Mesozoic ocean plate stratigraphy reveals a Franciscan plate separating Farallon and North America

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ABSTRACT

Ocean plate stratigraphy preserved in the Franciscan Complex recorded the Mesozoic plate tectonic evolution of the North American Cordillera and eastern Pacific basin. New and published ocean floor and accretion ages for Jurassic–Cretaceous oceanic crust, derived from detrital zircons and radiolarians, indicate that eastward younging ocean floor existed between the Farallon and North American plates during the Mesozoic. Moreover, plate reconstruction shows that, to the south, this lithosphere subducted southward at an intra-oceanic subduction zone beneath Caribbean lithosphere, which was still part of Farallon during the Early Cretaceous. The east-younging lithosphere was thus not the Farallon plate, but a separate Franciscan plate. We infer that it formed as part of a back-arc basin during the Cretaceous, bounded by eastward-dipping subduction zones on both its western and eastern margins. Northward translation of the western intraoceanic subduction-related terranes, likely driven by oblique Kula plate subduction, may explain why low-latitude intraoceanic arc records are currently only found from British Columbia northwards.

INTRODUCTION

Most global plate kinematic models based on magnetic anomalies of the Pacific plate show that the western North American subduction zone, at which the Cordilleran orogen formed, accommodated subduction of the major Farallon plate that was spreading relative to the Pacific and Izanagi plates of the Panthalassa Ocean (e.g., Seton et al., 2012). However, detailed observations of the geological record and mantle structure call this simple view into question. Seismic tomography identified two belts of lower mantle anomalies that may signal two parallel and synchronous Mesozoic subduction zones in the region (van der Meer et al., 2012; Sigloch and Mihalynuk, 2013; Clennett et al., 2020; Fuston et al., 2025). Accreted intraoceanic arc rocks in the Canadian and Alaskan Cordillera, showing Mesozoic equatorial to mid-paleolatitudes from paleomagnetic data, also imply an additional plate boundary between Farallon and North America and the existence of at least one additional oceanic plate (e.g., Dickinson and Lawton, 2001; Tikoff et al., 2023; Andjić et al., 2025). However, in the absence of direct evidence for the age, formation, and evolution of this plate, there is little consensus on the eastern Paleo-Pacific plate tectonic evolution (Pavlis et al., 2019).

Direct geological evidence that could shed new light on this debate, but has so far not been widely used, is available in the Franciscan Complex of California (Fig. 1A). This complex contains well-described sequences of accreted ocean plate stratigraphy (OPS; Isozaki et al., 1990). These consist of ocean floor basalts and pelagic sediments that record the minimum age of the ocean floor that was subducted, and trench fill that shows their episodic accretion between ~175 and ~50 Ma at the Californian margin (Dumitru et al., 2015; Wakabayashi, 2025). Moreover, constraints on Cretaceous eastern paleo-Pacific intra-oceanic plate configuration is available to the south of California, by an intraoceanic subduction system now preserved in the Caribbean region, with a well-known tectonic and magmatic history (e.g., Boschman et al., 2019). When combined, the data from the Caribbean and Californian domains may provide a novel but so far unexplored lead on oceanic plate configurations in the eastern Pacific region.

Here, we explore whether the Franciscan OPS may represent Farallon crust made at the western ridge of Farallon, with the Izanagi or Pacific ridges, or whether it instead requires an additional ridge/plate system in the eastern Panthalassa Ocean. We provide new age and whole-rock geochemical data for OPS sequences in the Franciscan Complex that accreted during a poorly dated but critical time interval in the middle to Late Cretaceous. By combining Franciscan and Caribbean plate tectonic perspectives, we provide reconstructions of the eastern Panthalassa for the Cretaceous and discuss the implications of different options for explaining Cordilleran geological records and modern mantle structure alike.

