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Express Letter

The “lost Inca Plateau”: cause of flat subduction beneath Peru?

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Abstract

Since flat subduction of the Nazca Plate beneath Peru was first recognized in the 1970s and 1980s a satisfactory explanation has eluded researchers. We present evidence that a lost oceanic plateau (Inca Plateau) has subducted beneath northern Peru and propose that the combined buoyancy of Inca Plateau and Nazca Ridge in southern Peru supports a 1500 km long segment of the downgoing slab and shuts off arc volcanism. This conclusion is based on an analysis of the seismicity of the subducting Nazca Plate, the structure and geochemistry of the Marquesas Plateau as well as tectonic reconstructions of the Pacific–Farallon spreading center 34 to 43 Ma. These restore three sub–parallel Pacific oceanic plateaus; the Austral, Tuamotu and Marquesas, to two Farallon Plate counterparts; the Iquique and Nazca Ridges. Inca Plateau is apparently the sixth and missing piece in an ensemble of ‘V-shaped’ hotspot tracks formed at on-axis positions. We argue the mirror image of the Inca Plateau, the Marquesas Plateau, is an ancient edifice overprinted by recent volcanism, in disagreement with the widely accepted young (<5 Ma) hotspot model for plateau formation.

Keywords: Nazca Plate; subduction; Nazca Ridge; Peru; reconstruction

1. The Marquesas plateau

The crustal structure of the Marquesas is typical of oceanic plateaus. A seismic refraction investigation [1] across the center of the archipelago discovered anomalous oceanic crust 15–17 km thick, including a 2–8 km thick, 275 km wide ‘crustal root’ with p-wave velocities between 7.2 and 7.75 km/s. While, those workers interpreted the structure as the result of recent crustal underplating, they noted the vast crustal root was not spatially related to any individual edifice. Such crustal thicknesses and velocities are in good agreement with large oceanic plateaus, i.e. Kerguelen [2], Shatsky Rise [3], Manihiki [3], Ontong Java [3], known from magnetic anomalies and geochemistry to have formed at on-axis positions.

Furthermore, the lithospheric flexure and basin fill are not compatible with the age of recent volcanism. A flexural and seismic stratigraphic study of the volcanoes and archipelagic apron concluded a light ‘crustal root’ was necessary to explain the modest flexural signal and that the lack of bathymetric expression of the flexural moat indicated it is overfilled

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[4]. The volume of the moat infill (240,000 km^3) is 2.5 times greater than the young volcanic edifices (90,000 km^3) [1] and of comparable thickness at the NW corner of the plateau (volcanism >5 Ma) as at the SE corner of the plateau (volcanism ca. 0.5 Ma). Thus, it appears impossible that (a) the moat fill represents only debris shed from collapsing islands or that (b) up to 2 km of bioclastic sediments accumulated in the middle of the Pacific solely in the last 0.5–5 Ma. However, if we postulate an on-axis origin for the Marquesas then the flexure and apron are more readily understood. The Marquesas Plateau at its time of formation was isostatically compensated by the thick (620,000 km^3), buoyant crustal root [1]. The archipelagic apron presumably had several tens of millions of years to accumulate and fill the flexural moat before the recent volcanic islands reloaded the system between 5 Ma and present and topped off the fill giving it its current convex shape.

