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Slab tears and intermediate-depth seismicity

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[1] Active tectonic regions where plate boundaries transition from subduction to strike slip can take several forms, such as triple junctions, acute, and obtuse corners. Well-documented slab tears that are associated with high rates of intermediate-depth seismicity are considered here: Gibraltar arc, the southern and northern ends of the Lesser Antilles arc, and the northern end of Tonga trench. Seismicity at each of these locations occurs, at times, in the form of swarms or clusters, and various authors have proposed that each marks an active locus of tear propagation. The swarms and clusters start at the top of the slab below the asthenospheric wedge and extend 30–60 km vertically downward within the slab. We propose that these swarms and clusters are generated by fluid-related embrittlement of mantle rocks. Focal mechanisms of these swarms generally fit the shear motion that is thought to be associated with the tearing process. **Citation:** Meighan, H. E., U. ten Brink, and J. Pulliam (2013), Slab tears and intermediate-depth seismicity, *Geophys. Res. Lett.*, *40*, doi:10.1002/grl.50830.

1. Introduction

[2] Subduction to strike-slip transitions are prevalent in active plate boundaries and can take several forms, such as triple junctions (Mendocino), acute corners (southeast Alaska), and obtuse corners (NE Caribbean) [*Bilich et al.*, 2001]. Most obtuse corners form a continuous transition from subduction to strike-slip faulting, as in the western Aleutian trench, likely due to plate stiffness [*Mahadevan et al.*, 2010]. However, some obtuse corners develop a tear in the downgoing slab, referred to as a Subduction-Transform Edge Propagator (STEP) fault [*Govers and Wortel*, 2005]. This term refers to the propagation of the tear into the subducting lithosphere as the slab rolls back over time, akin to opening a can of sardines. Slab retreat is facilitated by mantle-induced flow around the free edge of the slab [*Dvorkin et al.*, 1993; *Schellart*, 2007]. Its speed may depend on the length of the subduction zone [*Schellart*, 2007] and perhaps on the strength of subducting lithosphere [*Hale et al.*, 2010]. This tearing process has been associated with high levels of intermediate-depth seismicity in many regions, yet the mechanism that drives such tearing is not well understood. However, fluid-related embrittlement is often suggested as a mechanism for intermediate-depth earthquakes [*Raleigh and Paterson*, 1965].

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[3] Here we compare new observations of tear-related intermediate-depth seismic swarms in the northeast Caribbean (data from Meighan *et al*. [2013]) with three locations in which similar processes have been documented in previous studies: Gibraltar [*Buforn et al*., 2004], the southern end of the Lesser Antilles arc in the Caribbean [*Clark et al*., 2008], and the northern end of the Tonga trench [*Millen and Hamburger*, 1998]. The lengths of these subduction zones adjacent to these tears vary widely, from 150 (Gibraltar) to 1000 (Lesser Antilles) to 2500 km (Tonga), and trench migration velocities vary from 9 (Gibraltar) to 18 (Lesser Antilles) to 158 mm/yr (Tonga) [*Schellart*, 2007]. A seismic swarm is defined as a large number of earthquakes that occur in a time span of hours or days, located within close proximity to one another, without a main shock [*Roland and McGuire*, 2009]. Clusters of earthquakes are similar to swarms except that main shocks are evident within the sequence of events [*Prieto et al*., 2012].

[4] Seismic observations from Gibraltar, the southern Lesser Antilles, and the northern Tonga trench regions show clearly defined downgoing slabs and evidence for active tearing. The fourth region has been the focus of our recent studies in the northeast Caribbean, where the eastern edge of the Puerto Rico trench meets the northern point of the Lesser Antilles trench at the subduction-to-transform plate boundary transition. The lack of a well-defined Wadati-Benioff Zone in this region has hindered our understanding of the prevailing tectonics, especially the geometry of the slab.

[5] In this paper we take a closer look at intermediate-depth seismicity patterns and slab tearing beneath the NE Caribbean and attempt to place these observations in a broader context, including additional observations of seismic swarms/clusters associated with other slab tears. Interpretations of the other three slab-tear regions provide tectonic analogs that aid in the characterization of the downgoing North American slab, in addition to improving upon the general understanding of how the tearing process triggers high rates of seismicity. This manuscript uses these observations to propose a likely mechanism for slab tearing at depths of ~50–150 km.

