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The wet Nicaraguan slab

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[1] Nicaraguan volcanoes show globally high concentrations of geochemical tracers from dehydration of subducting crust, which may reflect a slab with unusually high amounts of H_2O. To test this possibility, we measure seismic velocities at the top of the subducted plate and compare them with predictions for hydrated mafic rocks. Regional seismic *P* waves for intraslab events at 100–150 km depth show a high-frequency late arrival, apparently trapped in a low-velocity waveguide 2.5–6 km thick at the top of the downgoing plate, 14.5 ± 2.2% slower than surrounding mantle. The velocities can be explained by $\geq$5 wt % H_2O in the subducted crust, 2–3 times the hydration inferred for other slabs by similar methods. This interpretation implies extensive hydration of the Cocos Plate off Nicaragua, perhaps enhanced by up-dip fluid flow within the slab at >100 km depth. *INDEX TERMS:* 3660 Mineralogy and Petrology: Metamorphic petrology; 7203 Seismology: Body wave propagation. **Citation:** Abers, G. A., T. Plank, and B. R. Hacker, The wet Nicaraguan slab, *Geophys. Res. Lett.*, *30*(2), 1098, doi:10.1029/2002GL015649, 2003.

1. Introduction

[2] Arc lavas feature many geochemical tracers that require input from subducted oceanic igneous crust and sediment [*Miller et al.*, 1994; *Tera et al.*, 1986]. These geochemical signals vary significantly from arc to arc. Some variations are explained by differing sediment input [*Plank and Langmuir*, 1993], but for others the cause remains unclear. Are the variations primarily caused by differences in the hydration of the downgoing plate, or by the processes that transmit fluids from slab to arc? Part of the uncertainty lies in the lack of information on the state of the subducted material at depths where devolatilization occurs. Recent seismological evidence for a thin, low-velocity layer atop many slabs at subarc depths [e.g., *Abers*, 2000; *Helffrich*, 1996] provides some evidence that the slab remains at least partially hydrated to depths beyond the volcanic front.

[3] Globally, the Nicaraguan volcanic arc shows some of the highest levels of geochemical tracers for oceanic crustal fluid, including the global maximum concentration of ^{10}Be [*Tera et al.*, 1986] and among the highest B/La ratios [*Noll et al.*, 1996; *Patino et al.*, 2000]. One possible explanation is that the flux of slab-derived fluids is overall high here, and that Be and B are efficiently removed from the slab by these fluids [*Turner et al.*, 1998]. In Nicaragua, high B concentrations in lavas [*Leeman et al.*, 1994] have been used to infer a high contribution from altered oceanic crust [*Patino et al.*, 2000]. Here, we test for "wet" crust by measuring its seismic velocity at sub-arc depths, and find that the Nicaragua slab segment may be the most hydrated yet observed beneath a volcanic arc.

2. Data and Methods

[4] We examine signals from earthquakes >100 km depth that travel along the strike of the Cocos slab beneath Nicaragua. Such signals travel subhorizontally near the top of the slab for long distances and show considerable distortion as a consequence [*Gubbins et al.*, 1994]. Such signals show early low-frequency arrivals followed by later high-frequency and high-amplitude signals, a behavior best understood as dispersion caused by interaction with a low-velocity waveguide [*Abers*, 2000]. Comparison of the arrival times between the high- and low-frequency waves allows the velocity of the waveguide to be estimated, and the signal's frequency content constrains layer thickness. In the five Pacific arcs previously examined in this way, Alaska, the Aleutians, Kuriles, Honshu, and the Marianas, the waveguides are 5–8% slower than the surrounding medium for both *P* and *S* waves, and the waveguides are estimated to be 2–8 km thick [*Abers*, 2000].

[5] The Global Seismic Network station JTS, in central Costa Rica, records Nicaraguan events that have propagated along the strike of the downgoing plate (Figure 1). We analyze JTS broadband records from 20 earthquakes for the years 1995–1999 at depths of 100 – 250 km, distances of 1–5°, and magnitudes > 4.0. These records include many *P* waveforms that show secondary phases (Figure 2); *S* wave records are too noisy and complex to interpret.

[6] To understand the path taken by these signals, raypaths are traced in a 3D velocity model of a dipping slab, with a top defined by contours of seismicity and a velocity 5% faster than the overlying mantle. Rays exit the slab at points ~50 km horizontally from the station and 75 km deep. Small perturbations to slab geometry (lateral shifts <20 km) or changes to velocity (to 8%) do not appreciably affect estimates of ray path lengths, although variations in event location of 25 km (characteristic of teleseismic mislocation) lead to 5–20 km scatter in ray exit depths. Errors in path length produce scatter in single-event velocity measurements that controls the error bars for velocity quoted below.