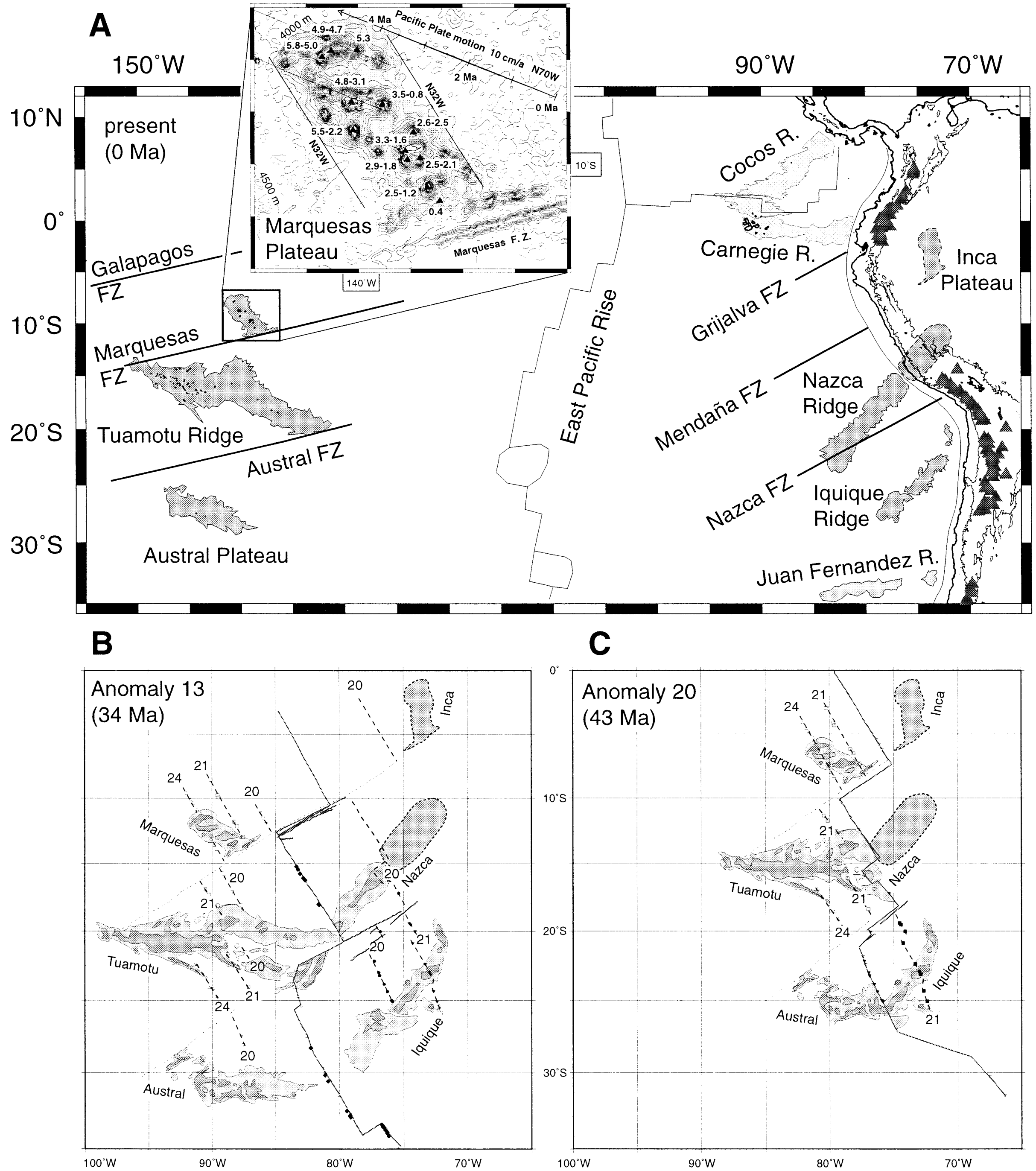
Geochemical studies of the oldest known Marquesas volcanic rocks (ca. 5–5.5 Ma) recovered from an 800 m deep drill hole on Eiao [5,6] at the NW edge of the archipelago, indicate that parent magmas were contaminated by incompatible element enriched materials located within the Pacific crust. This can be interpreted as indicating an intraplate magmatic event which intruded or thickened the oceanic crust prior to 5.5 Ma [6]. Similar explanations are favored to explain the wide isotopic variations of the Pitcairn–Gambier chain (SE of Tuamotu) [7] as well as the Australs [8].

The overall orientation of the Marquesas Plateau (N32W) is clearly oblique to the current N70W motion of the Pacific Plate (Fig. 1A inset). Interestingly though, three individual volcanic chains within the Marquesas are aligned in the N70W direction in agreement with current day plate motion models and radiometric dates on the central and southern chains indicate eastward younging age progressions from ca. 5 Ma in the W to 1.6–0.8 Ma in the E (Fig. 1A inset). This pattern of parallel chains is difficult to reconcile with the single hotspot model often proposed for the Marquesas [17,5]. The Marquesas swell and archipelagic apron, however, are oriented parallel to the Emperor direction suggesting this broader structure formed before 43 Ma.