A CARIBBEAN PERSPECTIVE ON EAST PANTHALASSA PLATE TECTONICS

The largely submarine Caribbean plate is predominantly composed of normal and thickened oceanic lithosphere that along its northern, eastern, and southwestern margins is as old as Jurassic (Montgomery et al., 1994). HP-LT metamorphic rocks in Cuba and Hispaniola and associated arc remnants that are found along the northern and eastern perimeter of the Caribbean plate (the "Great Arc of the Caribbean", GAC; Burke, 1988; Fig. 1B) indicate that a southward subduction zone was underway below this Jurassic lithosphere by ~140–135 Ma (e.g., Lázaro et al., 2009; Rojas-Agramonte et al., 2016). Plate tectonic reconstruction shows that the Caribbean plate collided with North and South American continental margins in northern Costa Rica and Colombia around 100 Ma, and subsequently moved between the Americas in the Mid-Cretaceous, and since that time overrode proto-Caribbean (Atlantic) instead of east Panthalassa ocean floor (e.g., Boschman et al., 2014, 2019). Around the same time that the oceanic Caribbean plate first started to collide with North and South American continental margins, the Central American subduction zone formed (Boschman et al., 2019). This subduction zone disconnected the Caribbean plate from the Farallon plate after ~100 Ma. Previous reconstructions assumed that, prior to 100 Ma, the Caribbean plate was located in a more or less stationary position adjacent to an "inter-American transform" (e.g., Pindell and Kennan, 2009), but this would require that a pre-100 Ma trench was present between the Caribbean and Farallon, for which there is no evidence. Instead, prior to 100 Ma, the Caribbean lithosphere including the northern GAC was part of the Farallon plate. Reconstructing the Farallon plate then restores the GAC above a south-dipping, ~E-W trending, near-equatorial subduction zone that around 130 Ma extended ~3500 km from the Americas into the Panthalassa Ocean (Boschman et al., 2019; see below). From this it follows that, if the Caribbean plate was part of the Farallon plate, the lithosphere to the north of the GAC subduction zone, i.e. facing the North American active margin, was not part of the Farallon plate but of a different plate.

FRANCISCAN PERSPECTIVE

A geological record of the subducted eastern Panthalassa lithosphere is preserved at the western margin of the United States and is composed of a series of accreted, fault-bounded litho-tectonic belts of oceanic and arc terranes (e.g., Pavlis et al., 2019). From west to east, these include a Mesozoic–Cenozoic subduction-accretion complex represented by the Franciscan Complex overlain by Middle to Upper Jurassic ophiolites of the Coast Range that recorded subduction initiation around ~180–170 Ma (Wakabayashi, 2025; Fig. 1A). Eastward lie Paleozoic to Lower Mesozoic intraoceanic arc complexes (i.e., Klamath Mountains, Blue Mountains, Sierra Nevada) accreted to North America by ~160 Ma, as well as older Paleozoic subduction-accretion complexes (Chapman et al., 2021). These are in tectonic contact with the former passive margin of the North American craton. The entire Cordillera and its major boundaries were intruded by Mesozoic subduction-related batholiths (e.g., Sierra Nevada), which supplied sediments to forearc basins that unconformably overlie the Coast Range ophiolites and the underlying Franciscan Complex since ~150 Ma (Orme and Surpless, 2019).

The Franciscan Complex contains Early Jurassic to Eocene OPS packages that were episodically accreted between ~175 and ~50 Ma (Wakabayashi, 2025) and that are thus relevant to study the lithosphere that existed to the north of the GAC-related subduction zone and that subducted below North America. OPS packages underlain by basalts with mid-ocean-ridge basalt (MORB) geochemical affinity (Ghatak et al., 2012) indicate that, throughout this period, the age of the subducted ocean increased, from Early Cretaceous (hence only a few 10s of Ma old during accretion) to Early Jurassic (Fig. 2), showing that the subducting plate aged westward (Fig. 3).