2. Tear Regions

2.1. Gibraltar arc in Figure 1a

[6] The Betic-Rif Cordillera is an arcuate mountain belt that is a result of Eurasian-African oblique convergence, forming what is known as the Gibraltar arc [*Gutscher et al*., 2002; *Lonergan and White*, 1997]. Both ends of the arc are likely to be STEP faults, as originally suggested by *Govers and Wortel* [2005] and more recently by studies of regional *P* wave tomography and seismicity summarized here. Seismic velocity anomalies in the tomography show a dipping slab along the arcuate subduction zone; however, a slab is not imaged along the northern STEP fault, suggesting a lithospheric tear along

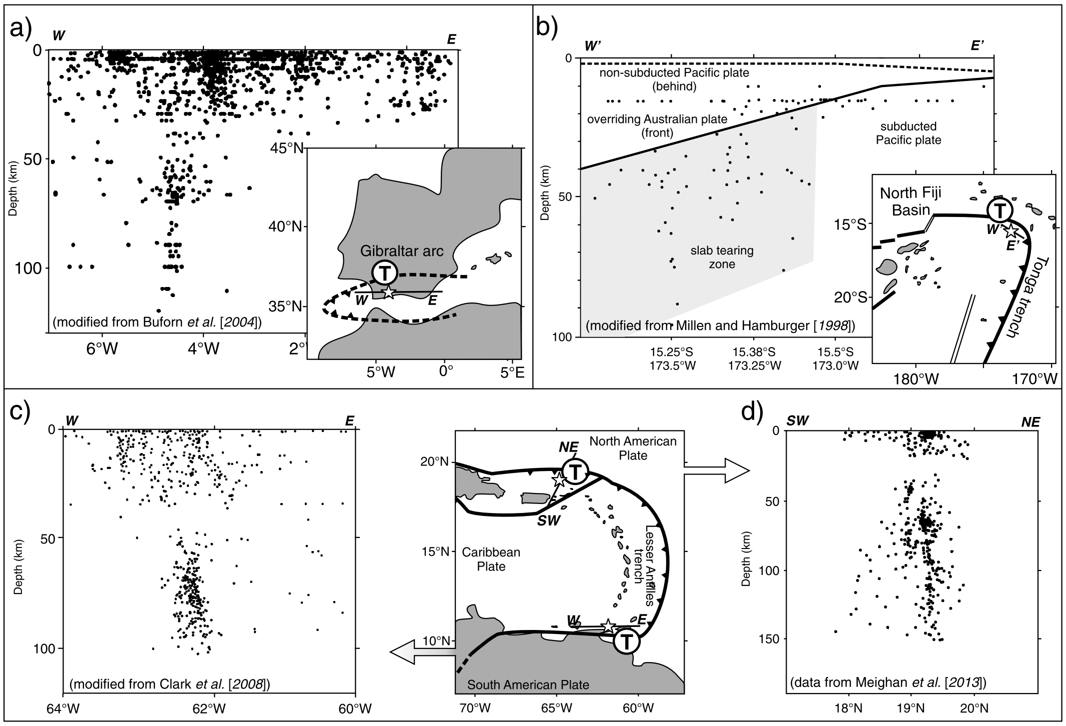

Figure 1. Location maps and corresponding hypocenter depth cross sections (plots are parallel-subparallel to plate motions) for four locations at which slab tears are associated with seismic sequences. Location map symbols: Bold black lines are standard plate boundaries, dashed black line is approximated plate boundary, "T" is the likely surface projection of the slab tear, "star" is the location of the seismic swarm/cluster/concentration. (a) Gibraltar Arc: cross section is ~600 km in length and illustrates the location of the intermediate-depth seismic activity concentration [from *Buforn et al*., 2004]. (b) Tonga Trench: cross section is ~140 km in length with swarm activity and corresponding tectonic interpretations from *Millen and Hamburger* [1998]. (c) SE Lesser Antilles Trench: cross section is ~800 km in length with the hypocenters of the Paria Cluster events are located between depths of 60 and 100 km [from *Clark et al*., 2008]. (d) NE Lesser Antilles Trench: cross section is ~450 km in length with the swarm (50–80 km) and discrete hypocenters (<150 km) plotted from data presented by *Meighan et al*. [2013].

the northern side [*Garcia-Castellanos and Villaseñor*, 2011; *Spakman and Wortel*, 2004].

