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Sub-slab mantle flow parallel to the Caribbean plate boundaries: Inferences from SKS splitting

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A B S T R A C T

Upper-mantle deformation near the margins of the Caribbean plate is investigated using observations of shear-wave splitting in teleseismic and local shear phases. The Caribbean plate is almost stationary in the hot-spot reference frame and is wedged between the North America, South America, Nazca and Cocos plates; collisional belts and major shear zones encircle the plate. Data from seismic stations operated by IRIS, GEOSCOPE, the Venezuelan Seismological Network, and the British Geological Survey have provided nearly 2000 seismic records for analysis. Analysis of shear-wave splitting in teleseismic core phases (e.g., SKS) at stations reveals fast shear-wave polarisations that are conformal to the plate boundary, paralleling the major structural features. The magnitude of the splitting is in general quite large (1.2–2.1 s). In northern Venezuela, the magnitude of splitting increases towards the Caribbean–South American collisional front. Local shear phases from earthquakes up to 200 km deep beneath northeastern Venezuela show very small amounts of splitting (0.1–0.3 s). Analysis of the depth dependence in the magnitude of the splitting suggests that most of the upper-mantle wedge is isotropic and the splitting in the local phases is mostly accrued in the crust and uppermost mantle. In NE Venezuela fast shear-wave polarisations in both the local and teleseismic phases closely parallel the fault systems in the region, suggesting that the crust and mantle are coupled in this area. Stations on the Island of Montserrat and near Bucaramanga, Columbia, also show very small magnitudes in local S-wave splitting, but large amounts of SKS splitting. In general, the small magnitude of the local S-phase splitting suggests that the teleseismic phases accrue considerable splitting beneath the top of the slab. We interpret the bulk of the splitting in terms of sub-slab flow that is forced around the Caribbean plate due to the convergence of the surrounding plates.

1. Introduction

The Caribbean region and its plate boundary zones provide a natural laboratory to study many different tectonic environments. The present day plate margin corresponds to variably-wide deformation belts of Mesozoic–Tertiary age. The western and eastern margins consist of collisional systems with variously evolved magmatic arcs (Central American Isthmus, Lesser Antilles). The northern and southern margins are marked by major shear zones (Montagua Belt in Guatemala, Greater Antilles, Northern Venezuela Cordilleras). Two different views of the tectonic evolution of the Caribbean are of interesting debate. One hypothesis proposes an allochthonous (Pacific) origin of the Caribbean (Alvarez, 1982; Pindell, 1985; Pindell and Barret, 1990). The other suggests an in-situ origin in an intra-plate setting between the two Americas (Meschede and Frisch, 1998). Knowledge of the structure and flow patterns of the mantle below the Caribbean region is of crucial importance to understanding the geodynamics of the region, and will offer insight into its tectonic development. Central to this is the relation between the mantle lithosphere and crustal features, and the relationship of deeper mantle flow to Caribbean plate motion. In this work, we address some of these issues by investigating the seismic anisotropy and, hence, style of crust and mantle deformation in the region.

Studies of seismic anisotropy provide insights into past and present dynamic processes within the solid Earth, including those associated with mantle convection, the formation and destruction of tectonic plates, and orogeny. Shear-wave splitting is a tell-tale signature of such anisotropy. On entering an anisotropic medium, two shear waves will propagate with polarisations approximately orthogonal to each other and with different velocities. The difference in arrival times between the two quasi-S waves is known as shear-wave splitting or birefringence. The orientation of the shear wave provides constraints on the elastic symmetry of the medium and the delay time between the two shear waves is an indicator of the magnitude of the anisotropy. These parameters, polarisation and delay time, offer insights into deformation processes.

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Numerous mechanisms can cause seismic anisotropy, but they all reflect underlying order within a medium. In the mantle, anisotropy is most commonly attributed to the preferred alignment of crystals due to plastic deformation or lattice preferred orientation (LPO). Olivine is the most common mantle mineral in regions shallower that roughly 410 km and shows most pronounced LPO when deformation is accommodated via dislocation glide. A large number of factors control the LPO development, including grain size, presence of fluids, strain rate and temperature. Most mantle peridotites show significant olivine LPO (Mainprice et al., 2000), where most commonly the *a*-axis aligns with the shear direction. However, the presence of water can lead to different texture patterns and strengths. For example, in regions of high water content and high stress, the *c*-axes of olivine crystals will align sub-parallel to the shear direction (Jung and Karato, 2001). This so-called B-type fabric may be present in parts of the mantle wedge in subduction zones (Kneller et al., 2005).

Alternatively, a preferred orientation of inclusions, or shape-preferred orientation (SPO), can be very effective in generating anisotropy. The alignment of fracture sets or thin vertical cracks is thought to be the dominant mechanism for anisotropy in the crust (Crampin, 1984; Silver, 1996). Compositional layering, where there is a strong contrast in elastic stiffness between layers, is another SPO mechanism (Backus, 1962). Within the mantle, the preferred alignment of ellipsoidal melt inclusions in rift settings can generate significant amounts of anisotropy (Kendall, 1994; Kendall et al., 2005). It is conceivable that such melt-related mechanisms may be at play in subduction regions.