RESULTS

OPS units characterized by basal MORB-affinity basalts were sampled at three localities to check the ages of ocean floor and accretion (Figs. 1, 2; Supplemental Material). At Alexander Avenue (column 8 in Fig. 2), massive basalts are overlain by red cherts grading upward into green cherts. Radiolarians from the basal red cherts yielded UA12-17 to UA12-19 zones (Carter et al., 2010), indicating a mid-Pliensbachian age (~188.5–188 Ma; Gradstein et al., 2020). Similar ages were obtained from cherts interbedded with pillow basalts at the Golden Gate View Point (UA17) and from a chert 4 m above the basalt-chert contact on Mount Diablo (UA12). Overall, our new ages provide a more accurate chert age than the Pliensbachian–Toarcian range previously reported from comparable OPS intervals in the Marin Headlands (Murchey, 1984). At Alexander Avenue, radiolarians from the uppermost 0.2 m of green cherts beneath the clastic rocks yielded UA11-12 to UA12-14 zones (O'Dogherty, 1994), indicating a late Albian age (~103 Ma; Gradstein et al., 2020) and excluding previous Cenomanian age assignments (Murchey, 1984) for the same interval. Accretion of the MORB basalt-chert OPS package therefore occurred shortly after ~103 Ma, in agreement with the 100 ± 2 Ma maximum depositional age of detrital zircons (DZ) from overlying clastic rocks at nearby Rodeo Cove (McPeak, 2015).

OPS units with intrusions of ocean island-affinity basalts (OIB) were sampled at the Permanente quarry (Figs. 1, 2; Supplemental Material). In the main quarry pit (column 9 in Fig. 2), DZ from clastic rocks overlying pelagic limestones intruded by OIB basalts yielded a maximum depositional age of 93.6 ± 0.2 Ma (1s, n = 47, mean square weighted deviation [MSWD] = 0.88; YC2σ(3+), Dickinson and Gehrels, 2009), indicating Turonian accretion, consistent with the youngest limestone ages (Sliter and McGann, 1992). A second OPS package (column 11 in Fig. 2), 300 m east, consists of 13 m of red cherts overlying deformed basalts of undetermined affinity. Campanian radiolarians and DZ ages from overlying clastic rocks (81.5 ± 0.6 Ma, 1s, n = 8, MSWD = 1.3) indicate accretion at ~82–80 Ma. Together, these new ages show that the Permanente OIB-like OPS, previously believed to have accreted at ~65 Ma (Tarduno et al., 1985), had already accreted by ~90–80 Ma. This reveals a Franciscan-wide, prolonged period without accretion between ~80 and ~50 Ma.

DISCUSSION AND CONCLUSIONS

Plate kinematic reconstruction of lost oceanic lithosphere is challenging due to data scarcity. However, under the predictions of plate tectonic theory–e.g., ocean floor becomes older away from a ridge, transforms form ridge-perpendicular, and plates are on all sides surrounded by plate boundaries that end in triple junctions–we deduce possible scenarios that we evaluate in the light of our new data.

The reconstructed GAC–then part of the Farallon plate–shows that the lithosphere that was subducting below North America (and the GAC) was not part of the Farallon plate. We refer to this third plate as the "Franciscan plate". Franciscan OPS shows that the Franciscan plate that accreted after ~120–140 Ma was westward aging from ~140 to ~200 Ma (Fig. 2). This Jurassic–Cretaceous Franciscan plate lithosphere must have formed at a ridge in the east that was active between ~200 and ~140 Ma. This ridge must have been active before as well as after the ~180–170 Ma initiation of subduction at the Franciscan margin and may have initially been associated with the evolution of a Triassic–Jurassic intraoceanic arc complex that is presently found to the east of the Franciscan Complex in the Sierra Nevada and Klamath Mountains (e.g., Dorsey and Lamaskin, 2007). The strong westward aging trend suggests that the orientation of this ridge was roughly N-S striking, and it must have subducted at the Franciscan margin during the Earliest Cretaceous (Wakabayashi, 2025).

