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The lack of correlation between flat slabs and bathymetric impactors in South America

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ABSTRACT

Flat slab subduction has been attributed to various causes including mantle wedge dynamics, overriding by the upper plate, age of the subducting plate, and subduction of anomalously thick oceanic crust. One often favored explanation for flat slabs is the subduction of buoyant features on the oceanic plate in the form of an aseismic-ridge or oceanic plateau. We show through plate tectonic reconstructions of the Marquesas, Tuamotu, and Austral plateau, assuming that features on the conjugate plate can be used as proxies for subducted bathymetric anomalies, that there is very little correlation between the subduction of such anomalies and historic zones of flat subduction in South America. It is apparent that subduction of a bathymetric anomaly need not lead to a flat slab and not all flat slabs are associated with the subduction of a bathymetric anomaly.

1. Introduction

Approximately 10 percent of present day subduction zones are considered to have flat slabs, which means that their dip angle beyond the seismogenic zone is very shallow (Gutscher et al., 2000). This phenomenon has been shown to exist in the geologic record where cycles of alternating flat and normal-dip subduction are proposed (DeCelles et al., 2009; James and Sacks, 1999; Ramos and Folguera, 2009). Thickened oceanic crust, overriding of the upper plate, and mantle wedge suction are some of the proposed causes of shallow slabs (van Hunen et al., 2004). Perhaps the most frequently invoked explanation for these zones of flat to shallow subduction is excess positive buoyancy related to what we refer to as an impactor, the subduction of a bathymetric anomaly due to locally thickened oceanic crust (Anderson et al., 2007; Cross and Pilger, 1982; Gutscher et al., 1999, 2000; Liu et al., 2010; Livaccari et al., 1981; Nur and Ben-Avraham, 1983; Pilger, 1981; Saleeby, 2003). The argument for impactors as the cause of flat slabs is based on visual correlation between subducting features and shallow slabs. One of the clearest examples of this is the subduction of the Juan Fernandez Ridge where flat subduction is occurring in central Chile (Anderson et al., 2007) (Label 12 in Fig. 1).

However, the actual increase in buoyancy due to thickening of the oceanic crust in the form of a seamount or oceanic plateau is generally quite small, and decreases rapidly with age of the plate (Cloos, 1993). Other geologic processes such as serpentinization of oceanic mantle lithosphere can create a buoyancy anomaly exceeding that due to thickening of the crust in the form of seamounts, but the overall buoyancy increase remains small (Kopp et al., 2004; Skinner and Clayton, 2011). Geodynamic investigations of the effects of subduction of thick crust (Gerya et al., 2009; van Hunen et al., 2004) indicate that a buoyant impactor is not a sufficient explanation for zones of flat subduction.

2. Tracking conjugate features

To investigate the correlation of impactors and flat slabs in the past we look for time and space coincidence of these phenomena by plate tectonic reconstructions. There are several island-chains and plateaus on the Pacific plate, and if we assume that these were formed at the East Pacific Rise (EPR) and hence likely had a conjugate on the Farallon (Nazca) Plate (Gutscher et al., 1999), then we can model the time and space interactions of these features with the trench. We reconstruct a set of bathymetric anomalies that mirror the Marquesas, Tuamotu, and Austral seamounts/plateaus. We use the EarthByte plate model (Müller et al., 2008) to reconstruct Pacific plate features to the time and location of their formation on the Pacific–Farallon/Nazca spreading ridge. We then create a feature at the ancient spreading ridge and track its location relative to South America forward in time as it moves as part of the subducting plate. See Supplementary Fig. 1 for more details of the reconstructions. For times older than chron 21 there are no isochrons preserved on the Nazca plate and we must assume symmetric spreading (Seton et al., 2012), in addition any subducted ridge jumps also introduce uncertainty into the reconstructions. Note that the observed ridge jumps in the eastern Pacific are younger than the features we are

