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Mantle wedge hydration in Nicaragua from local earthquake tomography

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SUMMARY

The continental margin of Nicaragua and Costa Rica is characterized by significant lateral changes from north to south such as a decreasing dip of the slab, a decreasing magma production and a shift in the volcanic front. To investigate this transition, a joint on- and offshore local earthquake tomography was performed. Low *P*-wave velocities and high V_p/V_s ratios, indicative for hydration, were found in the upper-mantle and lowermost crust beneath the Sandino Basin. The mantle wedge hydration can be estimated to 2.5 wt. per cent beneath south Nicaragua. In contrast, the mantle wedge beneath north Costa Rica is weakly or not hydrated. The hydration leads to a local gap in the seismicity in Nicaragua. The lateral transition between the hydrated and non-hydrated areas occurs within a distance of about 10 km. This transition coincides with a change in the crustal thickness in the order of 5–10 km, thickening to the south, and in the tectonic regimes. The change in the tectonic regimes towards a stronger extension along the margin of Nicaragua could be the key for understanding the observations: the extension may support the opening of pathways for a wide zone of fluid migration and hydration through the overriding plate which are identified with areas of low V_p, high V_p/V_s and low seismicity.

Key words: Hydrothermal systems; Seismic tomography; Subduction zone processes; Continental margins: convergent.

1 INTRODUCTION

Mantle wedge hydration caused by fluids derived from the subducting slab is believed to control the downdip limit of the seismogenic zone (e.g. Hyndman *et al*. 1997; Peacock & Hyndman 1999). It seems to be influenced by various parameters, such as the age of the incoming plate, dip of the plate interface, volume of the subducted sediment, rate of convergence, thickness of the overriding crust (Hyndman *et al*. 1997; Oleskevich *et al*. 1999; Peacock & Hyndman 1999) and stress state of the overriding plate (Heuret & Lallemand 2005; Seno 2005; Heuret *et al*. 2007). The downdip limit of the seismogenic zone is important for the generation of megathrust earthquakes because it determines the length of the rupture zone in the landward direction. In the relatively warm subduction zones of Cascadia (Bostock *et al*. 2002; Brocher *et al*. 2003) and south west Japan (Kamiya & Kobayashi 2000) this limit coincides with the mantle wedge corner and an aseismic zone explained by the slippery behaviour of serpentine at the contact between the subducting oceanic crust and the overriding forearc mantle (Kamiya & Kobayashi 2000; Bostock *et al*. 2002; Brocher *et al*. 2003; Zhang *et al*. 2004). In cold subduction zones, the lack of mantle wedge hydration can be explained by the existence of a thicker continental crust. In such a case, the major part of the water goes into the forearc crust rather than into the forearc mantle (Hyndman & Peacock 2003). The hydration process is further important because the hydrated forearc mantle represents a big reservoir in the global hydrologic cycle (Zandt 2002) and may provide water for forearc volcanism or lubricating faults (Brocher *et al*. 2003).

The degree of the mantle wedge hydration depends on the amount of water that is carried with the incoming plate down to greater depths. The initial hydration of the subducting crust and mantle is thought to take place near the mid-ocean ridges and near the trench along bend-related faults, representing a reservoir of fluids and fluid rich sediments. The release of fluids in dehydration reactions can trigger intermediate depth earthquakes at the uppermost part of the slab (Hacker *et al*. 2003; van Keken 2003; Ranero *et al*. 2003), creating pathways for water into the overriding mantle wedge (Carlson & Miller 2003; Hacker *et al*. 2003; Husen *et al*. 2003; Hasegawa & Nakajima 2004).

Recent seismic investigations have shown that the incoming Cocos Plate of the Nicaraguan convergent margin, generated at the East Pacific Rise (EPR), is hydrated (Ivandic *et al*. 2010; Lefeldt & Grevemeyer 2008; Lefeldt 2008). In the investigation area of this study (Fig. 1), the hydration corresponds to an almost uniformly