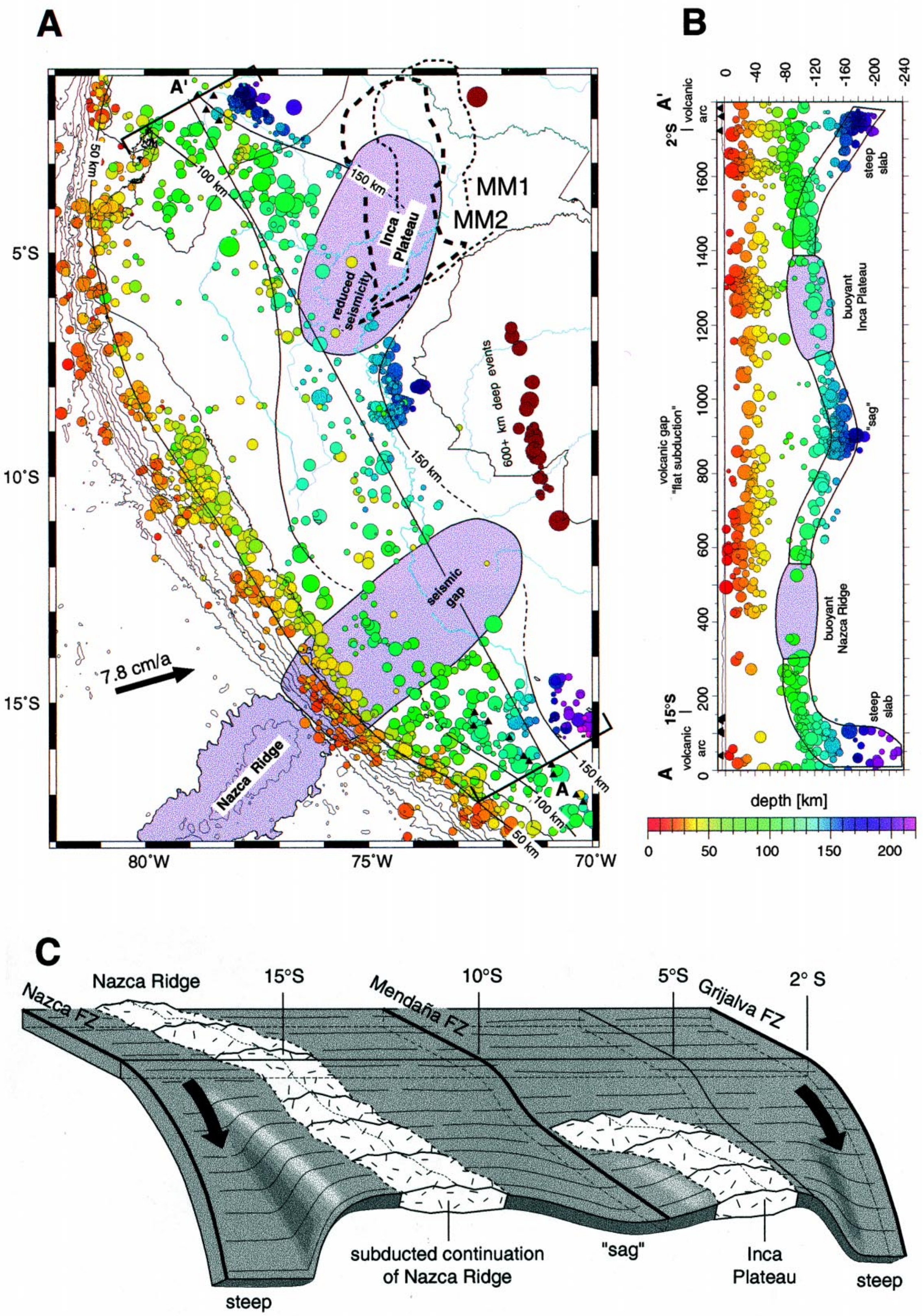
New kinematic reconstructions were made using the latest available magnetic anomaly data [16,13–15] and rotation poles corrected from Rosa and Molnar [12] (Fig. 1B,C). Despite the paucity of magnetic anomaly data older than Anomaly 13 on the Pacific and Nazca plates, it was possible to obtain reconstructions which satisfy all fracture zone and magnetic anomaly constraints. Thus, four oceanic plateaus are restored to conjugate on-axis positions at 34 Ma and 43 Ma (Fig. 1B,C). A modern analog of this process of ‘V’ shaped on-axis hotspot trace formation is the Galapagos Hotspot, with the conjugate Cocos and Carnegie Ridges (Fig. 1A). Whereas the Nazca Ridge and the Tuamotu Ridge are long known from drilling, dredging and kinematic reconstructions to be older (25–50 Ma) conjugate structures [18–21], the ancient (30–34 Ma) edifice underlying the Australs was only recently discovered, with the researchers concluding this plateau formed “near a mid-ocean ridge” [22]. The Austral Plateau has since been overprinted by recent (<10 Ma) hotspot volcanism [8,22] and similarly, we interpret the Marquesas as an older edifice overprinted by younger volcanism.