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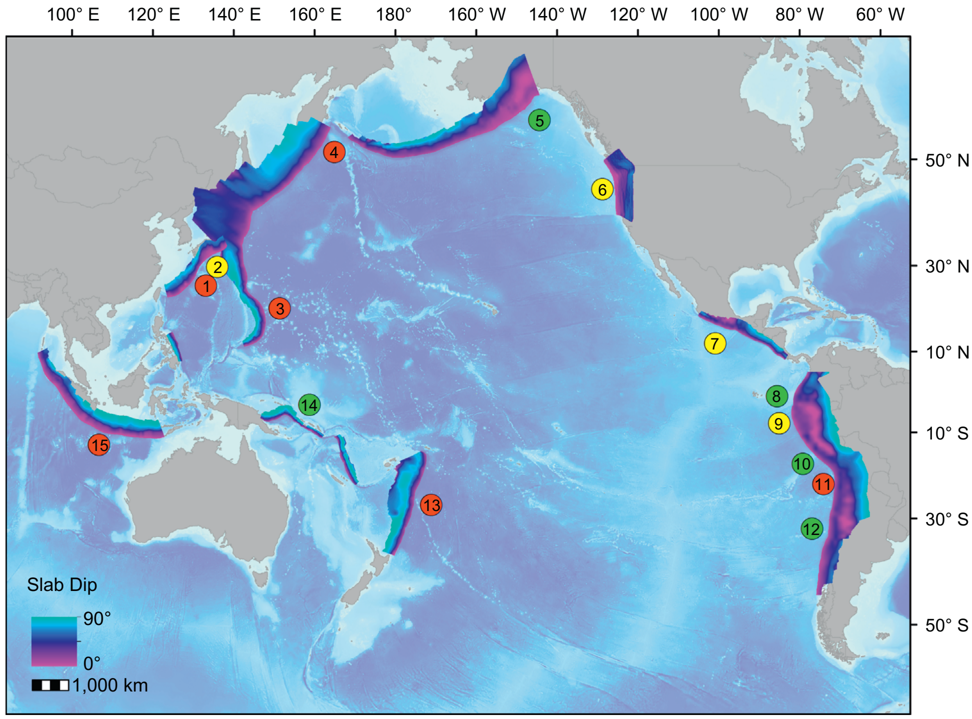

Fig. 1. Map of slab dip for subduction zones around the Pacific basin. Data for subduction zone geometry are from Hayes et al. (2012). Numbered circles represent our interpretation of the validity of the buoyancy hypothesis at each location where we have data constraining changes in the geometry of the subducted slab. Circles are colored red where there is a subducting bathymetric anomaly but no associated flat slab, yellow where there is a flat slab without any apparent subducting bathymetric anomaly, and green where a change in the geometry of the subducting slab and a bathymetric anomaly are coincident. See text for discussion of numbered circles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reconstructing and do not affect our locations based on finite rotations (Cande and Haxby, 1991).

We have confidence in our rotation model and methods based on the agreement of the location of our hypothetical conjugates with observable bathymetric features shown in Supplementary Fig. 3 and the ability of our reconstructed conjugates to predict the location of observed magnetic isochrons (Fig. 2). Our method of reconstruction is an improvement over past studies because we use global plate circuits that allow us to constrain positions relative to South America through time. Additionally the rotation models that we use cover a longer span of time than those used previously and provide finite rotations for a larger number of isochrons, which means the size and orientation of conjugate bathymetric features can evolve based on plate motions instead of being predefined. We have tested the plate rotation model used in our reconstructions (Müller et al., 2008) against four other published rotation models (Mayes et al., 1990; Pardo-Casas and Molnar, 1987; Pilger, 1981; Tebbens and Cande, 1997). See Supplementary Tables 1 and 2 for the rotations used. Supplementary Fig. 2 shows the close agreement between these models in reconstructing chrons 10 and 13. Note that our reconstruction of the Inca Plateau is 600 km east of the original location proposed by Gutscher et al. (1999). We believe that our reconstructions, that use data from both sides of the spreading ridge, do a better job predicting the location of observable features. A key feature that cannot be accounted for by the half-stage rotation model used in previous reconstructions is the observed asymmetry in spreading along the East Pacific Rise (Müller et al., 2008).

