Mantle flow at the highly arcuate northeast corner of the Lesser Antilles subduction zone: Constraints from shear-wave splitting analyses

Michael Hodges and Meghan S. Miller
DEPARTMENT OF EARTH SCIENCES; UNIVERSITY OF SOUTHERN CALIFORNIA, 3651 TROUSDALE PARKWAY, LOS ANGELES, CALIFORNIA 90089-0740, USA

ABSTRACT

Seismic anisotropy is used to investigate deformation in subduction zones, where many dynamic processes are at play. Recently, a global pattern of trench-parallel subslab mantle deformation in subduction zones has emerged through shear-wave splitting measurements. We investigated the Lesser Antilles in the Caribbean to find that the northeast corner of the subduction zone presents an interesting setting in which to observe seismic anisotropy, where the trench-parallel subslab splitting signal may become complicated due to oblique subduction. Here, we present 201 shear-wave splitting measurements of SKS and SKKS phases from teleseismic events recorded at 20 broadband seismic stations in the northeastern Caribbean. We observe average apparent fast polarization directions (Δ) that are primarily trench-parallel, with average delay times (δf) ranging from 0.5 s to 2.0 s. Our results suggest trench-parallel mantle flow is continuous along the northeastern plate boundary where the Lesser Antilles subduction zone changes strike from nearly east-west trending to north-south trending. Our preferred explanation for the observed splitting pattern is that the dominant process is subslab mantle return flow.

INTRODUCTION

Subduction zones represent locales of the downgoing portion of Earth’s convective convector belt, where dense oceanic lithosphere descends into the deep mantle. Much effort is spent trying to understand the evolution and history of deformation at these plate boundaries. In the Caribbean, convergent motion between the North American and Caribbean plates is accommodated by the Lesser Antilles subduction zone (Fig. 1), where the Caribbean plate migrates coherently in an east-northeast direction in the North America reference frame (Mann et al., 2002). The oceanic lithosphere subducts beneath the Caribbean plate, perpendicular to the trench in the middle of the subduction zone, and subparallel with the trench at the cusps of the arc (Molnar and Sykes, 1969). This change in subduction geometry corresponds to increasingly oblique motion along the northern and southern extents of the arc until it becomes almost purely strike slip. The origin of the Cretaceous-age Caribbean plate is debated, but there are two leading hypotheses. In one scenario, the Caribbean plate originated within the Farallon plate that was subducting beneath North and South America (e.g., Pindell and Barrett, 1990). In the other, the Caribbean plate formed east of the Farallon plate, between the Americas (e.g., Meschede and Frisch, 1998; James, 2009). One of the preferred models for the Cenozoic evolution of the Caribbean plate is that westward subduction of Atlantic lithosphere at the Lesser Antilles trench has been occurring since the Eocene, resulting in at least 1100 km of subduction into the lower mantle (Müller et al., 1999). The Caribbean plate has migrated eastward under a subduction roll-back regime, becoming narrower with more curvature through time.

In the northeast Caribbean, the subduction zone is highly arcuate, resulting in oblique-type subduction (Fig. 1). The existence of the Puerto Rico slab beneath the Caribbean has been inferred from Wadati-Benioff seismicity and global positioning system (GPS) data (e.g., McCann and Pennington, 1990; Calais et al., 1992), although the lithospheric structure and kinematics at this plate boundary are still questioned. A south-dipping Wadati-Benioff seismicity zone (Engdahl et al., 1998) is present to ~150 km depth (Fig. 1), and body wave tomography images support that the Puerto Rico slab is attached to the North American plate and has moved laterally as far east as eastern Hispaniola (e.g., van Benthem et al., 2013). Seismicity in the area shows sinistral, oblique focal mechanisms, and GPS measurements support strain partitioning of the translational and convergent motion (Calais et al., 1992, 2002; Dolan et al., 1998). South-dipping subduction is inferred to be caused by underthrusting of the slab beneath the Caribbean plate beneath Puerto Rico, brought by westward motion of the North American plate. This corner of the subduction zone is home to multiple microplates, including the Puerto Rico microplate, which has rotated counterclockwise since the late Miocene (Byrne et al., 1985; Reid et al., 1991; Dolan et al., 1998).