3. Results

[7] The secondary phase is clearest for events with depths of 100–150 km, and shows linear moveout relative to direct

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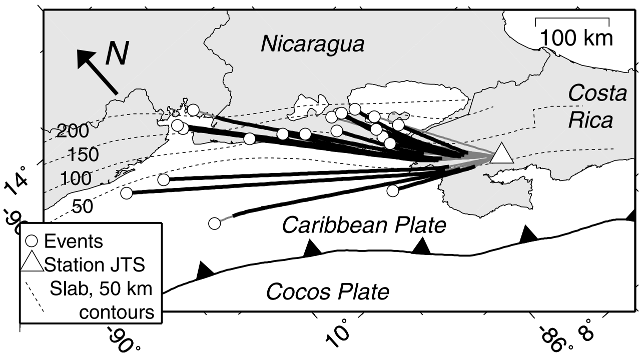

Figure 1. Central America and raypaths. Thin dotted lines contour top of seismicity. Hypocenters (circles) from PDE catalog. Thick black lines show portions of raypaths within the fast slab, and thick gray lines show portions above it.

P (Figure 2). Its relative velocity is estimated in two ways. First, linear regression of picked secondary arrivals (Figure 2) provides an apparent velocity that is 14.5% ± 2.2% slower than the direct arrival. Their moveout reaches zero at range of 50 km, suggesting that the delay is produced >50 km distant from the station. At this distance signals depart the slab on their way to the surface (Figure 1), confirming the supposition that the secondary arrival is slab-derived. Events deeper than 160 km show secondary arrivals at inconsistent times, or do not show them. Either the deeper earthquakes are not located in a portion of the slab capable of generating them (deep in the subducting mantle), or the relevant structure is not present at these depths (e.g., eclogite has formed).

[8] Second, we fit measured dispersion of the *P* wave train to a velocity model, as described in *Abers* [2000]. In an example (Figure 3), the dominant arrival at frequencies above 1.5 Hz arrives ~3 seconds later than the initial, low frequency signal. The measured dispersion curve is inverted for 2 parameters describing the waveguide needed to produce that behavior, a fractional velocity perturbation of the layer relative to surroundings, $\delta \ln Vp$, and the layer thickness H, using a simplex nonlinear minimization scheme. This one record gives $\delta \ln Vp = -14\%$ and H = a 3.9 km. Sensitivity tests (white lines) show that 50% changes to layer thickness (to 2.1 km or 6.9 km) result in predicted dispersion that significantly violates the data.

[9] Dispersion curves for the 7 events shallower than 151 km are jointly inverted using this scheme, giving $\delta \ln Vp = -0.145 +0.031/-0.038$ and $H = 2.9 + 0.5/-0.4$ km (90% confidence limits from bootstrap tests). In other words, velocities within the waveguide appear to be 14.5% slower than surroundings, the same value inferred from Figure 2. These results assume dispersion by fundamental-mode acoustic excitation of the waveguide. Numerical experiments (not shown) suggest that the fundamental-mode approximation may underestimate layer thickness by up to a factor of two depending upon details of source location and focal mechanism, so the upper bound on layer thickness should be twice the inversion estimate, or $H = 2.5 - 6.0$ km.

[10] The ray geometry and travel-time systematics place constraints on the origin of these signals. First, the secondary phases arrive as little as 1 s after the first *P*, too early to represent signals caused by interaction with upper-plate crust except within 10 km of JTS. Such a scatterer would not produce the linear moveout and dispersion. Second, velocity estimates from phase moveout (Figure 2) and from 3D ray tracing are identical, suggesting that ray bending caused by the subducting slab does not bias velocity estimates. Third, velocity anisotropy probably does not produce the variation of observed signals between Nicaragua and other slabs [*Abers*, 2000]. Ray paths are along-strike in all cases, and at both Nicaragua and the Aleutians the subducting crust was generated at ridges subparallel to the trench. Hence, effects of anisotropy should similar between Nicaragua and the other slabs. In conclusion, a low-velocity waveguide along the top of the subducting slab best explains the observations.

4. Discussion

[11] The layer thickness determined here for Nicaragua is comparable to other northern Pacific arcs (Alaska, the Aleutians, Kuriles, Honshu, and the Marianas), but the wave speed anomaly is roughly double the 5–8% seen elsewhere [*Abers*, 2000]. The 2.5–6.0 km layer thickness is comparable to part or all of the subducted oceanic crust, so we infer that the signal originates from propagation in slow subducted crust. Other possibilities may exist (discussed below), but the layer thickness (> 2.5 km) precludes a narrow shear zone or metasediments (which should be 400 m thick prior to compaction and dehydration [*Kelly et al.*, 2001]), as has been suggested by previously [*Kerrick and*