In order to visualize the spatial and temporal relations between our conjugate features and the proposed historic zones of flat subduction, we track points along the centerline of the bathymetric anomalies and calculate the distance from each flat slab. The proximity of the subducting feature is plotted in Fig. 3, together with a gray box that represents the spatial and temporal extent of the flat slab as reported by Ramos and Folguera (2009). For one of our conjugate features to be considered as a cause for the flat slab we expect it to intersect the target region near the onset of shallow subduction. The results for each slab are discussed below:

Carnegie slab (3 Ma–present): Although the Carnegie slab is a very small target, we track several impactors that arrive at the trench well before the development of the flat slab. The lithosphere currently subducting here is related to Nazca–Cocos spreading that started after 26 Ma and Pacific–Nazca conjugates are not applicable to this flat slab at this point.

Peruvian slab (11–0 Ma): The Peruvian slab has numerous impactors that reach well into the target zone and can be considered as possible causes of the flat slab. The issue with the Peruvian slab, however, is that there have been impactors for the twenty million years preceding the present day flat slab. If this portion of the South American margin has been consistently seeing bathymetric highs subduct it cannot be the subducting bathymetric high itself that supports the flattening of the slab. As shown in Fig. 2, our reconstruction of the conjugate to the Marquesas Plateau is 600 km to the east of the location of Gutscher et al. (1999). This makes it less likely to be the direct cause of the flat slab in Peru.

Altiplano slab (40–32 Ma to 27–18 Ma): The Altiplano slab appears to be anti-correlated with impactors. This portion of the margin has seen numerous impactors but they all postdate the flattening of the slab, and the majority of them arrive once the slab has resumed a steep geometry.

Puna slab (18–12 Ma): The short lived Puna flat slab has no impactors at the onset, but again there are impactors that occur once the slab has ceased to be flat. The impactors that hit after the flat slab are on the larger end of what we have measured, so we cannot use the size of impactor to explain why some have an effect while others do not.