Seismic anisotropy has emerged as an important observable variable with which to constrain subduction zone deformation (e.g., Russo and Silver, 1994; Long, 2013). Global observations of anisotropy in subduction zones show a dominant pattern of trench-parallel apparent fast polarization directions forming the basis for a trench-migration–controlled model for the development of seismic anisotropy, in which the migration of a trench induces subslab, three-dimensional mantle return flow, aligning intrinsically anisotropic minerals in a trench-parallel orientation (Long and Silver, 2008, 2009b).

In this study, we analyzed shear-wave splitting of SKS phases to infer mantle deformation and evolution in the northeastern Caribbean subduction zone. We analyzed broadband data from 20 stations in the northeast Caribbean and compared them to results from previous studies to further study the nature of mantle deformation and evolution of subslab structure, with an emphasis on the northern cusp of the Caribbean arc, where the convergent motion transitions from perpendicular to highly oblique motion.
Figure 1. (A) Overview map of the Caribbean–North American plate boundary. White triangles represent the locations of seismic stations used in our study, and dots represent seismicity with magnitude 3.5 and above. (B) Zoomed-in view of our area of study, which is indicated by the black outline in A. DR—Dominican Republic; PR—Puerto Rico.
METHODS

Seismic anisotropy refers to the dependence of seismic wave speeds on the polarization and propagation direction. One manifestation of seismic anisotropy is shear-wave splitting. Shear waves are split into two orthogonally polarized components with different speeds when traveling through anisotropic media (Silver and Chan, 1988, 1991). Anisotropy of shear waves from a single event at a single station can be parameterized by the polarization direction (φ) of the fast-arriving phases and the delay time (δt) between the two shear-wave phases. There are many ways that fabric is formed that produce seismic anisotropy within Earth, including alignment of material such as partial melt or fluid-filled cracks by a shape-preferred orientation (SPO), but the dominant source of anisotropy observed in the upper mantle appears to be through the strain-induced lattice preferred orientation (LPO) of mantle minerals, mainly olivine (Silver, 1996; Savage, 1999; Karato et al., 2008). A simplifying assumption is made about the relationship between deformation in the upper mantle and LPO by taking into account the dependence on environmental factors such as pressure, temperature, deviatoric stress, melt fraction, and water content; after making this assumption, the nature and geometry of mantle flow can be inferred, and tectonic and geodynamic models can be validated through the measurement of splitting parameters (e.g., Savage, 1999; Long and Becker, 2010).

The ray-path geometry of teleseismic SKS phases has several advantages that allow for mapping mantle anisotropy by measuring shear-wave splitting at multiple stations. SKS phases are converted from P waves to S waves as they exit the core-mantle boundary, meaning that the observed anisotropy is constrained to the receiver side of the core-mantle boundary; they also acquire a known radial polarization upon conversion at the core-mantle boundary, meaning that any energy recorded on the transverse component is indicative of anisotropy; and their near-vertical incidence angle means that SKS phases provide excellent lateral resolution (Silver and Chan, 1988, 1991). Splitting parameters are path-integrated measurements, however, and therefore they have poor depth resolution. In the simplest case of a single, homogeneous layer of anisotropy with a horizontal symmetry axis in the upper mantle, the φ will align with the direction of maximum shear (Long and Becker, 2010). If the zone of anisotropy is multilayered, heterogeneous, or has a dipping symmetry axis, then the “apparent” splitting parameters that result may be highly complex, which must be accounted for in order to relate them to mantle deformation (Long and Becker, 2010).

Splitting measurements presented in this study were made using the MATLAB package SplitLab (Wüstefeld et al., 2007). To find the best-fitting splitting parameters for a single seismogram, SplitLab uses three different techniques of which we use two, the rotation-correlation (RC) method (e.g., Bowman and Ando, 1987), and the minimum-energy (SC) method (Silver and Chan, 1991). For a split shear wave, energy is recorded on the radial and transverse components of a seismogram, and the particle motion will be elliptical. Both the RC and SC techniques perform a grid-search for the φ and δt that best linearize the particle motion on the radial Q and transverse T, or Q-T plane, thereby removing the effect of splitting. The RC method maximizes the cross-correlation coefficient between the two horizontal components of the waveform to find the best-fitting splitting parameters, while the SC method searches for the minimum energy of ground displacement on the transverse component. The time window over which the grid search is performed is manually selected. This allows for control on the quality of measurements by both visual inspection and quantification (Fig. 2). Each measurement