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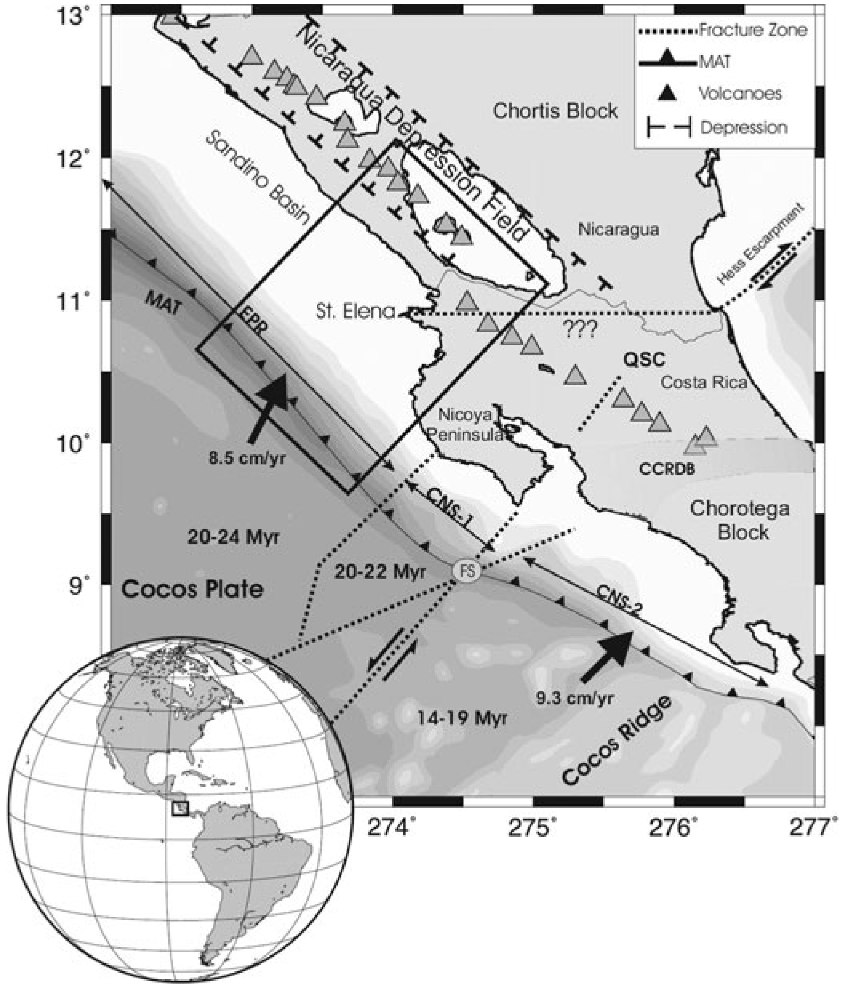

Figure 1. Tectonic settings of Costa Rica and Nicaragua. Offshore tectonic structures are from Barckhausen *et al*. (2001). MAT, Mid-America Trench; EPR, East Pacific Rise; CNS-1, Cocos-Nazca Spreading Center 1; CNS-2, Cocos-Nazca Spreading Center 2; FS, Fisher Seamount. Onshore tectonic structures are from Marshall (2007), McIntosh *et al*. (2007), Frischbutter (2002), Walther *et al*. (2000), Protti *et al*. (1994). CCRDB, Central Costa Rica Deforming Belt; QSC, Quesada Sharp Contortion. The rectangle box indicates the study area.

dense pattern of normal faults that are extending all along the bending Cocos Plate near the trench offshore south Nicaragua and north Costa Rica. Within the investigation area the incoming plate shows quite a uniform bathymetric and seismic structure, as evidenced by numerous seismic reflection and wide-angle studies (Ranero *et al*. 2003; Berhorst 2006; Grevemeyer *et al*. 2007; Hutnak *et al*. 2007; McIntosh *et al*. 2007; Ivandic *et al*. 2010). Some 10 km south of our investigation area, a pronounced crustal discontinuity was found across the transition from Cocos–Nazca Spreading Center-1 (CNS-1) to EPR crust by Walther & Flueh (2002). Newmann *et al*. (2002) found a marked change of 5–10 km in the depth of the updip limit of the seismogenic zone of Nicoya peninsula across this plate suture. To the north, in our study area, the age and crustal thickness of the plate are essentially the same, but the trench deepens, the density of bend faults at the ocean floor and their offsets landward of the outer rise seem to increase slightly to the north (von Huene *et al*. 2000; Ranero *et al*. 2003). In addition, a thermal transition is documented along the entirely EPR generated seafloor, *ca*. 40 km from the EPR–CNS boundary (Hutnak *et al*. 2007).