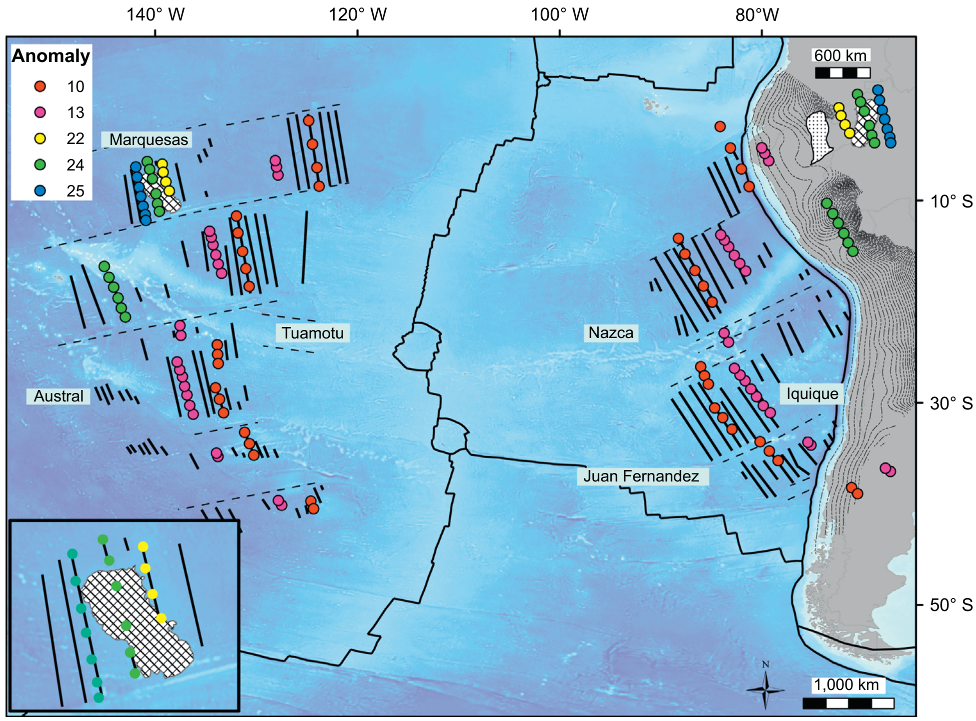

Fig. 2. Map of present day South America showing the location of our reconstructed magnetic isochrons. Black dashed lines are 20 km slab depth contours from Hayes et al. (2012). Magnetic isochrons are from Cande et al. (1989), with relevant chrons labeled. Colored circles on the Pacific plate are construction points along magnetic isochrons and are used to reconstruct the location of conjugate features on the Nazca plate. The inset map shows the Marquesas plateau at a larger scale to make the relationship between the plateau and magnetic isochrons clear. The stippled feature is the MM2 reconstruction from Fig. 2A of Gutscher et al. (1999). Note that our reconstruction of the isochrons that bound the Marquesas plateau require a 600 km eastward shift of the Inca plateau. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Pampean slab (12 Ma to present): The Pampean slab has a several impactors once the slab has gone flat. This flat slab is currently explained by the subduction of the Juan Fernandez Ridge, however, this small discontinuous chain of volcanoes was not formed on a spreading ridge so we have no way to constrain the size, shape, or extent of any portion of it that has already been subducted.

Payenia slab (13–5 Ma): From our analysis there are no conjugate impactors that can be associated with the Payenia flat slab.

3. Discussion

We have looked at the correlations between flat slabs and impactors more closely with a detailed global data set and have found that the correlations are not as strong as previously thought. In some cases show there is no apparent correlation. Fig. 1 represents our assessment of the buoyancy hypothesis at subduction zones around the globe based on the visual correlation of a subducting bathymetric anomaly and a change in slab geometry, as defined by Slab 1.0 (Hayes et al., 2012). Each numbered circle is discussed in the following section. In South America, the along trench width of the Peruvian flat slab is five times greater than the width of the Nazca Ridge which leads us to question the buoyancy of the impactor as the direct cause of the flat slab. While the Carnegie Ridge (8 in Fig. 1), Nazca Ridge (10), and Juan Fernandez Ridge (12) coincide with flat flabs, the Iquique Ridge (11) subducts without producing a flat slab and based on our reconstruction of the Inca Plateau there is no subducting anomaly to support the northern Peruvian flat slab (9). In Cascadia (6) and Mexico (7), we have shallow slabs but no indication of an impactor offshore. The Emperor Seamounts (4), Magellan Seamounts (3), Roo Rise (15), and Louisville Ridge (13) all subduct with no apparent change in the geometry of the associated subducting slab. Japan presents some of the best evidence against the buoyancy hypothesis, namely that the shallow slab is anti-correlated with the down-going bathymetric ridges. The shallow segment of the Nankai subduction zone is centered over the Shikoku basin (2), not the subducting Palau-Kyushu or Izu-Bonin ridges (1). Two extreme examples of locations where buoyancy has changed the subduction zone geometry are the Ontong Java Plateau (14), where the largest igneous province (Neal et al., 1997) has caused a reversal of subduction, and the moderately sized yet anomalously thick Yakutat terrane (5) that has impeded subduction in Alaska (Christeson et al., 2010; Gulick et al., 2007).

The recent compilation of the history of flat slabs in South America through time as defined by Ramos and Folguera (2009) allows us to extend the comparison of impactors and flat slabs back in time in this region. This compilation, plus the fact that this margin only involves two plates for most of its length and history, make this an excellent test of the impactor hypothesis. The present plate geometry in this region has been stable since the 23 Ma creation of the Nazca and Cocos Plates from the Farallon plate (Lonsdale, 2005). We recognize that there are more detailed descriptions of the temporal variations in slab geometry for portions of the South American margin (Kay and Coira, 2009). Our analysis focuses on a more general binary system that classifies a slab as normal or flat. The variation in location and timing of flat slabs as proposed by different authors (Kay and Coira, 2009; Ramos and Folguera, 2009) is less than the discrepancies we find between our reconstructions and target zones and hence does not affect our interpretations.