[7] Event clusters or swarms are not reported in this region; yet, a concentration of earthquakes is observed at 4.5°W, 36°N in the depth range of 60–100 km, with focal mechanism solutions dominated by dip-slip motions, including normal, subvertical, and a few reverse [*Buforn et al*., 2004; *Ruiz-Constán et al*., 2009]. Stress tensors computed from the focal mechanisms show tension subparallel to plate motion near the slab top and compression subparallel to plate motion within the slab [*Buforn et al*., 2004; *Ruiz-Constán et al*., 2009]. The component of vertical extension beneath the Gibraltar Arc, inferred from focal mechanisms, is interpreted to indicate a slab that is being stretched downward through processes driven by gravitational instability [*Buforn et al*., 2004].

2.2. Tonga Trench in Figure 1b

[8] The Pacific plate is being subducted along the Tonga trench and, at its northern corner, a STEP fault is tearing the downgoing slab [*Govers and Wortel*, 2005]. Seismicity and focal mechanism solutions provide evidence for tearing of the Pacific slab and its subsequent down warping [*Millen and Hamburger*, 1998]. Seismic swarms within the Pacific plate (40–88 km depth) are dominated by strike-slip events along the corner transition, where the swarms abruptly terminate along the northern edge of the subduction zone [*Millen and Hamburger*, 1998]. Furthermore, hinge-type faults with subvertical dip-slip earthquakes are interpreted as intraplate tearing of the Pacific slab, suggesting that tearing occurs over the entire thickness of the elastic lithosphere [*Millen and Hamburger*, 1998]. The combination of the observed distribution of swarm events and the events' focal mechanisms suggests active STEP fault propagation within the tearing Pacific plate as it enters the Tonga trench.

2.3. Lesser Antilles Trench: SE Corner in Figure 1c

[9] The southern portion of the Lesser Antilles trench is where the South America plate subducts beneath the Caribbean plate. Seismicity patterns, tomography, and other seismological methods have improved our understanding of the local tectonics of northern Venezuela, especially regarding the position of the downgoing slab and tear propagation point [*Clark et al*., 2008].

[10] Seismicity variations delineate a vertical STEP fault extending through the lithosphere of the South America plate [*Clark et al*., 2008]. These clustered events, ranging from 51 to 108 km depth, are confined to a subvertical zone approximately 40 km in diameter and are described as having a "fingerlike" distribution [*Clark et al*., 2008]. The cluster of seismic events at this southern corner of the Lesser Antilles

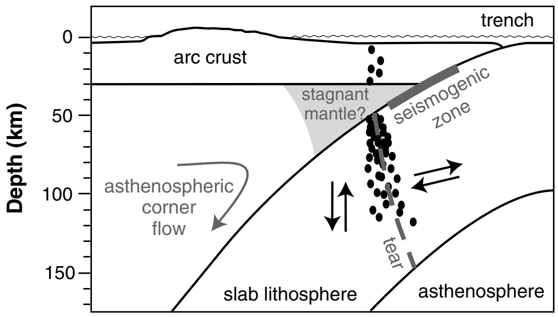

Figure 2. Model of slab tear at a subduction zone illustrating the relationship between depth, rheology, the downgoing slab, seismicity, and motions determined from hypocenters and focal mechanism solutions. Black dots mark the location of tear-related seismic activity. Side-by-side black arrows indicate vertical and strike-slip motions of the tear-related earthquakes.

trench is known as the Paria Cluster, which *Clark et al.* [2008] identify as the point of active tear propagation.