The Franciscan-Farallon plate boundary was not a spreading ridge, for that would produce an opposite aging pattern. Instead, this plate boundary could have been a long-lived transform fault or a subduction zone. A transform fault would have accommodated predominantly southward motion of the Franciscan plate relative to the Farallon plate, to accommodate subduction beneath the GAC and eventually would have been subducted when the GAC began colliding with North America in northern Costa Rica, around 100 Ma (e.g., Escuder-Viruete et al., 2015). However, it would be difficult to explain how a transform plate boundary thousands of kilometers in length could form at high angles relative to the spreading direction and associated fracture zones of both the Farallon and the Franciscan plates.

It is thus more likely that the Farallon-Franciscan plate boundary was a subduction zone. From our analysis, we cannot constrain the polarity of this hypothetical subduction zone. Kinematically, the subduction zone could have been west- or east-dipping, with the Farallon plate acting as the upper plate if west-dipping, or as the lower plate if east-dipping. In the former case, an arc would have formed on the Farallon plate and reached the western North American margin along with the GAC–around 100 Ma in the south, and possibly earlier or later towards the north depending on trench strike. If instead the Farallon plate had subducted beneath the Franciscan plate in an eastward-dipping subduction zone (Fig. 3), the Franciscan plate would have moved eastward toward North America at a slower rate than the Farallon plate (including the GAC). This scenario would have enabled simultaneous convergence along the Farallon-Franciscan, Franciscan-North American, and Caribbean-Franciscan boundaries. Such a plate geometry implies that the subduction zone located on the western edge of the Franciscan plate may have reached North America well after the GAC collided with the southernmost tip of North America at ~100 Ma (Escuder-Viruete et al., 2015; Boschman et al., 2019; Fig. 3), and, depending on the obliquity of post-100 Ma subduction, may not have collided at a different latitude than where it formed.

Previous reconstructions have also called for the presence of a Mesozoic intraoceanic subduction zone to the west of North America. The double, ~N-S trending band of anomalies beneath North America and the western Pacific imaged by seismic tomography interpreted as slab remains of a Triassic to Cretaceous intraoceanic subduction system (van der Meer et al., 2012; Sigloch and Mihalynuk, 2013; Clennett et al., 2020; Fuston et al., 2025) do not continue south of the equator, and their pattern is fully consistent with our reconstruction of the Franciscan plate. Based on slab shape, interpretations of the western band of slabs suggest that intra-oceanic subduction was eastward (Fuston et al., 2025; Sigloch and Mihalynuk, 2013).

A geological record of intraoceanic subduction of Cretaceous or older age is conspicuously absent in western Mexico or California. However, an intraoceanic arc of this age is well-known from

Vancouver Island to Alaska where it is included in the Wrangellia Superterrane that yielded low paleomagnetic paleolatitudes consistent with the predicted west-Franciscan plate trench (e.g., Tikoff et al., 2023; Andjić et al., 2025; Waldien et al., 2025). The northward translation of this arc has long been explained by the formation of the Kula plate that formed by break-up of the Pacific and Farallon plates and left magnetic anomalies on the former that reveal rapid northward spreading between ~80 and 50 Ma (Grow and Atwater, 1970). Whole or partial coupling of the west-Franciscan arc to this plate could allow its northward translation to the modern location of the Wrangellia Superterrane. Our new ages from the Permanente quarry indicate that there was no accretion in the Franciscan Complex during the 80–50 Ma interval (Fig. 2). This suggests that the geological record of the western Franciscan plate arc may have reached the North American margin around ~80 Ma and subsequently moved northward as a forearc sliver until ~50 Ma ("hit and run"; e.g., Tikoff et al., 2023). However, because there is no evidence of direct collision (Wakabayashi and Reyes, 2025), an alternative scenario involves both subduction zones remaining active during the northward translation of the western Franciscan plate arc.

These plate kinematic scenarios, based solely on the Caribbean and Franciscan geological records, are non-unique and require further integration with additional data sources, such as seismic tomography and the accreted north Cordilleran terranes. Nevertheless, our study illustrates that the Franciscan OPS provides a novel perspective on the long-standing debate over the plate tectonic history of the eastern Panthalassa.