On the whole the subduction system in South America does not support the hypothesis that flat slabs are solely caused by

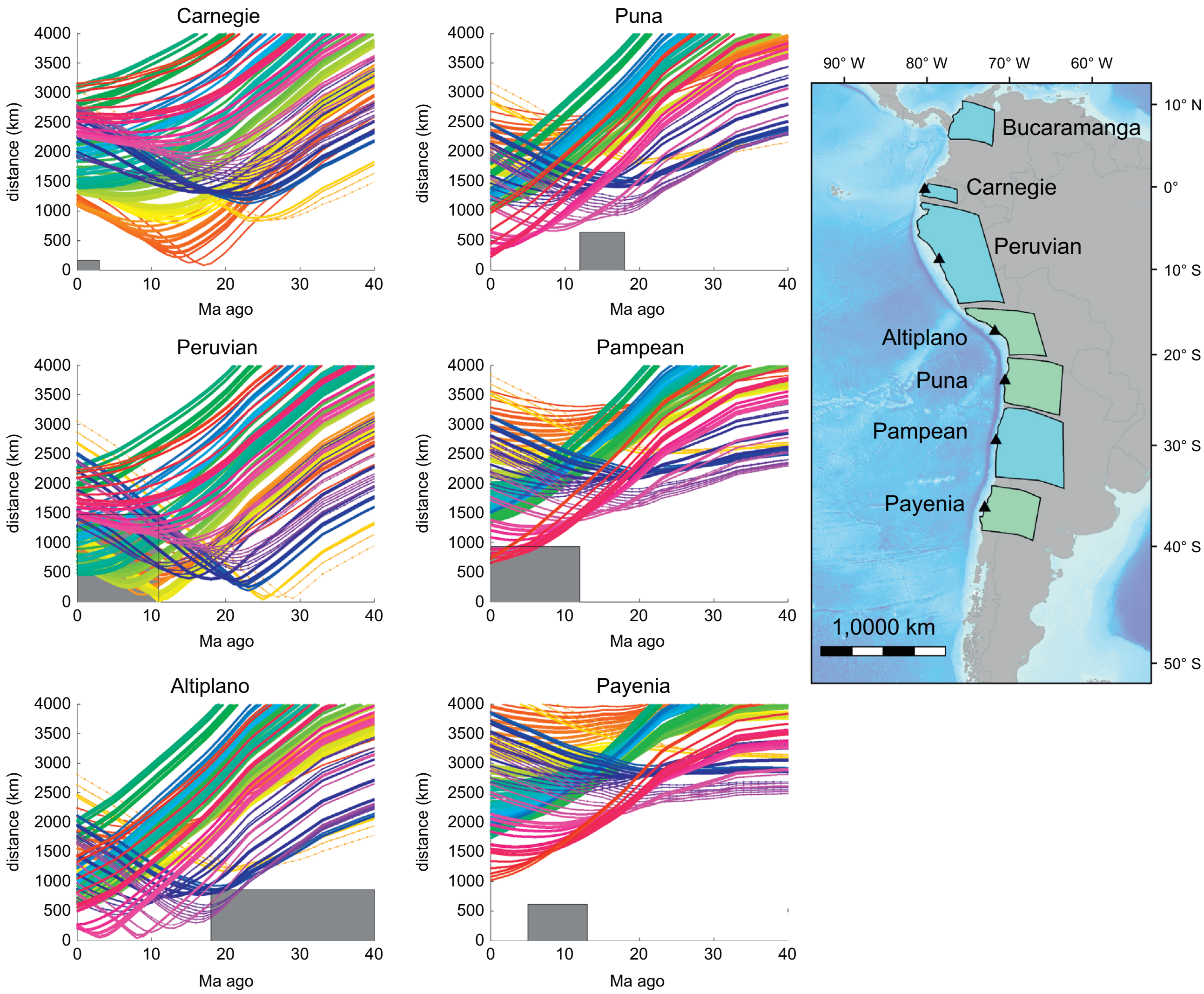

Fig. 3. Location of Pacific–Farallon/Nazca conjugate features relative to a given flat slab. We have placed points along Pacific plate bathymetric highs, and created conjugate features using standard plate reconstruction techniques and the rotation model of Müller et al. (2008). A plot for each flat slab shows the proximity of a reconstructed point on the bathymetric anomaly to that flat slab, plotted as a function of time. The thickness of the line scales with the crustal volume in a 100 km × 200 km box around the Pacific plate conjugate point. The grey box represents the spatial and temporal extent of the flat slab from Ramos and Folguera (2009). We expect impactors to pass through this target zone if the buoyancy hypothesis is the cause of the flat slab. The map shows the location of the flat slabs along the South American margin (Ramos and Folguera, 2009). The black triangles are the point from which our distances are calculated. See Supplementary Table 3 for information about the conjugate points.

subducted bathymetric anomalies. The present day connection of the Pampean slab with the Juan Fernandez Ridge, the Peruvian slab with the Nazca Ridge, and the Carnegie slab with the Carnegie Ridge are the only examples where there is a correlation, out of 15 cases. We argue against these as the cause of the flat slabs based on the fact that the Nazca Ridge is not as wide as the flat slab it creates and that the Juan Fernandez Ridge is a discontinuous structure and neither has large anomalous buoyancy.

We find that there is not a very good correlation between possible subducting anomalies in the past and inferred periods of flat or shallow subducting along the South American margin. The lack of a correlation between subducting anomalies and flat slabs in both the past and present implies that it cannot be the direct cause of flat slab subduction. If we look at the present-day spatially correlated flat slabs and subducting anomalies we can see that the flat slabs are not confined to the location of the subducting anomaly, which further casts doubt on the anomaly as the direct cause. We envision a change in mantle dynamics induced by the subducting anomaly as one possible explanation for flat slabs that persist in the wake of a subducting anomaly. This does not rely on the buoyancy of the subducting anomaly itself.