In contrast, the overriding plate shows large-scale geological changes from the northwest to the southeast, shown in Fig. 1. For example, a deep forearc and intra and backarc basins are found in Nicaragua but are absent in northern Costa Rica (McIntosh *et al*. 2007). The active volcanic front of Nicaragua shows a marked landward displacement coincident with the political boundary of Nicaragua and Costa Rica. High concentrations of 10Be and B/La are found at the volcanoes in the Nicaraguan section whereas the concentrations are low in Costa Rica (Noll *et al*. 1996; Patino *et al*. 2000; Hoernle & Hauff 2007).

Considered together, each of the plates may contribute to the system causing lateral variations in the subduction system on the large scale. However, the lateral variations of the incoming plate appear minor compared to the changes in the overriding plate in the sector of our study. Therefore, we hypothesize that the structure, composition and the tectonics of the overriding plate play a crucial role in the system, too. These findings suggest that the continental margin of S Nicaragua and N Costa Rica is an excellent site to study the interplay of the dehydration of the downgoing plate, the (possible) hydration of the mantle wedge and the influence of tectonics and structure of the overriding plate.

We approach this theme by applying a joint on- and offshore local earthquake tomography. We present *P*- and *S*-wave tomographic images and hypocentre locations from a temporary network leading to an improved view of the deep water cycle at subduction zones. On a more regional scale the area has been investigated recently based on an onshore seismic network (Syracus *et al*. 2008). In comparison to the study of Syracus *et al*. (2008) our network was regionally more restricted but shows a higher station density and includes offshore data leading to a generally increased resolution and improved image of the mantle wedge.

2. GEOLOGY AND TECTONIC SETTINGS

2.1 General situation

The current plate tectonic setting of the Central America is characterized by the subduction of the Cocos Plate and its predecessor, the Farallon Plate, beneath the Caribbean, which has been established 23 Myr ago (Barckhausen *et al*. 2001). The breakup of the Farallon Plate into Cocos and Nazca Plates initiated the CNS (CNS-1), causing a crustal stretching several hundred kilometres wide (Lonsdale 2005). At 19.5 Myr the ridge jumped and changed its strike to E–W, generating the CNS-2. The EPR and CNS are separated by a triple junction fracture zone in northern Costa Rica where the old patterns of CNS (CNS-1) have not been subducted yet. The northern remnant of the Farallon Plate fracture is proposed to be located somewhere between the EPR and CNS derived crust, offshore Nicoya Peninsula (Walther & Flueh 2002). The composition and segmentation of the Cocos Plate are clearly defined by magnetic anomalies (Barckhausen *et al*. 2001), multibeam bathymetry (von Huene *et al*. 1995, 2000), seismic studies (Walther & Flueh 2002; Sallares & Charvis 2003; Walther 2003; Wilson *et al*. 2003; Sallares *et al*. 2005; Hutnak *et al*. 2007) and geological sampling (Hauff *et al*. 1997; Werner *et al*. 1999; Wilson *et al*. 2003; Hoernle & Hauff 2007). These studies show that the part of the Cocos Plate generated along the EPR subducts under Nicaragua and northern Costa Rica. At the trench it is 20–24 Myr old. The part of the Cocos Plate generated at the CNS-1 is 20–22 Myr old where it is subducting beneath Nicoya, and 14–19 Myr old where it subducts beneath central and southern Costa Rica (Barckhausen *et al*. 2001).

Onshore southern Nicaragua and northern Costa Rica the transition from the oceanic Chorotega Block to the continental Chortis Block is found although the exact boundary is not known. This transition probably occurs along the Hess Escarpment-Santa Elena lineament (Fig. 1; Bowland 1993; Astorga 1997; Itturalde 1998). Itturalde (1998) proposed that the Chorotega and Chortis blocks shifted along this lineament since the Miocene and formed the current location of these two blocks. Variations in the gravity field suggest that the crustal blocks have different thickness and composition (Elming & Rasmussen 1997; Mann *et al*. 2007; Flueh & von Huene 2007). Based on a receiver function study MacKenzie *et al*. (2008) showed that the crustal thickness is rather uniform across the border of the Chorotega and Chortis blocks in the backarc (32–34 km) but show strong local and regional variation in the forearc where it changes in average from *ca*. 30 km in the NW (S Nicaragua) to *ca*.40 km in the SE (N Costa Rica).