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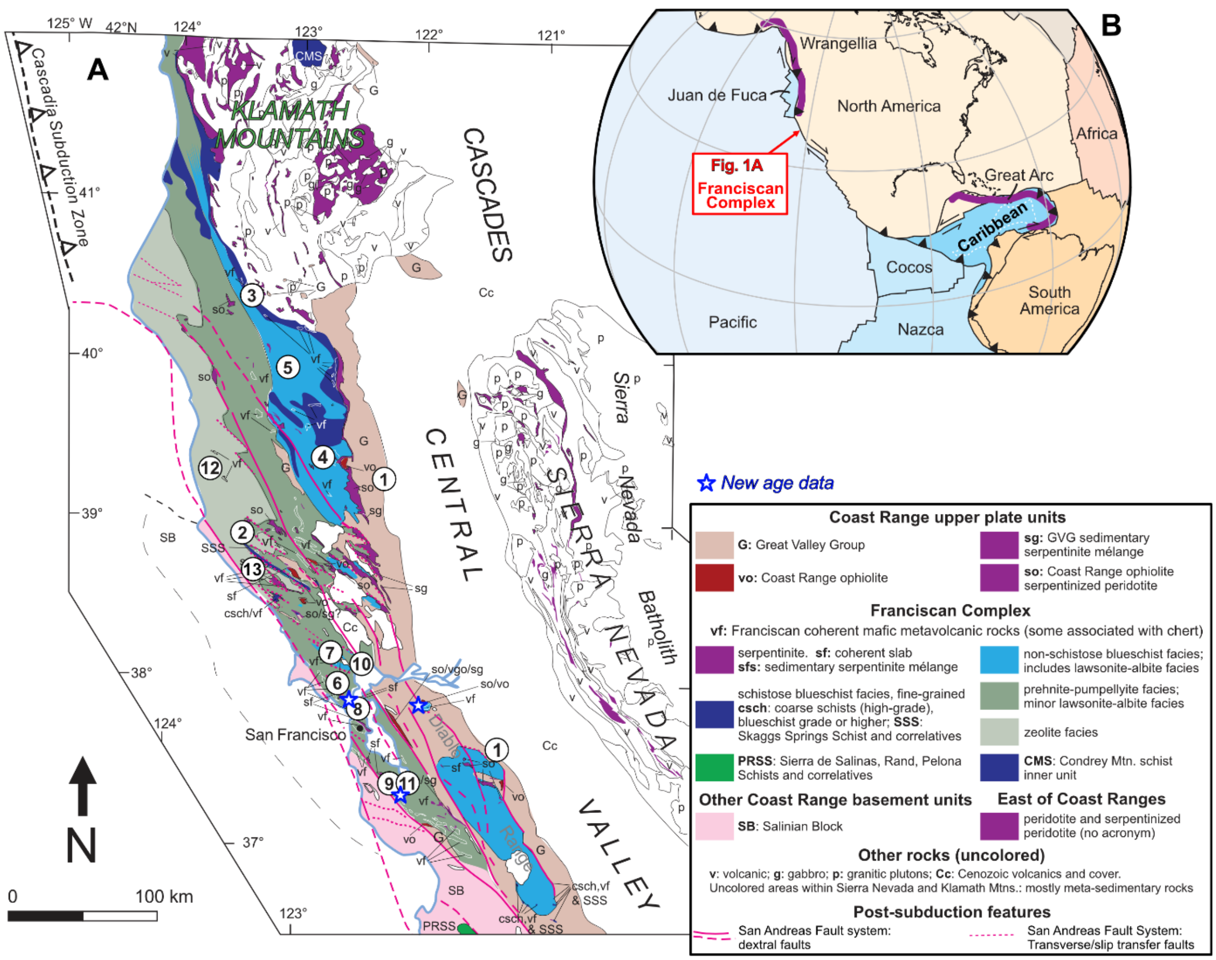

Figure 1. (A) Map showing ophiolitic rocks of California, centered on the Coast Ranges (modified from Wakabayashi, 2025). Locations of OPS columns in Fig. 2 are shown. **(B)** Plate tectonic setting of the eastern Pacific.