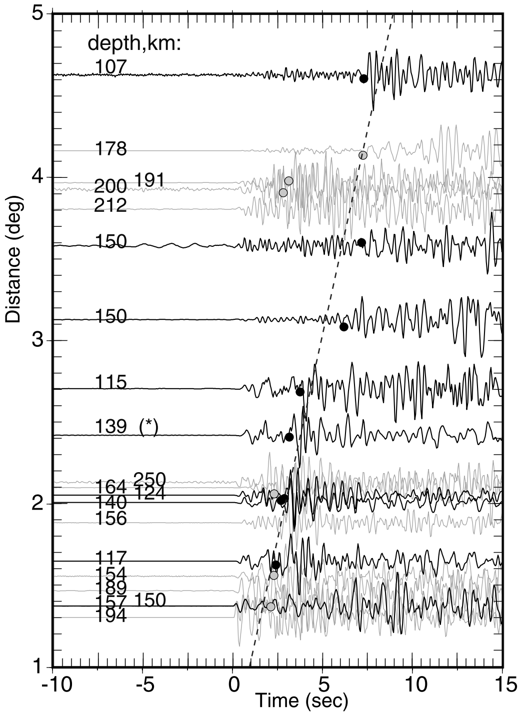

Figure 2. Record section aligned by first *P* arrival. Vertical component broadband record is bandpass filtered at 0.75–8.0 Hz. Depths labeled on left. Gray lines: event depths > 150 km; circles: picked high-frequency secondary arrivals, gray for event depth >150 km. Dashed line shows linear regression on secondary arrivals for events <150 km deep.

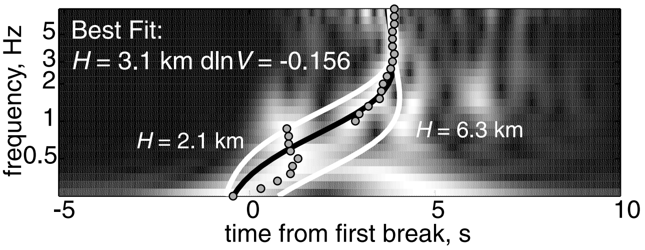

Figure 3. Spectrogram for record designated by (*) on Figure 2. Lighter shades correspond to higher power in arrivals; circles show maximum-energy at each frequency. Thick black line shows best fit for a low-velocity waveguide for White lines show effect of increasing or decreasing assumed layer thickness 50%.

Connolly, 2001]. Likewise subduction may erode the base of the upper plate beneath the Nicaraguan forearc [*Ranero et al.*, 2000], providing an additional source of material, but it seems unlikely that such a process could produce a layer >2.5 km thick.

[12] We compare the Nicaragua waveguide velocities to predictions made for metamorphosed mafic and ultramafic rocks using the database of *Hacker et al.* [2002a] (Figure 4). All seismic velocities are calculated at a common pressure (3 GPa) and temperature (400°C) and referenced to a nominal background composition for surrounding mantle (pyrolite).

[13] First, we consider the possible equilibrium mineralogies at pressures of 2.5–5 GPa, corresponding to the depths sampled seismically (80–150 km). The equilibrium mineralogy of mafic rocks ranges from lawsonite-rich blueschist (low temperature, 5.4 wt% H_2O) to eclogite (high temperature, dry). Surrounding mantle harzburgites could hydrate to serpentinite or chlorite-bearing assemblages. The H_2O content of these rocks correlates with $\delta \ln Vp$ (Figure 4), such that only rocks containing 5–8 wt% H_2O can produce the observed low velocity layer in Nicaragua. The appropriate mafic assemblage is a fully saturated jadeite-lawsonite blueschist, requiring 5.4 wt % crystallographically bound H_2O throughout the layer. The other North Pacific slabs can be explained by partial saturation of the same assemblage or higher-temperature rocks. The absence of eclogite at Nicaragua indicates a substantial part of the crust stays relatively cool, consistent with rapid subduction rate, the presence of earthquakes to 300 km depth (following the logic of *Peacock and Wang* [1999]) and thermal modeling extrapolated from Costa Rica [*Hacker et al.*, 2002b].

[14] Second, we consider compositions that may have been transported metastably to depth (Figure 4, open circles). Metastability is favored for rapid subduction, large grain sizes, and low H_2O content [*Hacker*, 1996]. During subduction, fine-grained, hydrous assemblages (e.g., hydrated open circles on Figure 4) are unlikely to survive to >2.5 GPa without re-equilibrating, as even trace quantities of H_2O can greatly catalyze reaction rates, but anhydrous, coarse-grained gabbro may persist to such depths. Metastable gabbro does have the appropriate seismic velocities.