2.2 Nicaraguan margin under extension

The Pacific margin of Nicaragua is characterized by a steepening slab dip and a seaward migration of the volcanic chain over the past million years (McIntosh *et al*. 2007; Mann *et al*. 2007; Carr *et al*. 2003). The subduction direction is oblique to the margin causing the forearc terrane to move slowly northwest, parallel to the margin and to the volcanic arc, with an increasing component of extension to the north (Turner *et al*. 2007; La Femina *et al*. 2009). Relative to the interior of the Caribbean Plate this motion is accommodated by faulting in the low-lying Nicaragua depression (La Femina *et al*. 2002) leading to the formation of an extensional basin and arc parallel shearing (Fig. 1). The Sandino forearc basin off northern Nicaragua has a thickness of 14–22 km (McIntosh *et al*. 2007). The formation of the Sandino Basin is most probably associated with an extension of the underlying crust and mantle wedge and with a thinning of the overriding plate as such. Walther *et al*. (2000) suggested that the initial formation of the Sandino Basin happened during a seaward retreat and new initiation of the subduction zone. This view is supported by the observed seaward migration of the volcanic chain in Nicaragua and by numerical modelling (Cailleau & Oncken 2008). Regarding the water cycle, an extensional stress regime is important because it favours the formation of fluid pathways within the overriding plate (Seno 2005).

2.3 Hydration of the incoming plate

Numerous seismic marine multichannel reflection and onshore-offshore wide-angle refraction surveys were carried out in the past decade to investigate the Nicaraguan convergent margin (e.g. Ranero *et al*. 2000; Walther *et al*. 2000; McIntosh *et al*. 2007). The following findings are of special relevance for this study. Half-grabens filled with sediment form at the top of the Cocos Plate as it bends into the trench. High resolution bathymetric mapping of the incoming plate showed that bending-related faulting is pervasive across most of the ocean trench slope. Multichannel seismic reflection data show that these faults can cut 20 km into the lithosphere (Ranero *et al*. 2003). Ranero *et al*. (2003) suggested that they promote fluid flow down to the mantle depth and cause hydration of the mantle between the outer rise and the trench axis. Analysing seismic velocities and offshore seismicity (Berhorst 2006; Grevemeyer *et al*. 2007; Ivandic *et al*. 2008; Lefeldt 2008; Lefeldt & Grevemeyer 2008) brought further evidence that the incoming Cocos Plate is hydrated although much reduced in volume.

Additional evidence for an increased degree of hydration and serpentinization is perhaps provided by geochemical data from the volcanic arc. These data suggest that mafic magmas in Nicaragua have water concentrations among the highest worldwide (Carr *et al*. 2003; Kutterolf *et al*. 2007). Also, the seismological data suggest that the regional *P*-waves from the intraslab events at 100–150 km depth show high-frequency late arrivals, apparently trapped in a 2.5–6 km thick low-velocity waveguide at the top of the downgoing plate. Such low velocities can best be explained by 5 wt. per cent of water in the subducted crust which corresponds to 2–3 times the hydration inferred for the other slabs (Abers *et al*. 2003).

Thus it seems to be well established that the slab contains a high concentration of fluids in Nicaragua.

3 DATA BASE AND METHOD OF INTERPRETATION

An amphibious seismic network was operated off- and onshore northern Costa Rica and Nicaragua between 2005 December and 2006 June, involving 20 ocean bottom seismometers and 30 seismic stations on land. 860 earthquakes of high signal-to-noise ratio with 10 770 *P*-phase and 6898 *S*-phase readings were used to perform local earthquake tomography (Fig. 2). The 1-D background model given in Table 1 was used for the preliminary location of the events and as an initial model for the 3-D inversion.