The combined weight of these arguments strongly suggests that the Marquesas are a large oceanic plateau formed at an on-axis position ca. 45–50 Ma. Inca Plateau, its mirror image, thus becomes the sixth and missing piece in the puzzle. The genesis of these six plateaus appears to be related to the megascale mantle upwelling termed the South Pacific Superswell [23]. We propose that fracture

Fig. 1. Formation and subduction of oceanic plateaus (A) Tectonic setting of oceanic plateaus and the Andean margin. Andes shown by the 2000 m contour [9] with active volcanoes (triangles), location of currently active spreading center (East Pacific Rise) and major Pacific–Farallon fracture zones (*FZ*). Ancient oceanic plateaus (defined by the −4000 m contour) are shaded medium gray. Young conjugate hotspot traces formed at the Galapagos Hotspot (defined by the −2500 m contour) are shaded light gray. Subducted portion of Nazca Ridge and the position of the Marquesas mirror image (Inca Plateau) are shown dashed. (inset): Bathymetric map of Marquesas Archipelago with age dates for recent volcanoes [10,5]. Bathymetry from Smith and Sandwell’s TOPEX data base [9]. 250 m contours shown as fine lines, with 1000 m contours shown bold. Marquesas Plateau is shaded gray above 4000 m depth. Note the structural trend of the plateau parallel to the Emperor direction (N32W). Current Pacific plate motion (10 cm/a at N70W) [11] is shown with a scale



for each 1 Ma (100 km) of motion. (B) Reconstruction of Farallon–Pacific spreading center at Chron 13 (34 Ma), using rotation pole: Lat. 69.1, Long. −103.6, Rot. 49.6 (for fixed Nazca Plate) [12]. (C) Reconstruction of Farallon–Pacific spreading center at Chron 20 (43 Ma), rotation pole: Lat. 70.9, Long. −116.4, Rot. 60.0 (for fixed Nazca Plate) [12]. Magnetic anomalies 20, 21 and 24 (dashed lines) and picks (small symbols) are shown. Plateaus are shaded gray (−4000 m and −2000 m contours) [9]. Anomalies on the Nazca Plate and the Pacific Plate south of the Austral FZ are from Cande and Haxby [13] and Tebbens and Cande [14] and on the Pacific Plate north of the Austral FZ from Munschy et al. [15] and Kruse [16].


A
A'
A
50 km
100 km
150 km
MM1
MM2
Inca Plateau
reduced seismicity
600+ km deep events
seismic gap
7.8 cm/a
Nazca Ridge
5°S
10°S
15°S
80°W
75°W
70°W
B
volcanic arc
2°S
15°S
steep slab
buoyant Inca Plateau
"sag"
volcanic gap "flat subduction"
buoyant Nazca Ridge
0
-40
-80
-120
-160
-200
-240
1600
1400
1200
1000
800
600
400
200
depth [km]
0
50
100
150
200
C
Nazca FZ
Nazca Ridge
15°S
Mendaña FZ
10°S
5°S
Grijalva FZ
2° S
steep
subducted continuation of Nazca Ridge
"sag"
Inca Plateau
steep

zone–ridge intersections in this area subjected to extension during plate motion reorganizations triggered this excess magmatism. Such a plate reorganization prior to Anomaly 21 has been described for the Marquesas and Austral Fracture Zones [24], and agrees well with our proposed timing for the formation of the six plateaus.

2. Subduction and seismicity beneath the Andean margin

If the Marquesas are an ancient plateau, then according to kinematic reconstructions its conjugate must have subducted beneath Northern Peru 10–12 Ma ago. In order to search for evidence of the subducted Inca Plateau, the seismicity of the Peru subduction zone was examined using the most complete catalog of relocated teleseismic events available [25]. Both the seismicity map with Wadati–Benioff contours (Fig. 2a) and an Andes parallel seismological section (Fig. 2B) confirm the well established general picture of a flat dipping slab and associated volcanic gap from 2ºS to 15ºS [26–28]. Steep slab segments in S. Ecuador and S. Peru, with their associated arc volcanism are seen at the northern and southern ends, respectively, of this section. The relative high in the Nazca slab at 11–14ºS, seen in the cross section (Fig. 2B) correlates with a pronounced intermediate depth seismic gap and constrains the subducted continuation of Nazca Ridge. The seismic gap is a commonly observed effect when a large asperity (oceanic plateau, ridge or seamount province) collides with a convergent margin [29]. The predicted position of Inca Plateau based on the kinematic reconstructions (Fig. 1) is shown in relation to the seismologically predicted position (Fig. 2A), corresponding to a local shallowing of the downgoing slab and a reduction in seismicity. A correction in the position of the Marquesas mirror image is also made for the dip of the subducting plate (Fig. 2A).