2.4. Lesser Antilles Trench: NE Corner in Figure 1d

[11] The North America plate is obliquely subducting beneath the Caribbean plate along the obtuse northern corner of the Lesser Antilles arc, northeast of Puerto Rico and the Virgin Islands. Subduction under an obtuse corner is expected to create geometric complications and as some have suggested, segmentation of the slab [*ten Brink and López-Venegas*, 2012; *ten Brink*, 2005; *Dillon et al*., 1996; *McCann and Sykes*, 1984; *Meighan and Pulliam*, 2013; *Meighan et al*., 2013]. An actively propagating slab tear is suggested to be the dominant process affecting local tectonics, based on the trench's bathymetry and negative gravity anomaly, stress changes along the trench corner related to seafloor asperities, timing of the trench collapse, seismic anisotropy, continuous Global Positioning System (GPS) vector analyses, and seismic swarm activity [*ten Brink and López-Venegas*, 2012; *ten Brink*, 2005; *Meighan and Pulliam*, 2013; *Meighan et al*., 2013].

[12] These plate features are concentrated at 65°W and include a wider and deeper Puerto Rico trench to the west, where the North America plate subducts at a steeper angle into the mantle than it does along the trench segment east of 65°W [*ten Brink*, 2005]. This is also the sharpest point of the trench corner, where the slab is subjected to increased lateral strain [*ten Brink*, 2005]. Additionally, an aseismic volcanic ridge attached to the North America plate, known as Main Ridge seamount, is being subducted at the eastern portion of the Puerto Rico trench, adjacent to this location [*ten Brink*, 2005; *McCann and Sykes*, 1984]. Modeling studies have shown that subduction of seafloor asperities, such as seamounts, create crustal stress variations in the downgoing slab and can form strike-slip faults upon trench entry [*Dominguez et al*., 2000]. These faults have been observed and mapped around the edges of the Main Ridge seamount by *ten Brink* [2005]. Furthermore, seamounts are resistant to subduction [*Gutscher et al*., 1999] and stress modeling has confirmed that large tensile stresses have developed within the slab, down dip of the seamount [*ten Brink*, 2005; *Toda and Stein*, 2002]. Mantle flow patterns inferred from crustal seismic anisotropy studies, generally parallel the Caribbean plate boundaries [*Meighan and Pulliam*, 2013; *Piñero-Feliciangeli and Kendall*, 2008; *Russo et al*., 1996; *Russo and Silver*, 1994]. One exception was observed off the NE corner of Puerto Rico where flow (inferred from crustal anisotropy) is trench normal and suggests passage of mantle material through a gap in the slab [*Meighan and Pulliam*, 2013]. Counterclockwise rotations inferred from GPS observations and the occurrence of historic and recent seismic swarms off the NE corner of Puerto Rico imply that the subducted portion of the North American plate is actively tearing at this location [*ten Brink and López-Venegas*, 2012; *Meighan et al*., 2013].

[13] Intermediate-depth earthquakes (50–150 km depth) in this region are concentrated off the northeast corner of Puerto Rico (~65°W). This area includes frequent seismic swarms that have been localized to depths of 50–80 km [*Meighan et al*., 2013]. Swarm events are dominated by strike-slip focal mechanisms, while the discrete events range from dip (both normal and reverse) to strike slip and become increasingly oblique slip with increasing depth [*Meighan et al*., 2013]. These events were used in crustal stress inversions, whose analysis suggested that the downgoing lithosphere is separated by a tear into two slabs at approximately longitude 65°W, and that two distinct stress patterns represent the state of stress in the two portions of the bifurcated slab [*Meighan et al*., 2013]. The locus of seismic swarms likely marks the point of continued tear propagation [*ten Brink*, 2005; *Meighan et al*., 2013]. Our study takes the intermediate-depth hypocenters from *Meighan et al*. [2013], and we show that they form a narrow subvertical "column", spanning 50–150 km depth, similar to the pattern of the Paria Cluster beneath Venezuela.