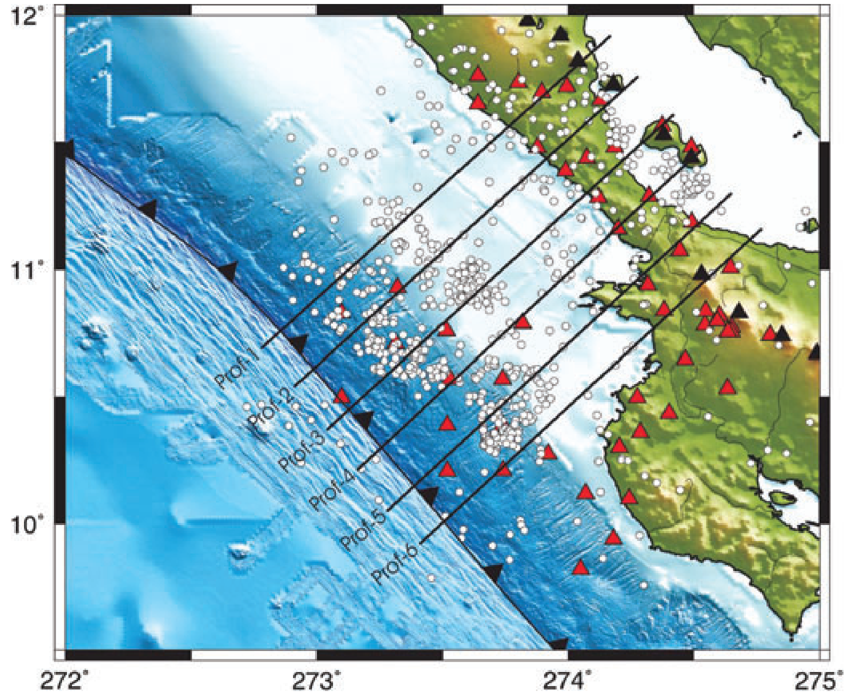

Figure 2. Distribution of the events (white circles) used for Local Earthquake Tomography. Red triangles denote the seismic stations and black triangles indicate the volcanoes. The lines represent the profiles for vertical sections shown in Figs 5 and 6.

Table 1. Background model of V_p and V_s applied in the tomographic inversion.

Depth (km)	V_p (km s^{-1})	V_s (km s^{-1})
0.00	2.40	1.34
10.00	4.29	2.41
16.00	6.30	3.53
19.00	6.88	3.86
22.00	7.00	3.93
41.00	7.90	4.43
80.00	8.20	4.60
124.00	8.35	4.69
310.0	8.66	4.92

The 3-D seismic velocity structure, hypocentre locations and station corrections were calculated iteratively and simultaneously by using the LOTOS-06 (Local Tomography Software) of Koulakov *et al*. (2007). The inherent matrix inversion was performed by an iterative least squares method (Paige & Saunders 1982; Van der Sluis & van der Vorst 1987). The underlying ray tracing is based on the bending method (Um & Thurber 1987). The velocity field is represented by a grid of nodes set up in vertical planes according to the ray density. Node spacing varies between 5 km minimum and 30 km maximum. Between the nodes, the velocity anomalies are interpolated bilinearly. To avoid gridding artefacts, the inversion was performed for four differently oriented planes (grids rotated by 0º, 22º, 45º and 67º). Then the results for the different grid orientations were averaged.

To see if the tomographic inversion produced reliable images of the real subsurface structure, we investigated the stability of inversion results by applying several synthetic tests following the sequence described in Dinc *et al*. (2010). Here we only present the results of the checkerboard and realistic velocity anomaly tests. The initial configuration of the checkerboard model is presented in Fig. 3 (lower left corner). The anomalies represent alternating high and low velocity blocks of 7 per cent amplitude with respect to the background velocity model (Table 1). The block size is 40×40 km in the horizontal and 50 km in the vertical direction. We show the reconstruction results for *P*- and *S*-wave velocity models at depth levels of 30 and 50 km in Fig. 3 which coincide with the mantle wedge corner. It can be seen that the *P*-wave velocity anomalies are well reconstructed in shape and amplitude beneath the entire study area at those depths. The opposite sign of the anomaly at 50 km depth is caused by the alternating high and low velocities at every 50 km depth and shows the robustness of the result. The aim of the realistic anomaly test (Fig. 4) is to figure out how well the vertical anomalies would be reproduced for a synthetic velocity model, showing a similar subsurface structure as the S Nicaragua/N Costa Rica subduction zone (Fig. 4 left-hand side, compare with Fig. 5, profile 4). The tomographic image (Fig. 4 right-hand side) reproduces the shape and amplitude of the input model well.

4 RESULTS OF THE TOMOGRAPHIC INVERSION

The 3-D inversion was terminated after five iterations. RMS traveltime residuals were reduced from 0.36 s to 0.22 s for *P*-wave data and from 0.73 s to 0.35 s for *S*-wave data (Table 2).

