenix, Farallon, and Izanagi plates. There are several lines of evidence, however, that indicate that the plate kinematic evolution of the northwestern Panthalassa Ocean involved more than just the single Izanagi Plate. The accretionary record of Hokkaido contains a remnant intra-oceanic arc (the Oku-Niikappu Complex) and seismic tomographic images of the lower mantle below the Pacific Ocean reveal wave speed anomalies, interpreted as slab remnants of intra-oceanic subduction. Furthermore, marine magnetic anomalies of the Pacific Plate record a change in spreading orientation between the Pacific Plates and the plates of the northwestern Panthalassa domain between 146.6 and 137.9 Ma. To account for these observations, we present a tectonic reconstruction of intra-oceanic subduction evolution, in which arc extinction resulted from ridge subduction. We reconstruct a three-plate system in the northwestern Panthalassa Ocean (Pacific, Izanami, Izanagi), where-by arrival of the Pacific-Izanami ridge in the Izanami-Izanagi trench (associated with the Oku-Niikappu arc) was followed by renewed spreading in a slightly different direction, leading to the observed change in Izanagi-Pacific spreading orientation and post-extinction extension in the Oku-Niikappu arc basement. Reconstruction of the Izanagi Plate places the Oku-Niikappu arc during its extinction at ~145 Ma near the Telkhinia slabs. From our reconstruction, it follows that the outer zone of Japan was separated from the inner zone by a major back-arc basin during the Cretaceous. Our proposed back-arc basin model reconciles the presence of low-latitude fauna in the outer zone with evidence for subduction along the MTL during the Cretaceous. Our analysis shows the value of exposures of Ocean Plate Stratigraphy in accretionary complexes in the development of plate kinematic reconstructions of lost oceanic plates, particularly when combined and validated with marine geophysical and seismic tomographic data.

## Data Availability Statement

No new data are presented in this study.

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