3. Discussion

[14] This manuscript presents several characteristic features delineated by seismicity at the location of a proposed slab tear in each of these four subduction zones (Figure 2). Frequent seismic sequences (e.g., swarms and clusters) start below the subduction interface at depths of 30–50 km. The upper depth of the seismic activity is similar for both tears adjacent to continental crust (e.g., SE Caribbean) and to oceanic crust (e.g., NE Caribbean). Therefore, the tear behavior is likely a function of the thermomechanical structure of the subducted slab. At these depths, the slab is likely overlain by a mantle wedge and is not in a direct contact with the overlying arc crust. There appears to be a seismic gap in the region just above the seismic sequences in all four locations (cross sections in Figure 1), which is likely associated with a mantle wedge [*van Keken et al*., 2011]. The details of these hypocenters are documented in the cited literature, for example, events in the SE Caribbean have an average vertical location error of ±2 km [*Clark et al*., 2008], and details of the event location procedure in the NE Caribbean are the subject of a companion paper [*Meighan et al*., 2013]. *Millen and Hamburger* [1998] interpreted the tear in the Tonga subduction zone to start below the seismogenic zone. It is unknown whether the seismogenic zone extends to deeper or shallower depths than the top of the swarm region for the other tears reviewed here.

[15] The tearing process is expected to displace the sinking slab vertically downward as well as horizontally backward relative to the reference slab or plate. It can be thought of

as Mode III fracture [*Anderson*, 2005], namely, an out-of-plane shear. However, for the tear to propagate, it also needs to undergo a Mode II (in-plane) shear. These mixed fracture modes should be expressed as subvertical dip-slip and strike-slip focal mechanisms, respectively, as is observed. The majority of the Tonga, SE Caribbean, and NE Caribbean seismicity indeed have subvertical dip-slip and strike-slip focal mechanisms [*Clark et al*., 2008; *Meighan et al*., 2013; *Millen and Hamburger*, 1998]. The area of concentrated seismicity at the edge of the Gibraltar arc shows mainly dip-slip focal mechanisms, with a few subvertical motions [*Buforn et al*., 2004; *Ruiz-Constán et al*., 2009].

[16] The seismic sequences extend downward to depths of 30–60 km below the inferred slab's surface, which is a geometry also described in studies by *Clark et al*. [2008] and *Millen and Hamburger* [1998] (see Figure 1b for an example of the latter). Events at 60 km below the slab surface are also below the expected seismogenic zone [*Hyndman et al*., 1997; *Peacock*, 2001] and with slab temperatures of 750 °C–800 °C, which is hotter than the inferred temperatures of the seismogenic zone [*van Keken et al*., 2011]. Fluid-related embrittlement, in which rocks undergo sudden weakening and change from ductile to brittle behavior during their dehydration, is often suggested as a mechanism for intermediate-depth earthquakes [*Raleigh and Paterson*, 1965]. Fluid-related embrittlement requires the existence of hydrous minerals within the subducting slab. *Hacker et al*. [2003] predicted the presence of rocks containing hydrous minerals within the top ~50 km of old slabs reaching 160 km into the mantle and compared their predictions with the observed Double Benioff Zone seismicity in some subducting slabs. The thickness of the hydrated slabs is predicted to increase with slab age, which is related to the thermal structure of the plate [*Hacker et al*., 2003]. The plates entering the subduction zones in the four locations discussed here are of Cretaceous age or older, which explains the large depth range of seismicity associated with the tearing.

[17] Finally, *Faccenda et al*. [2012] proposed that fluids within the slab migrate to form a Double Hydrated Zone, which can be correlated with the seismicity belts of a Double Benioff Zone. The migration is in response to changing deviatoric stresses from unbending of the slab at depth [*Faccenda et al*., 2012]. The presence of a tear is another imposed deviatoric stress that will likely cause fluid to migrate, explaining the vertical distribution of intermediate-depth earthquakes at the four locations described here.

4. Conclusions

[18] Vertically distributed earthquake swarms detected in the NE Caribbean, a subject of our analyses, were compared to seismic sequences at several other locations worldwide at which evidence for slab tears has been published previously. In all of these locations, the shallowest sequence occurrences are at the top of the slab, below the asthenospheric wedge and extend 30–60 km downward. We suggest that fluid-related embrittlement of mantle rocks likely generates these sequences of seismic activity. Focal mechanisms of these swarms generally fit the shear motion that is thought to be caused by tearing. These sequences of seismicity point to the locus of tear propagation, where plate motions continue along the subduction-transform plate boundary corner transition. Detailed studies of tear-related seismicity can help understand not only the process of lithospheric tearing but also shed light on subduction zone earthquakes and metamorphism in general.