Here we investigate shear-wave splitting beneath the Caribbean region; this will allow us to evaluate the seismic anisotropy structure in this area and offer insight into lithospheric anisotropy and the dominant style of mantle flow in the region. There are a number of challenges in interpreting observations of seismic anisotropy in the upper mantle beneath the Caribbean as many mechanisms will be at play. Many factors control anisotropy at plate boundaries (Blackman and Kendall, 2002). Viscous coupling between the plates and convecting mantle will effectively generate olivine LPO. The plates themselves will preserve the signature of anisotropy inherited at the time of their formation. The presence of melt and water may generate different styles of anisotropy in the upper-mantle wedge (e.g., melt-induced SPO or B-type fabric). Finally, deformation at the various plate boundaries in the Caribbean will modify the fossil lithospheric anisotropy. Cumulatively, these mechanisms will lead to multiple layers of anisotropy, evidence of which is revealed by directional dependencies in apparent splitting parameters in near vertically travelling seismic phases (Silver and Savage, 1994). To address these issues we use observations of shear-wave splitting in teleseismic phases, such as SKS and SKKS, to map variations in anisotropy in the region. Where possible, this is augmented by studies of splitting in local shear phases, which can be used to further constrain depth variations in the anisotropy.

1.1. Tectonic setting

The Caribbean Plate represents a lithospheric fragment between four major plates: the North-and South-American, the Cocos and the Nazca Plates. It moves eastwards relative to the North American and the South American plates at a relatively slow rate of around 1–2 cm/yr (Jordan, 1975; Stein et al., 1988; DeMets et al., 1990).

More locally, at the eastern part of the Caribbean Plate boundary, the Atlantic oceanic lithosphere subducts at the Lesser Antilles Trench (see Fig. 1). The volcanic arc is Neogene in age, is about 850 km long and extends from eastern Venezuela in the south to as far north as the western Puerto Rico–Virgin Islands. Various studies of the active seismicity along the entire length of this boundary reveal a Wadati–Benioff zone extending down to a depth of 150–200 km (Stein et al., 1988; Russo et al., 1993). The average dip is 50–60° in the North and vertical south of Grenada (Girardin and Gaulon, 1983). The subducted slab is 120 to 180 km beneath the present line of volcanic islands (Wadge and Shepherd, 1984). Tomographic images show a deeper high-velocity anomaly which has been interpreted tentatively as the remnants of Atlantic lithosphere subducted to a depth of 500 to 600 km (Van der Hilst, 1990).

At the western margin the Cocos plate subducts beneath the Caribbean plate along the Middle American Trench. This has controlled the tectonics on this part of the boundary zone developing some important structural features in the region, which include a large transform fault and deformation belts. The Panama fracture zone, which is a right-lateral transform fault, lies off the southern border of the boundary and is the boundary zone between the Cocos and Nazca Plates. The Cocos Ridge, located west of this boundary zone, is also being subducted beneath southern Costa Rica as part of the Cocos Plate. To the north of the Panama fracture zone lies a convergent margin between the Panama block and the Caribbean, called the Panama Deformation Belt. This tectonic feature extends from the Caribbean coast of Colombia to inland within Costa Rica. The Wadati-Benioff geometry at the western border of the Caribbean Plate shows a decrease in the maximum depth of earthquakes from 220 km under Nicaragua to less than 50 km under southern Costa Rica (Protti et al., 1994). In central Mexico, near the trans-Mexican Volcanic Belt, tomographic images indicate low-angle subduction structure interpreted as the subduction of the Cocos plate (Van der Hilst, 1990). The same is observed in the segment from south of Mexico to the Nicoya Peninsula near the south-westward continuation of the Hess Escarpment. In other segments of the Middle American Trench, tomographic images do not indicate the down-going Cocos Plate (i.e., beneath northern Mexico, Isthmus of Tehuantapec and Panama). The remanent subducted Farallon plate is visible and continuous across the 660 discontinuity and also visible in the lower mantle.

The northern Caribbean margin consists of a 2000 km-long series of faults that connects the Lesser Antilles trench in the east to the Middle American trench in the west (see Fig. 1). The plate motion that occurs across the predominantly east–west striking major faults is primarily left-lateral. It is a tectonically active margin characterised by intermediate crustal thicknesses, high seismicity, large Bouger gravity and magnetic anomalies, late Cenozoic volcanic activity in central Hispaniola, and active oceanic volcanism in the Cayman trough spreading center.

In the south, the Caribbean and South American Plates interact in a wide and complex deformation zone. This region is the site of island arc accretion to a continent, a process thought to be a primary mechanism in the construction of continents. In broad terms the boundary consists of a right-lateral transpressional fault of approximately 1000 km length, connecting two trench zones at either end. At present a fold and thrust belt/foreland basin system is developing between the two subduction zones (Avé Lallemant, 1997). The north-western boundary of this zone is the result of a complex interaction between the Caribbean, South America and Nazca plates. The plate boundary in eastern Colombia and western Venezuela, consists of an active transpressional zone, 600 km wide, that extents from the northern flank of the Southern Caribbean deformation belt south-westward into the Merida Andeas. The whole area comprises a set of discrete tectonic blocks which move independently among the surrounding larger plates (Caribbean, South America and Nazca) (Audemard and Audemard, 2002). The blocks are bounded by a series of faults in that region, the Oca-Ancon in the north, the Bocono in the Merida Andea and the Santa Marta-Bucaramanga fault in Colombia. The Oca-Ancon and Bocono faults are characterised by right-lateral, strike–slip motion and responsible for most of the shallow seismicity observed in this area. Two different subducting slabs are proposed in this north-western area, one of older age corresponding to Caribbean Plate subduction (Taboada et al., 2000) and the other of younger age