In the Peru flat slab segment, the oceanic crust begins subducting at a 30º angle, then flattens out and is sub-horizontal between 100 and 150 km depth before steepening and descending into the mantle [27,30–33]. Because the buoyancy of Nazca Ridge alone cannot suffice to support a 1500 km long section of the Nazca Plate, various models have been proposed to explain the flat subduction beneath Peru; (1) interplate hydrostatic suction [34], (2) a second oceanic plateau, an offset continuation of Carnegie Ridge [30], (3) a northward kink in the subducted extension of Nazca Ridge [28], (4) a delay in the basalt to eclogite phase change for young (<70 Ma), but cool (<600ºC) oceanic lithosphere [35], and (5) the negative curvature of the subducting plate beneath convex sections of a continental margin [36].

The seismological section (Fig. 2B) however, demonstrates that the widely accepted model of a strictly horizontal slab over 1500 km [27,32] is too simple. The flat slab segment exhibits a 20–40 km lithospheric ‘sag’ approximately mid way between relative highs at 5ºS and 13ºS (Fig. 2B). This suggests a double buoyant plateau model, with the Nazca Plate supported by two light bodies, each holding up a ca. 500 km portion of the slab (Fig. 2C). It is interesting to note that the subducting Juan Fernandez Ridge in Central Chile (Fig. 1) alone supports a ca. 500 km long flat slab segment of the Nazca plate and causes a volcanic gap between 28ºS and 32ºS [26,29,37]. Geochemical studies here and in the Peru gap note that prior to cessation, magmatism exhibited a shift towards more negative ε_{Nd} and higher $^{87}Sr/^{86}Sr$ ratios [37,38]. In the Peru volcanic gap, the youngest volcanism occurred in the ‘sag’ re-

Fig. 2. Seismicity and model of Peru flat slab segment (A) Seismicity (1964–1995) $M_b > 4.0$ in the Peru area from Engdahl et al.'s hypocenter relocation database [25]. Shallow events (<70 km) omitted >200 km east of trench. Active volcanoes (black triangles), bathymetry (1000 m contours) [9], relative plate convergence [11] and depth contours to Wadati–Benioff zone indicated. Location of seismological section A–A′ (B) shown. Location of Marquesas mirror image (*MM1*) from kinematic reconstruction (Fig. 1B,C) shown before and after an 80 km correction (*MM2*) for dip of Nazca Plate to 150 km depth. (B) Seismological section A–A′ beneath the Andes showing steep slab segments at the N and S ends with active arc volcanism. The 1500 km long flat slab portion of Nazca Plate is supported by two buoyant bodies, Nazca Ridge to the S and Inca Plateau to the N, with an intervening sag. (C) 3-D perspective sketch of the proposed model (view looking W), showing the geometry of the Nazca Plate and the two buoyant ridges each holding up a 500 km section of the subducting Nazca Plate with a sag in between.

gion at 2.7 Ma (Yungay Formation of the Cordillera Blanca) [38]. This is consistent with a double buoyant plateau model where volcanism would shut off last in the intervening sag.

At this time, the only model mutually consistent with the entire set of observations (crustal structure and flexure, geochemistry, alignment and reconstructions) from the oceanic plateaus on the Pacific and Nazca (Farallon) plates as well as with the seismicity in Peru is the Inca Plateau model. Tests of this model range from investigations of the deep lithospheric structure beneath South America to studies on its mirror image, the Marquesas Plateau. In South America this could include tomography of the subducted lithosphere beneath Northern Peru. Previous large scale teleseismic tomographic studies in the region [33] were targeted towards deeper mantle structure and lacked the resolution to image subducted oceanic plateaus. A further test would be to improve dating and isotopic studies [28,38] of the most recent volcanic products in the Peru volcanic gap using modern techniques. Finally, the most direct test on the Marquesas would be radiometric dating of dredge or drill samples of the old volcanic edifice beneath the young Marquesas Islands, as was successfully done for the Tuamotu and Austral plateaus [18,19,22].

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