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References

Anderson, T. L. (2005), *Fracture Mechanics: Fundamentals and Applications*, 3rd ed., CRC Press.

Bilich, A., C. Frohlich, and P. Mann (2001), Global seismicity characteristics of subduction-to-strike-slip transitions, *J. Geophys. Res.*, *106*, 19,443–19,452.

Buforn, E., M. Bezzeghoud, A. Udías, and C. Pro (2004), Seismic sources on the Iberia-African plate boundary and their tectonic implications, *Pure Appl. Geophys.*, *161*, 623–646, doi:10.1007/s00024-003-2466-1.

Clark, S. A., M. Sobiesiak, C. A. Zelt, M. B. Magnani, M. S. Miller, M. J. Bezada, and A. Levander (2008), Identification and tectonic implications of a tear in the South American plate at the southern end of the Lesser Antilles, *Geochem. Geophys. Geosyst.*, *9*, Q11004, doi:10.1029/2008GC002084.

Dillon, W. P., N. T. Edgar, K. M. Scanlon, and D. F. Coleman (1996), A review of the tectonic problems of the strike-slip northern boundary of the Caribbean plate and examination by GLORIA, *Geol. United States Seafloor View Gloria*, 135–164.

Dominguez, S., J. Malavieille, and S. Lallemand (2000), Deformation of accretionary wedges in response to seamount subduction: Insights from sandbox experiments, *Tectonics*, *19*, 182–196.

Dvorkin, J., A. Nur, G. Mavko, and Z. Ben-Avraham (1993), Narrow subducting slabs and the origin of backarc basins, *Tectonophysics*, *227*, 63–79.

Faccenda, M., T. V. Gerya, N. S. Mancktelow, and L. Moresi (2012), Fluid flow during slab unbending and dehydration: Implications for intermediate-depth seismicity, slab weakening and deep water recycling, *Geochem. Geophys. Geosyst.*, *13*, Q11004, doi:10.1029/2008GC002084.

Garcia-Castellanos, D., and A. Villaseñor (2011), Messinian salinity crisis regulated by competing tectonics and erosion at the Gibraltar arc, *Nature*, *480*, 359–363, doi:10.1038/nature10651.

Govers, R., and M. J. R. Wortel (2005), Lithosphere tearing at STEP faults: Response to edges of subduction zones, *Earth Planet. Sci. Lett.*, *236*, 505–523, doi:10.1016/j.epsl.2005.03.022.

Gutscher, A., J. Malavieille, S. Lallemand, and J. Y. Collot (1999), Tectonic segmentation of the North Andean margin: Impact of the Carnegie Ridge collision, *Earth Planet. Sci. Lett.*, *168*, 255–270.

Gutscher, M. A., J. Malod, J. P. Rehault, I. Contrucci, F. Klingelhoefer, L. Mendes-Victor, and W. Spakman (2002), Evidence for active subduction beneath Gibraltar, *Geology*, *30*, 1071–1074.

Hacker, B. R., S. M. Peacock, G. A. Abers, and S. D. Holloway (2003), Subduction factory 2. Are intermediate-depth earthquakes in subducting slabs linked to metamorphic dehydration reactions?, *J. Geophys. Res.*, *108*(B1), 2030, doi:10.1029/2001JB001129.

Hale, A. J., K.-D. Gottschaldt, G. Rosenbaum, L. Bourgouin, M. Bauchy, and H. Mühlhaus (2010), Dynamics of slab tear faults: Insights from numerical modelling, *Tectonophysics*, *483*, 58–70, doi:10.1016/j.tecto.2009.05.019.

Hyndman, R. D., M. Yamano, and D. A. Oleskevich (1997), The seismogenic zone of subduction thrust faults, *Isl. Arc*, *6*, 244–260.

van Keken, P. E., B. R. Hacker, E. M. Syracuse, and G. A. Abers (2011), Subduction factory: 4. Depth-dependent flux of H_2O from subducting slabs worldwide, *J. Geophys. Res.*, *116*, B01401, doi:10.1029/2010JB007922.

Lonergan, L., and N. White (1997), Origin of the Betic-Rif mountain belt, *Tectonics*, *16*, 504–522.