Figure 2. Example of splitting measurement from SplitLab at station ANWB using the rotation correlation method. (A) Plot showing the Q component (radially away from the earthquake, inclined perpendicular to the P wave motion) as a blue dashed line, the tangential component as a red line, and the window used in the measurement highlighted with gray. (B) Detailed information about the source, receiver, and the measurement. (C) Polar plot with symbols plotted at the back azimuth and inclination of the arrival as well as sticks to indicate the observations of fast-axis orientation and delay time. (D) Plots showing Q and T components corrected by the observed splitting parameters into a fast and slow orientation, shifted by the delay time. Part D shows the correction into Q and T components. (E) Particle motion in the horizontal plane. The blue dashed line is the particle motion before the correction, and the red line shows the particle motion after the correction. (F) Misfit spaces of delay time (x-axis) and fast axis (y-axis). The gray and black areas are the minimum misfit. SNR—signal to noise ratio.
is classified as a split or a null and then qualitatively assigned a quality of “good,” “fair,” or “poor,” based upon the quality of the seismogram, the linearity and cleanliness of the linearized particle motion, the agreement between the two measurement techniques, and the statistical uncertainty for the measured $\phi$ and $\delta t$. Depending on the station used, we chose the method that gave the most consistent results in terms of the previous criteria; for most stations, the RC method was chosen. The method used and the values are given in Table 1.

**DATA AND RESULTS**

We analyzed 201 SKS and SKKS splitting measurements from 20 broadband seismic stations in the northeast Caribbean available through the IRIS Data Management Center (http://www.iris.edu/bq/). Stations used are part of the Puerto Rico seismic network (PR) (15), the Netherlands Antilles seismic network (NA) (3), the U.S. Geological Survey (USGS) Caribbean network (CU) (1), and the USGS Global Seismograph Network (IU) (1). Events of magnitude 6.0 and greater with distances between 88° and 135° that occurred between 2003 and 2014 were selected. These events are clustered into three different back-azimuthal regions, the NW, SW, and NE. Each seismogram was filtered in SplitLab between 0.01 and 0.2 Hz. Of the 201 splitting measurements, 93 were classified as “good,” and 125 were classified as “fair.” The list of the stations and the average results are shown in Table 1, and each measurement is listed in Table DR1.¹

We also attempted to obtain splitting observations from five ocean-bottom seismometers (OBS) that were deployed on the forearc of the Puerto Rico Trench for 5 mo during the 2007 GEOPRICO project (Carbó et al., 2005). The orientations of the horizontal components of these OBS stations are unknown, and in order to make splitting measurements, the orientations need to be determined by correlating Rayleigh wave records on the radial and vertical components to find the best-fitting orientation (Stachnick et al., 2012). However, the quality of the OBS data was such that the orientations could not be determined, and therefore, unfortunately, we do not report any results from these OBS stations.

A simple ENE-WSW trend is apparent in our individual and average splitting results. The individual splits are plotted showing the “good” and “fair” results (Fig. 3), and the average splitting results are plotted along with previous splitting results in the northeast Caribbean (Fig. 4). Average $\delta t$ values range from ~0.9 to 2.0 s, and average fast polarization directions range from nearly east-west to northeast-southwest. The number and quality of the measurements vary from station to station, depending on the noise and the availability of data (Tables DR1 and DR2 [see footnote 1]). The individual results show significant variability in $\phi$ and $\delta t$, but the trench-parallel pattern is still coherent, especially in the “good” individual splitting observations, which are similar to the average splits. Analysis from stations CBYP, MGP, and MLPR yielded only fair splits. At stations AGPR, EMPR, HUMP, MGP, MLPR, MPR, PCDR, and SJG, we report splitting results as computed by the SC method. While the two methods utilized by SplitLab (Wüstefeld et al., 2007) were in disagreement at these stations, the SC method yielded more consistent results with the higher signal-to-noise ratio events and lower uncertainty, and the results computed by the RC method were noisy and inconsistent. An example comparing the RC and SC method from station HUMP is included in the GSA Data Repository (Fig. DR1 [see footnote 1]). We still classified some of these results as “good,” because of the consistent high quality of the results from the SC method and despite the disagreement between the two methods. Figure 5 gives three different examples from station HUMP of good results where the SC method was chosen.

