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Effect of hydrothermal circulation on slab dehydration for the subduction zone of Costa Rica and Nicaragua

Juan Carlos Rosas [a,*], Claire A. Currie [a], Robert N. Harris [b], Jiangheng He [c]

[a] Department of Physics, University of Alberta, 4-181 Centennial Centre for Interdisciplinary Science, Edmonton, AB, Canada
[b] College of Oceanic and Atmospheric Sciences, Oregon State University, 104 CEOAS Admin Bldg, Corvallis, OR, USA
[c] Pacific Geoscience Centre, Geological Survey of Canada, 9860 West Saanich Road, Sydney, BC, Canada

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A B S T R A C T

Dehydration of subducting oceanic plates is associated with mantle wedge melting, arc volcanism, intraslab earthquakes through dehydration embrittlement, and the flux of water into the mantle. In this study, we present two-dimensional thermal models of the Costa Rica–Nicaragua subduction zone to investigate dehydration reactions within the subducting Cocos plate. Seismic and geochemical observations indicate that the mantle wedge below Nicaragua is more hydrated than that below Costa Rica. These trends have been hypothesized to be due to a variation in either the thermal state or the hydration state of the subducting slab. Despite only small variations in plate age along strike, heat flow measurements near the deformation front reveal significantly lower heat flow offshore Nicaragua than offshore Costa Rica. These measurements are interpreted to reflect an along-strike change in the efficiency of hydrothermal circulation in the oceanic crust. We parameterize thermal models in terms of efficient and inefficient hydrothermal circulation and explore their impact on slab temperature in the context of dehydration models. Relative to models without fluid flow, efficient hydrothermal circulation reduces slab temperature by as much at 60 °C to depths of ~75 km and increases the predicted depth of eclogitization by ~15 km. Inefficient hydrothermal circulation has a commensurately smaller influence on slab temperatures and the depth of eclogitization. For both regions, the change in eclogitization depth better fits the observed intraslab crustal seismicity, but there is not a strong contrast in the slab thermal structure or location of the main dehydration reactions. Consistent with other studies, these results suggest that observed along-strike differences in mantle wedge hydration may be better explained by a northwestward increase in the hydration state of the Cocos plate before it is subducted.

1. Introduction

Subduction zones are sites where water is recycled into the mantle, making them an integral part of the global H_2O cycle (e.g. Rupke et al., 2004; Hacker, 2008). In the subducting plate, water exists as free water in pore spaces and bound in hydrated basalts in the oceanic crust and serpentine in the oceanic mantle lithosphere. For oceanic crust and mantle, hydration begins at and near mid-ocean ridges through the weathering of basalt and serpentinization of peridotite (Cannat et al., 1992; Kelley et al., 2001; Schroeder et al., 2002; Schmidt and Poli, 2003; Rouméjon and Cannat, 2014). Hydration continues through the life of the plate and may be enhanced near subduction zones where plate bending faults at the outer rise provide regions of enhanced permeability (Ranero et al., 2003). As the plate subducts, increasing pressure and temperature induce several metamorphic dehydration reactions, resulting in water release from the plate. The depth of these reactions is controlled by the thermal structure of the subduction zone. The released water lowers the melting temperature in the mantle wedge above the oceanic plate, inducing melting and arc magmatism (Schmidt and Poli, 1998), as well as intraslab earthquakes through dehydration embrittlement (Kirby et al., 1996; Peacock and Wang, 1999).

In this study, we address slab dehydration for the Costa Rica–Nicaragua section of the Middle-America Trench (MAT). Here, subduction of the Cocos plate is characterized by the rapid convergence of the young (16–24 Myr) Cocos plate below the Caribbean plate, at an average dip angle that changes from ~70° below Nicaragua to ~45° below Costa Rica at depths exceeding 60 km. The Cocos plate is generated at two different spreading centers,

* Corresponding author.
E-mail addresses: jrosas@ualberta.ca (J.C. Rosas), claire.currie@ualberta.ca (C.A. Currie), rharris@ceoas.oregonstate.edu (R.N. Harris), jiangheng.he@nrcan-rncan.gc.ca (J. He).

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the East Pacific Rise (EPR) and the Cocos–Nazca Spreading Centre (CNS), with both sides juxtaposed and subducting together offshore the Nicoya Peninsula (Fig. 1). Subduction in this area is associated with volcanism and the formation of the Central America Volcanic Arc (Carr et al., 2003), as well as megathrust earthquakes along the subduction interface (e.g. Protti et al., 2014).

Here, we investigate the relationship between thermal conditions, slab metamorphism and hydration of the overlying mantle wedge. Early studies suggested that there were no significant along-strike variations in the level of hydration of the mantle wedge for the Costa Rica–Nicaragua margin (e.g Carr et al., 2007). However, recent seismic tomography and attenuation studies of the mantle wedge show *P*- to *S*-wave velocity ratios of 1.86 and 1.7 and Q_s of 76–78 and 84–88 below Nicaragua and Costa Rica, respectively (Syracuse et al., 2008; Rychert et al., 2008; Dinc et al., 2011). These results are interpreted to indicate greater hydration of the Nicaraguan mantle. This interpretation is supported by geochemical studies. Arc magma geochemistry data show that Ba/La and Ba/Th concentrations are relatively low (25–50 and 0–500, respectively) above the CNS section of the subduction zone (Fig. 2a). Over the EPR section, these values increase steadily to the northwest (Patino et al., 2000), indicating that the arc magmas here are enriched in slab-derived fluids. Both sets of data are consistent with greater slab dehydration in the Nicaraguan part of the subduction zone (Carr et al., 2003).