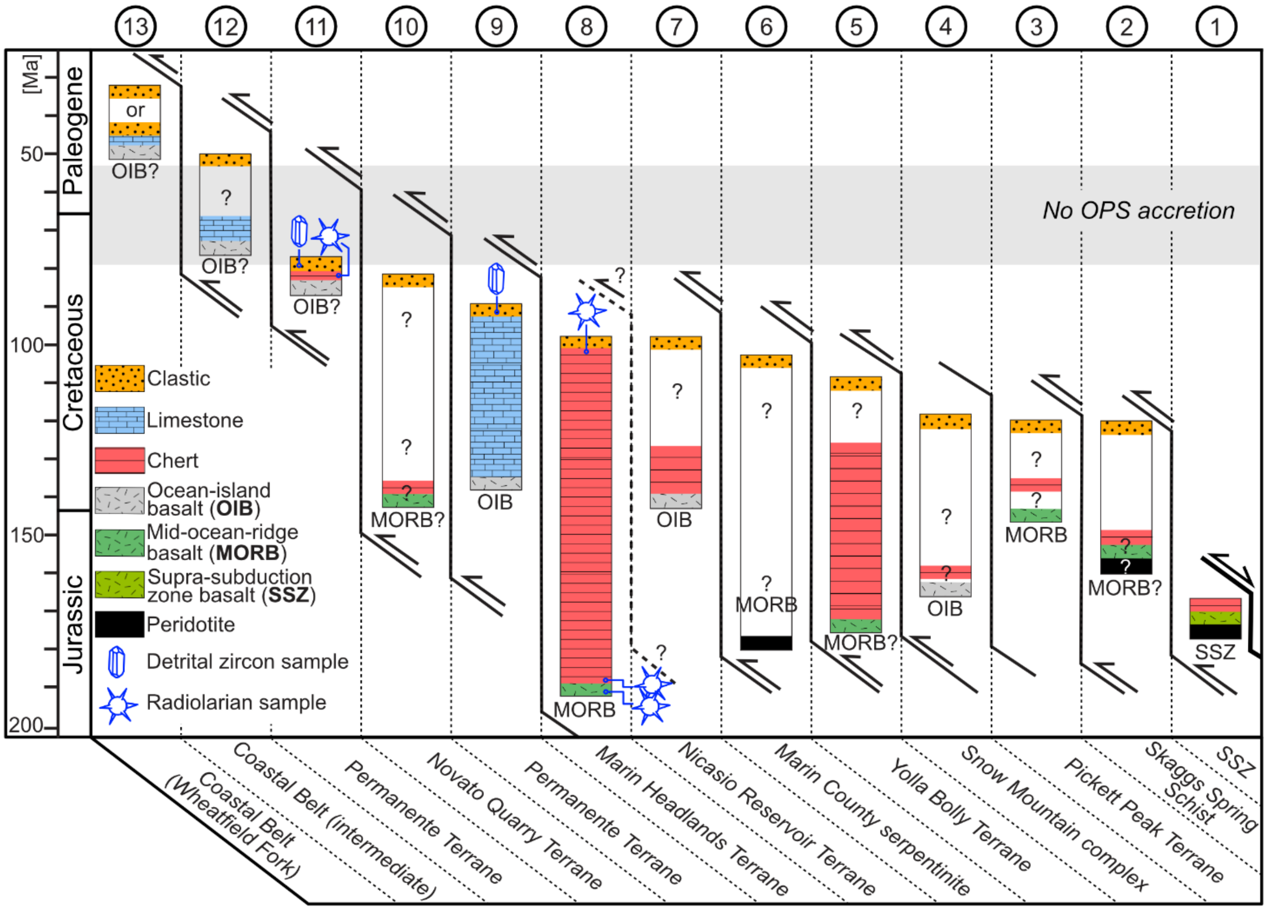

Figure 2. Age-scaled accretionary stacking order in the Franciscan Complex, with the order of OPS accretion denoted by numbers 1 to 13 (modified from Wakabayashi, 2025).