We recorded 118 null or near-null measurements at 11 stations, which are shown in Table DR2 (see footnote 1). There is no clear pattern in back azimuth at any particular station, making it unlikely that the initial polarization of these events had phases that were nearly parallel to either a fast or slow direction of symmetry of the anisotropic medium.

**DISCUSSION**

**Sources of Anisotropy**

Splitting measurements in subduction zones can be complex, because shear waves are sensitive to anisotropy in the subslab region, the slab itself, the mantle wedge, and the overriding plate (e.g., Long, 2013). The ray paths of the SKS waves travel through the upper mantle, the slab, the mantle wedge, and the crust. Although all of these contribute to the measured splitting signal, the upper mantle is considered to be the most significant because the volume of material is much greater than the slab, mantle wedge, and crust. The simplest model for upper-mantle anisotropy subduction zones is two-dimensional (2-D) entrained flow, which predicts trench-perpendicular $\phi$ as the subslab mantle is dragged along with the slab (e.g., McKenzie, 1969; Hall et al., 2000).

The mantle wedge has also been shown to contribute to seismic anisotropy. Global observations of mantle wedge anisotropy are complex and variable, with $\delta t$ ranging from ~0.1 s to ~1.5 s, and fast axes ranging from mostly trench-parallel, to mostly trench-perpendicular, to a mixture of both (Long and Wirth, 2013). Stations used in this study are close to

¹GSA Data Repository Item 2015203, Figure DR1: Comparison of minimum energy vs rotation correlation method for example splitting measurement. Table DR1: Individual splitting results. Table DR2: Null splitting results, is available at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org. Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
Mantle flow at the northeast corner of the Lesser Antilles subduction zone

Figure 3. All 201 individual splitting measurements including good results (red) and fair results (yellow) as well as the event map for these measurements.

Figure 4. Average splitting vectors for this study and previous studies. Yellow vectors represent the average results of “good” measurements from our study. Black vectors are individual source-side results from Lynner and Long (2013). White vectors are average SK(K)S results from Piñero-Feliciangeli and Kendall (2008). Red vectors are average SK(K)S results from Russo and Silver (1994). Blue vectors are average SK(K)S results from Meighan and Pulliam (2013). The cartoon arrow represents the inferred direction of mantle flow, based on the trench-migration–controlled model for subslab mantle flow.
Figure 5. Three example measurements from station HUMP in SplitLab from three different back azimuths of 33.6°, 233.6°, and 334.2°, showing only the minimum energy method. See Figure 2 for explanation of parts. SNR—signal to noise ratio. (Continued on following page.)
the trench and not over the mantle wedge itself; however, $\delta\theta$ from local S phases in the central Caribbean are only ~0.2–0.3 s, which suggests that the mantle wedge is nearly isotropic (Piñero-Feliciangeli and Kendall, 2008). We also find evidence for an isotropic wedge due to the strong agreement between results of different back azimuths, as we see little variation in $\phi$ and $\delta\theta$ for ray paths that sample the wedge and subslab differently (Fig. 5). The Caribbean slab is likely to be anisotropic, although measurements of anisotropy within and directly above slabs in other regions suggest that this may not contribute significantly to measured $\delta\theta$. Huang et al. (2011) isolated $\delta\theta$ in the Pacific slab in northeast Japan on the order of ~0.1 s using differences in splitting between local S phases from events in the upper part of the slab and the lower part of the slab. We cannot rule out the contribution of the mantle wedge and lithosphere, but the simplicity of the overall trench-parallel splitting pattern shows that its effect would likely be to constructively interfere with anisotropy in the upper mantle.

Observations on subduction zone anisotropy have shown that globally, trench-parallel $\phi$ is most common (Long and Silver, 2008, 2009a). Our results also show a clear trench-parallel pattern and $\delta\theta$ between ~0.9 s and 2 s, which are comparable to SKS splitting observations from other subduction zones, such as the Tyrrhenian subduction zone in Italy (0.5–2.7 s; Civello and Margheriti, 2004) and the Sumatra subduction zone (0.8–3.0 s; Collings et al., 2013).