[15] Thus, there are three possibilities for the composition of the waveguide at 100–150 km depth: fully saturated blueschists partly serpentinized harzburgite, or anhydrous gabbro. Although anhydrous metastable basalt or gabbro would produce the requisite seismic velocities, it is difficult to see why such an anhydrous layer would persist at Nicaragua and not elsewhere. A pronounced system of normal faults penetrate to depths of >20 km at the outer rise [*Ranero et al.*, 2001], which should provide effective conduits for hydration of the subducting crust and mantle offshore Nicaragua [*von Huene et al.*, 2000]. Such features exist at some many outer rises and could vary in their efficiency of hydration, but those off Nicaragua appear typical.

[16] A wetter subducting plate at Nicaragua would deliver greater H_2O to the mantle than elsewhere, as well as geochemical tracers for slab-derived fluids (e.g. boron). Indeed, mafic magmas in Nicaragua have H_2O concentrations among the highest globally [*Roggensack et al.*, 1997].

[17] Were the base or top of a serpentinized layer a dehydration boundary (subparallel to an isotherm), one would expect at least some cold subduction zones to show a waveguide several tens of km thick, the depth to serpentine-out boundary [*Hacker et al.*, 2002b]. Also, *Vp/Vs* constraints at other slabs are inconsistent with the high Poisson's ratio of serpentinite [*Abers*, 2000]. Hence, of the possibilities, the waveguide seems best explained as hydrated mafic crust.

[18] Still, this does not explain why the Nicaragua slab is twice as wet as other slabs (Figure 4). The 5 wt% exceeds estimates for oceanic crust from drilling oceanic basalts [*Staudigel et al.*, 1996]. Some process must extensively

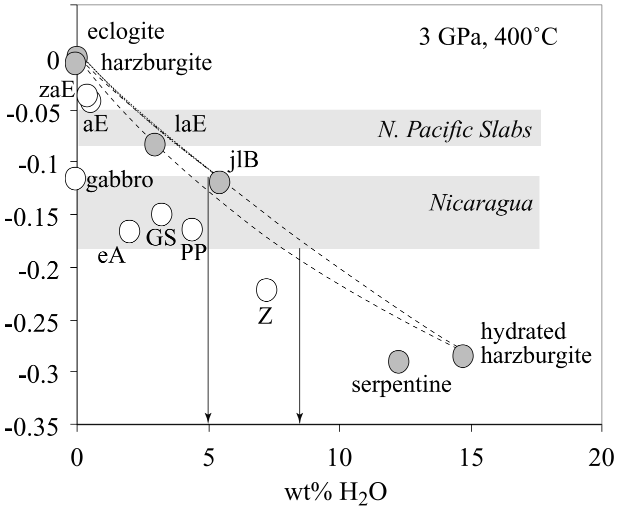

Figure 4. Observed and predicted variations in seismic velocities vs. crystallographically bound H_2O content for potential rock types at 3 GPa, 400°C. Gray circles: rocks stable at 3 Gpa; open circles: rocks in equilibrium at lower pressures. Abbreviations: aE, amphibole eclogite; zaE, zoisite-amphibole eclogite; laE, lawsonite-amphibole eclogite; jlB, jadeite-lawsonite blueschist; eA, epidote amphibolite; GS, greenschist; PP, prehnite–pumpellyite; Z, zeolite. Values and calculations from *Hacker et al.* [2002a]. $\delta \ln Vp$: fractional *P* velocity change relative to reference anhydrous mantle (pyrolite-2). Dashed lines: Hashin-Shtrikman bounds on velocities of mixtures between jlB and eclogite or between harzburgite and hydrated harzburgite (serpentine + chlorite + brucite). Horizontal gray bands: constraints on low-velocity channels from dispersion for N. Pacific Slabs [*Abers*, 2000] and Nicaragua (this study).

alter the oceanic crust such that it is saturated (>5 wt% H_2O) at the >2.5 GPa conditions sampled here. Vigorous hydrothermal circulation and resulting hydration has been inferred from low heat flow (<20 mW m^{-2}) on the Cocos plate seaward of the trench [*Langseth and Silver*, 1996]. However, it is unclear whether such cooling penetrates very deep into the oceanic crust. Fluids may be introduced by the extensive normal faulting at the outer rise offshore Nicaragua [*Ranero et al.*, 2001], although the observed faults are several km apart and so could not fully hydrates all of the crust. Perhaps, fluid produced by dehydration reactions at >75 depth in the slab migrates up dip and hydrate subducted crust at shallower levels [*Hacker et al.*, 2002b]. This scenario would require a pathway that allows fluids to ascend up the slab rather than into the overlying mantle wedge. The steep dip of the Nicaragua slab, relative to the other Pacific slabs studied, may facilitate such a pathway; the other steep slab studied, in the Marianas, also shows a waveguide that is slower than average. Possibly all three factors, hydrothermal circulation, outer-rise faulting and up dip fluid flow, contribute to making the slab beneath Nicaragua among the wettest in the world.

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