This corresponds to a variance reduction of 40 per cent for *P*-wave and 52 per cent for *S*-wave traveltime residuals with respect to the 1-D starting model. The following prominent features can be identified in the tomograms of Fig. 5–7:

(i) The cold and dense slab appears as a dipping high velocity structure anomaly with a dip angle of 35° in the upper 60 km depth, which steepens to *ca*. 70° down to 200 km depth (Fig. 5). The top of the slab coincides with the upper envelope of the earthquake distribution. The dip of the slab gets shallower from north (38°) to south (30°) in the upper 60 km depth. The dip angle does not change

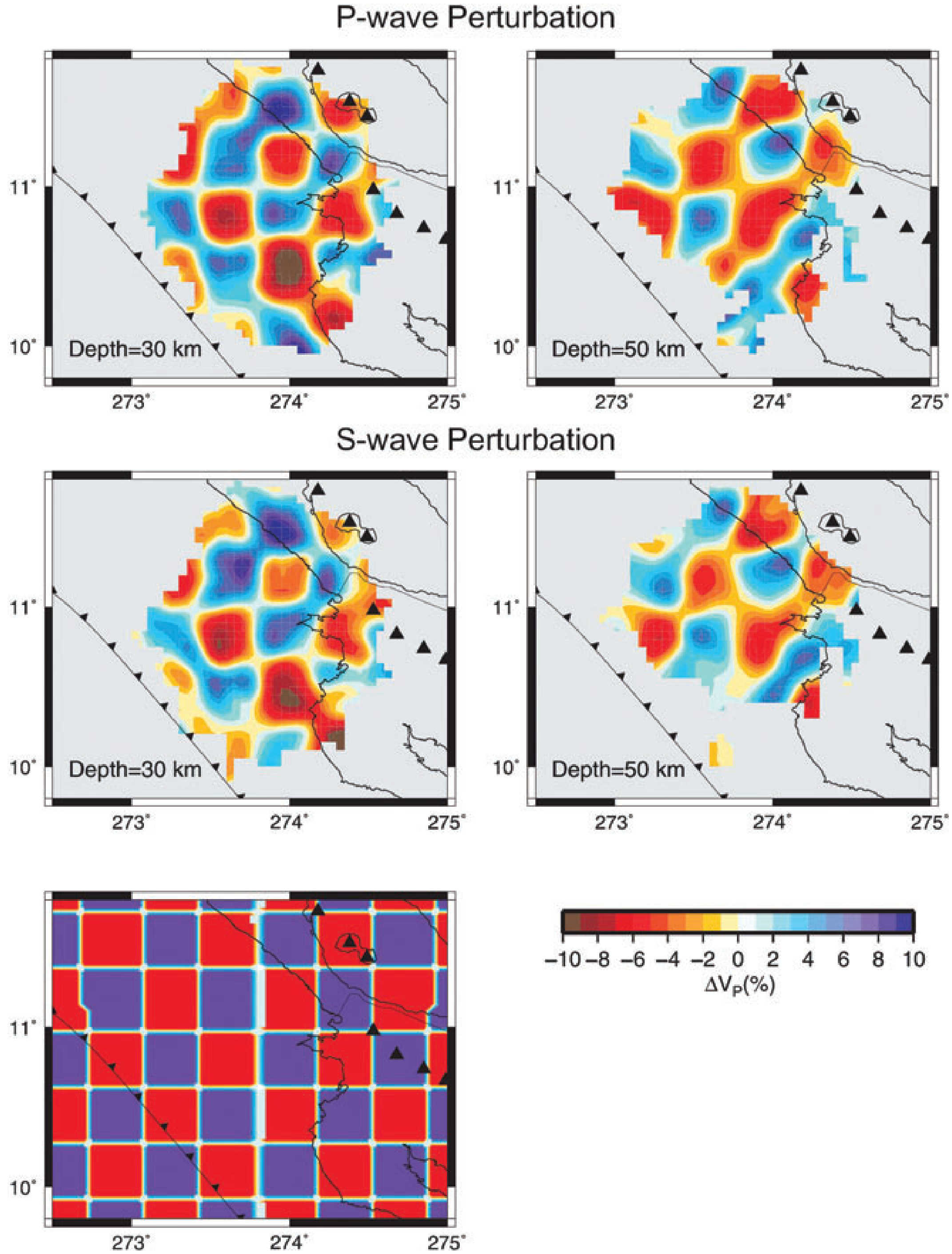

Figure 3. A checkerboard sensitivity test was performed to evaluate the resolution capability of the data set and sensitivity of the model for *P*-(upper row) and *S*-waves (middle row). A 40×40 km grid size in the horizontal and 50 km in the vertical direction with an amplitude of ±7 per cent was used for calculating the synthetic traveltimes for *P* and *S* (lower left corner). Calculated traveltimes are distorted using random noise with 0.1 s RMS for both *P* and *S* data.