In addition, our results agree well with previous SKS shear-wave splitting studies from the northeast Caribbean, which show trench-parallel $\phi$ (Meighan and Pulliam, 2013; Piñero-Feliciangeli and Kendall, 2008; Russo et al., 1996). At station SIG in central Puerto Rico, our average $\delta\theta$ of 1.4 ± 0.4 s and roughly east-west–trend- ing orientations agree with previously reported east-west–trending splitting results and $\delta\theta$ of 1.2 ± 0.2 s (Russo et al., 1996) and 1.29 ± 0.27 s (Piñero-Feliciangeli and Kendall, 2008). Meighan and Pulliam (2013) analyzed SKS phases from 28 stations across the northeast Caribbean and observe trench-parallel splits with average $\delta\theta$ ranging from 0.5 to 2.9 s (Meighan and Pulliam, 2013). They attributed the large magnitude $\delta\theta$ to trench-parallel anisotropy in the subslab mantle, but they also recognized a component of anisotropy from a vertical shear zone parallel to the plate boundary (Meighan and Pulliam, 2013). They suggested that the majority of anisotropy is located beneath the slab, and that there is a degree of decoupling between the subslab region and the region within and above the slab. Our results agree with these conclusions; however, the use of only SKS phases limits our ability to constrain the depth distribution of the trench-parallel anisotropy.

A study of seismic anisotropy beneath the Caribbean slab by Lynner and Long (2013) also showed a trench-parallel splitting pattern. They used a source-side splitting technique, which takes advantage of teleseismic S phases from events occurring within and beneath the slab and receiver stations outside the region of study, which eliminates contamination of the signal from above the slab (Russo and Silver, 1994). The source-side splits in the northeast Caribbean are clearly trench-parallel, with $\delta\theta$ ranging from ~1 s to ~3 s, averaging ~1.6 s. Lynner and Long (2013) interpreted these results to fit perfectly with a model for trench-migration–induced, subslab, trench-parallel mantle flow in subduction zones proposed in South America (Russo and Silver, 1994) and as a global phenomenon (Long and Silver, 2008, 2009a). The source-side splits allow for comparison of the subslab anisotropy to anisotropy inferred from SKS splits that sample the entire subduction system. The range in $\delta\theta$ in the northeastern Caribbean for the source-side splitting results (~1–3 s) is comparable to the range in $\delta\theta$ for SKS results at multiple stations measured by Meighan and Pulliam (2013) (~0.5–2.9 s), as well as our SKS results (0.9–2 s). If a large, cohesive region of anisotropic material is present above the slab, an increase or decrease in the $\delta\theta$ for SKS splitting results compared to source-side splitting results would be expected, due to constructive or destructive interference. The stations used by our study and Meighan and Pulliam (2013) are not in the same location as the events used in the source-side study of Lyn-
ner and Long (2013), and therefore individual results are not directly comparable. However, there are no obvious differences in the average splitting pattern observed by both methods, suggesting that the trench-parallel model for anisotropy adequately explains deformation in the Caribbean subduction zone.

In the central and western region of our study, where the subduction system is increasingly dominated by strike-slip motion, east-west to northeast-southwest shear strain of lithospheric material becomes a likely explanation for the observed east-west to northeast-southwest splitting. Most of the Puerto Rico slab is subducted beneath the Lesser Antilles trench, although farther to the west, the plate motion is largely lateral. Thus, it becomes difficult to distinguish between shear strain due to passive drag of the subslab mantle and mantle return flow around the subducting slab edge as the main contribution to the trench-parallel splitting. This is supported by the large δφ splits recorded by stations on Hispaniola, even further west of our study region, by Meighan and Pulliam (2013) (see also Fig. 4).

Slab Tearing

Previous studies have suggested the presence of a slab tear in the Puerto Rico Trench around 64.5°W, in the forearc region of the Caribbean plate. The Puerto Rico Trench is associated with the world’s most negative free-air gravity anomal, at ~380 mGal (ten Brink, 2005). West of 64.5°W, the Puerto Rico Trench shows evidence of an anomalously deep and wide trench floor, a tilted carbonate platform, and rotated and faulted blocks, which suggest that at 3.3 Ma, a portion of the Puerto Rico slab steepened 5° from a dip of 15° to 20°; this trench collapse is suggested to have been caused by the development of a shear zone or tearing in the slab (ten Brink, 2005).

A joint analysis of seismic data from both the GEOPRICO ocean-bottom seismographs and land-based seismometers revealed two tightly clustered swarms of earthquakes in the Puerto Rico Trench with magnitude <4 that lasted from 16 to 18 April 2007 (40 events) and 24 to 26 July 2007 (180 events; Meighan et al., 2013). Focal mechanism solutions for the larger 24–26 June swarm, which was centered around 64.5°W, show a combination of trench-parallel tensile stresses at shallower depths (50–100 km) and trench-perpendicular tensile stresses at greater depths (100–150 km). These results have been interpreted as evidence for a propagating slab tear (Meighan et al., 2013).