To explain the trends in mantle wedge hydration and arc geochemistry, two hypotheses have been explored: the slab hydration hypothesis and the thermal hypothesis. The slab hydration hypothesis calls on a variable hydration state of the subducting slab with larger amounts of water at the trench for the EPR side compared to the CNS side of the Cocos plate (Abers et al., 2003; Ranero et al., 2003; Naif et al., 2015). This extra water is proposed to be bound in the form of serpentinized harzburgite, as indicated by *P*-wave velocities of 7–7.5 km/s for the uppermost oceanic lithosphere near the trench that are consistent with 20–30% serpentinization (Hyndman and Peacock, 2003). The increase in water content correlates with a greater number of fault-bending fractures in the outer rise, indicating they might serve as pathways for water to penetrate to depths of ~12 km (Ranero et al., 2003; Van Avendonk et al., 2011).

The thermal hypothesis draws on variations in the along-strike thermal structure of the Costa Rica–Nicaragua subduction zone to explain the variable mantle wedge hydration. In general, the thermal structure of a subduction zone is controlled primarily by the age, convergence rate and geometry of the oceanic slab, as well as the rheology and flow pattern of the mantle wedge above the slab (Peacock, 1996; van Keken et al., 2002). Peacock et al. (2005) developed two-dimensional thermal models for different sections of the MAT to study slab dehydration and mantle wedge melting. These models are tailored to the age, convergence rate, geometry and material properties of the subduction zone and include a mantle wedge flow induced by viscous coupling with the subducting slab (Peacock, 1996; Batchelor, 2000). Their models demonstrate that a non-Newtonian mantle rheology is needed to obtain melting temperatures in the mantle wedge. However, age-dependent conductive cooling of the lithosphere yields only small differences in the thermal state of the subduction zone for different sections of the MAT, suggesting minimal along-margin variations in the slab dehydration depth. These models imply that the observed trends in arc geochemistry and mantle attenuation are not associated with variations in typical subduction parameters (e.g., slab age, convergence rate, and slab dip).

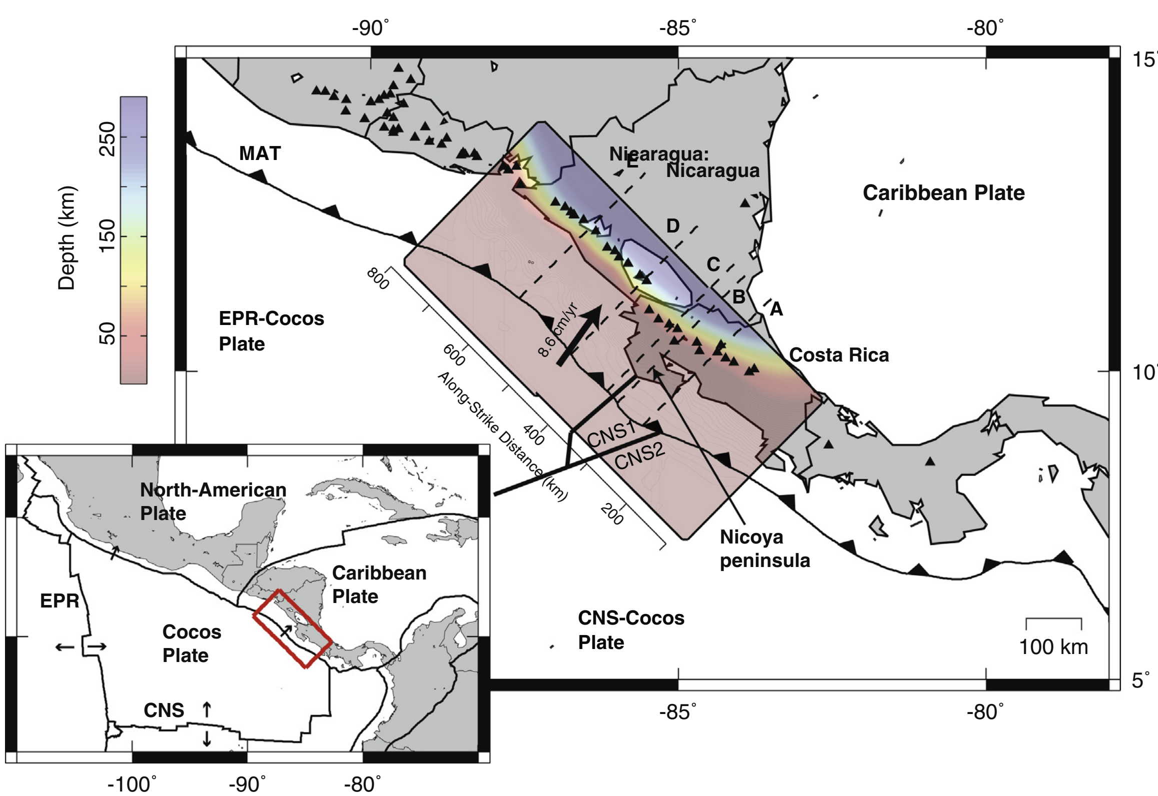

Fig. 1. Modeling area in Costa Rica–Nicaragua, with the regional tectonics shown in the inset. Color scale denotes slab depth, as obtained from Kyriakopoulos et al. (2015). Active volcanoes are shown with small black triangles. The Middle America Trench (MAT) runs approximately parallel to volcanic arc. Boundaries between EPR and CNS lithospheres are also shown (Barckhausen et al., 2001). Locations of profiles A through E are shown by dashed lines, and the along-strike coordinate system in this study is given. Plate boundaries are from Bird (2003). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)