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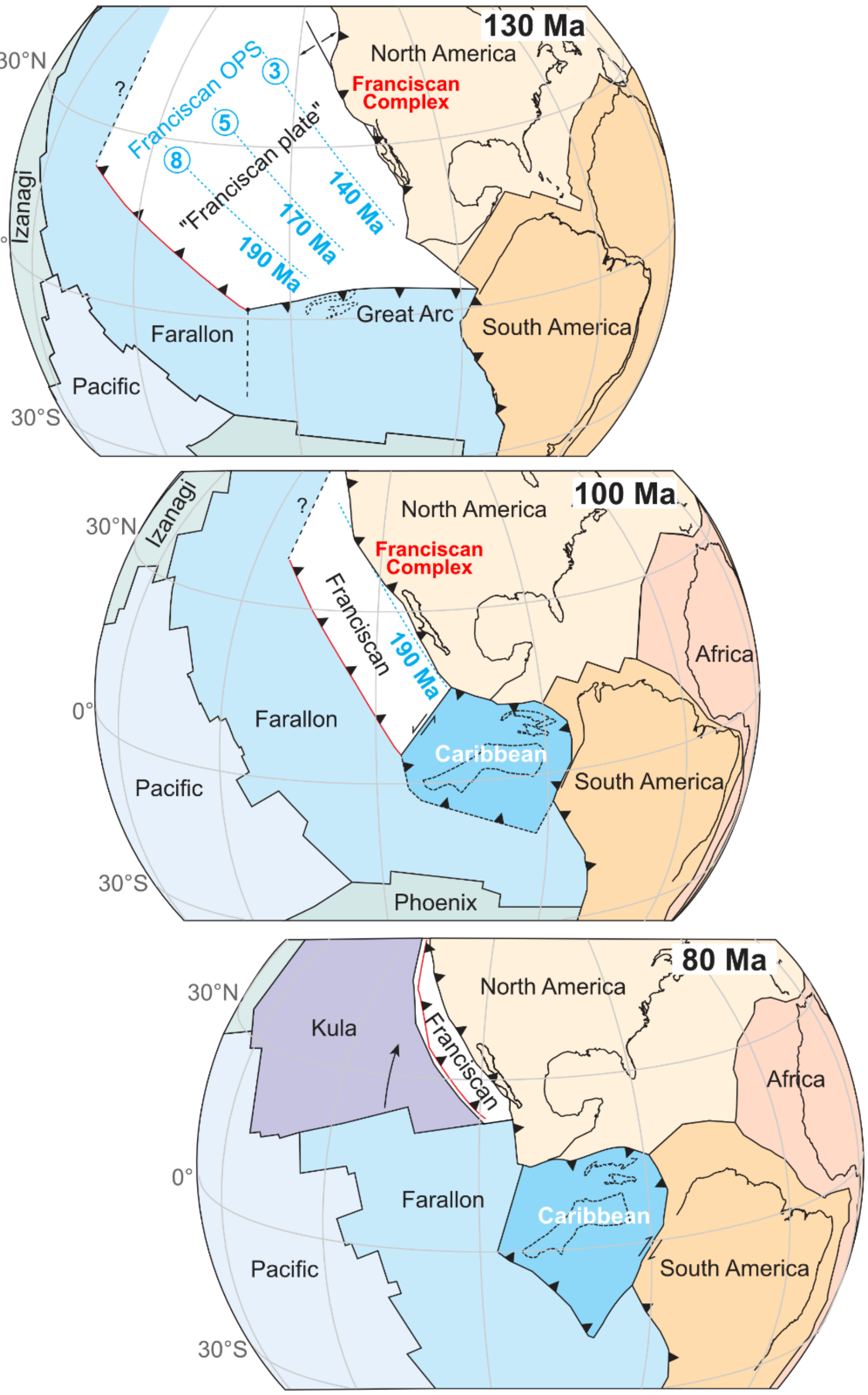

407 **Figure 3.** Reconstruction of the eastern Panthalassa at 130, 100, and 80 Ma.

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