Mahadevan, L., R. Bendick, and H. Liang (2010), Why subduction zones are curved, *Tectonics*, *29*, TC6002, doi:10.1029/2010TC002720.

McCann, W. R., and L. R. Sykes (1984), Subduction of aseismic ridges beneath the Caribbean Plate: Implications for the tectonics and seismic potential of the northeastern Caribbean, *J. Geophys. Res.*, *89*, 4493–4519.

Meighan, H. E., and J. Pulliam (2013), Seismic anisotropy beneath the Northeastern Caribbean: Implications for the subducting North American lithosphere, *Geol. Soc. France Bull.*, *184*, 67–76.

Meighan, H. E., J. Pulliam, U. S. ten Brink, and A. López (2013), Seismic evidence for a slab tear at the Puerto Rico Trench, *J. Geophys. Res. Solid Earth*, *118*, 2915–2923, doi:10.1002/jgrb.50227.

Millen, D. W., and M. W. Hamburger (1998), Seismological evidence for tearing of the Pacific plate at the northern termination of the Tonga subduction zone, *Geology*, *26*, 659–662.

Peacock, S. M. (2001), Are the lower planes of double seismic zones caused by serpentine dehydration in subducting oceanic mantle?, *Geology*, *29*, 299–302.
Piñero-Feliciangeli, L. T., and J.-M. Kendall (2008), Sub-slab mantle flow parallel to the Caribbean plate boundaries: Inferences from SKS splitting, *Tectonophysics*, *462*, 22–34, doi:10.1016/j.tecto.2008.01.022.
Prieto, G. A., G. C. Beroza, S. A. Barrett, G. A. López, and M. Florez (2012), Earthquake nests as natural laboratories for the study of intermediate-depth earthquake mechanics, *Tectonophysics*, *570-571*, 42–56, doi:10.1016/j.tecto.2012.07.019.
Raleigh, C. B., and M. S. Paterson (1965), Experimental deformation of serpentinite and its tectonic implications, *J. Geophys. Res.*, *70*, 3965–3985.
Roland, E., and J. J. McGuire (2009), Earthquake swarms on transform faults, *Geophys. J. Int.*, *178*, 1677–1690, doi:10.1111/j.1365-246X.2009.04214.x.
Ruiz-Constán, A., D. Stich, J. Galindo-Zaldívar, and J. Morales (2009), Is the northwestern Betic Cordillera mountain front active in the context of the convergent Eurasia–Africa plate boundary?, *Terra Nova*, *21*, 352–359, doi:10.1111/j.1365-3121.2009.00886.x.
Russo, R., and P. G. Silver (1994), Trench-parallel flow beneath the Nazca Plate from seismic anisotropy, *Science*, *263*, 1105–1111, doi:10.1126/science.263.5150.1105.
Russo, R. M., P. G. Silver, M. Franke, W. B. Ambeh, and D. E. James (1996), Shear-wave splitting in northeast Venezuela, Trinidad, and the eastern Caribbean, *Phys. Earth Planet. Inter.*, *95*, 251–275, doi:10.1016/0031-9201(95)03128-6.
Schellart, W. P. (2007), The potential influence of subduction zone polarity on overriding plate deformation, trench migration and slab dip angle, *Tectonophysics*, *445*, 363–372.
Spakman, W., and M. J. R. Wortel (2004), A tomographic view on Western Mediterranean geodynamics, in *The TRANSMED Atlas, The Mediterranean Region from Crust to Mantle*, 31–52.
ten Brink, U. (2005), Vertical motions of the Puerto Rico Trench and Puerto Rico and their cause, *J. Geophys. Res.*, *110*, B06404, doi:10.1029/2004JB003459.
ten Brink, U. S., and A. M. López-Venegas (2012), Plate interaction in the NE Caribbean subduction zone from continuous GPS observations, *Geophys. Res. Lett.*, *39*, L10304, doi:10.1029/2012GL051485.
Toda, S., and R. S. Stein (2002), Response of the San Andreas fault to the 1983 Coalinga-Nuñez earthquakes: An application of interaction-based probabilities for Parkfield, *J. Geophys. Res.*, *107*(B6), 2126, doi:10.1029/2001JB000172.