The presence of slab tears in other subduction zones has been suggested from other seismologic-based observations, such as seismicity clusters (ten Brink, 2005; Clark et al., 2008; Meighan et al., 2013), anomalies in tomography (e.g., Gover and Wortel, 2005; Miller et al., 2006; Rosenbaum et al., 2008; Miller et al., 2009), and changes in inferred seismic anisotropy (e.g., Civello and Margheriti, 2004; Abt et al., 2010; Poiritt et al., 2014).

According to the trench-migration-controlled model for trench-parallel mantle flow in subduction zones, slabs act as barriers, forcing the asthenosphere to flow laterally around them (Russo and Silver, 1994; Long and Silver, 2009b). If a tear exists in the slab, it will no longer act as a barrier in this location, and the mantle will flow through the slab tear in a trench-normal direction. This phenomenon was observed beneath Italy (Civello and Margheriti, 2004; Bacchesshi et al., 2007; Rosenbaum et al., 2008) and at the southern edge of the Caribbean arc near Venezuela (Growdon et al., 2009; Miller and Becker, 2012).

The shear-wave splitting analysis from the northeastern edge of the Caribbean by Meighan and Pulliam (2013) at two stations, ABVI and CDVI, in the Virgin Islands region also suggested the presence of a slab tear. They reported high-quality splitting measurements from one event at station ABVI, yielding trench-normal φ and δφ of 0.75 ± 0.45 s, and two events at station CDVI, yielding trench-normal φ and δφ 0.75 ± 0.53 s (Meighan and Pulliam, 2013). These stations are located between 64°W and 64.5°W, in the same location as the proposed slab tear (ten Brink, 2005; Meighan et al., 2013; Meighan and Pulliam, 2013). Our results at these two stations are clearly trench-parallel with larger δφ, i.e., 1.9 ± 0.74 s based on eight events at ABVI, and 1.5 ± 0.37 s based on four events at CDVI. These, combined with the source-side splitting results of Lynner and Long (2013), which are also continuously trench-parallel along the trench, lead us to conclude that the Puerto Rico slab is continuous along the northeast Caribbean and that there is no slab tear in the vicinity of 64.5°W, north of Puerto Rico, or that it is either too narrow or short-lived to have a significant imprint on the regional mantle strain and therefore the anisotropic signal. Based on the Wadati-Benioff seismicity, the Puerto Rico slab extends as far west as eastern Hispaniola, near 69°W (Fig. 1).

CONCLUSIONS

We observed a relatively simple pattern of trench-parallel shear-wave splitting for the northeast Caribbean, based on 201 SKS splitting measurements at 20 stations. These results agree with previous authors (Lynner and Long, 2013; Meighan and Pulliam, 2013; Piñero-Feliucangel and Kendall, 2008; Russo et al., 1996) who observed trench-parallel splitting, both in SKS splitting measurements and source-side splitting measurements. Our interpretation of the observed splitting pattern is that subslab flow of asthenospheric material is the primary cause of anisotropy; however, our results are inconsistent with earlier work that suggested a slab tear in the vicinity of the British Virgin Islands. Instead, we conclude that the Puerto Rico slab is likely continuous to the west to at least 68.5°W, or if not, that the slab tear has too weak of an effect on the regional mantle flow to make an anisotropic signal. The northeast Caribbean conforms to a model for subduction zone anisotropy in which trench migration induces threedimensional, subslab, lateral mantle flow.

ACKNOWLEDGMENTS

We thank Andreas Wüstefeld for developing and releasing SplitLab, which we depended on as the main tool for data analysis; IRIS, for making all of the data freely accessible; Cooper Harris, Leland O’Driscoll, Rob Poiritt, and Daoyuan Song for aiding in discussion during research group meetings; and the editor, Rob Govers, and one anonymous reviewer, who provided constructive comments that greatly improved the manuscript. Finally, thanks go to Doug Hammond for advising during the completion of this research for Michael Hodges’ undergraduate senior thesis. This work was supported by NSF CAREER grant EAR-1056438.

REFERENCES CITED