Based on our analysis of the flat subduction in central Mexico (Skinner and Clayton, 2011) we prefer a model of mantle hydration to induce shallow and flat slabs(Billen and Gurnis, 2001; Manea and Gurnis, 2007). The hydration process may be aided by subduction erosion brought on by the subducting of a bathymetric high in addition to highly altered and hydrated crust or mantle. There is evidence for the hydration process in Mexico in the form of a low viscosity layer that decouples the flat slab and the overriding crust (Kim et al., 2010). Additional evidence for hydration includes mantle xenoliths found in Mexico with water content in excess of 8 wt% (Blatter and Carmichael, 1998).

It appears that there is likely not a single cause of flat slabs. Over geologic time, the mantle can become transiently heterogeneous and it is these anomalies that lead to the diversity of subduction zone geometries that we observe today. The suggestion of orogenic cycles (DeCelles et al., 2009) may be a controlling process, with impactors only having an effect if the subduction is in the part of its cycle where the slab was shallowing. This could explain why in the present day, some zones are unaffected by impactors.

4. Conclusions

Our plate tectonic reconstructions of the South American margin and potential conjugate bathymetric anomalies when paired with the history of flat slabs compiled by Ramos and Folguera (2009) shows that there is no clear link between a subducting anomaly and zones of flat subduction. We have shown previously that the correlation between current flat slabs and subducting crustal anomalies does not exist and therefore buoyant bathymetric anomalies cannot be the sole cause of flat slabs. With this series of reconstructions we have shown that the correlation between bathymetric anomalies and flat slabs did not exist in the past and that the Inca Plateau was mislocated.

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Appendix A. Supplementry materials

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.epsl.2013.04.013.

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