significantly in the deeper parts but the number of events decreases in these depths from north to south.

(ii) The mantle wedge corner of the overriding plate, found between 30 and 70 km depths at 100–150 km distance from the trench, shows a 4 per cent decreased *P*-velocity with respect to 7.9 km s^{-1} and a high V_p/V_s ratio of 2.0. The zone of the high V_p/V_s ratios disappears from north (Nicaragua) to the south (Nicoya Peninsula, N Costa Rica), where it returns to the usual value of 1.7–1.8 (Fig. 5 and 6). The transition is well visible in the horizontal sections (Fig. 7). Whereas the low *P*-velocity anomaly extends and strikes almost uniformly parallel to the slab, we find that the high V_p/V_s ratio anomaly extending downwards beneath 30 km terminates abruptly at 274°E (Fig. 7). Therefore, a significant difference exists in V_p/V_s between Nicaragua and N Costa Rica. This transition occurs close to the southern edge of the Sandino forearc basin and near the border between the Chortis and Chorotega blocks. Also, it coincides with a line between the Madera (Nicaragua) and Orosi volcanos (N Costa Rica) along which the

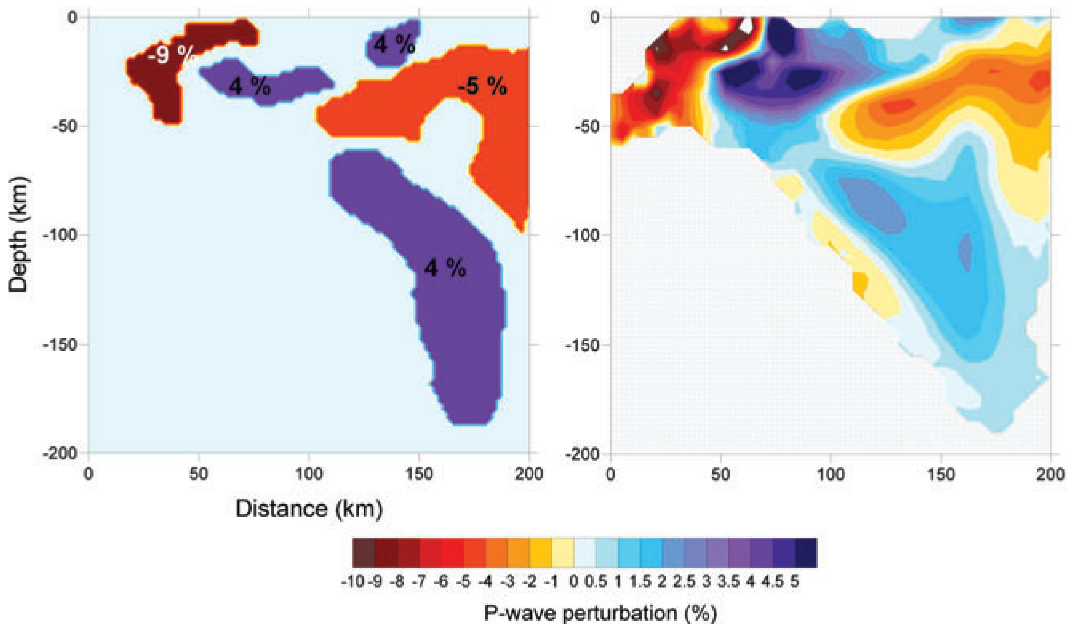

Figure 4. Synthetic test to check the vertical resolution with realistic anomalies. The left image is a synthetic model created on the basis of the results of real data inversion along profile 4 in Fig. 5. The right image is the recovered model. Noise of 0.15 s RMS was added to the synthetic traveltimes. The main anomaly patterns are well reproduced by the inversion.

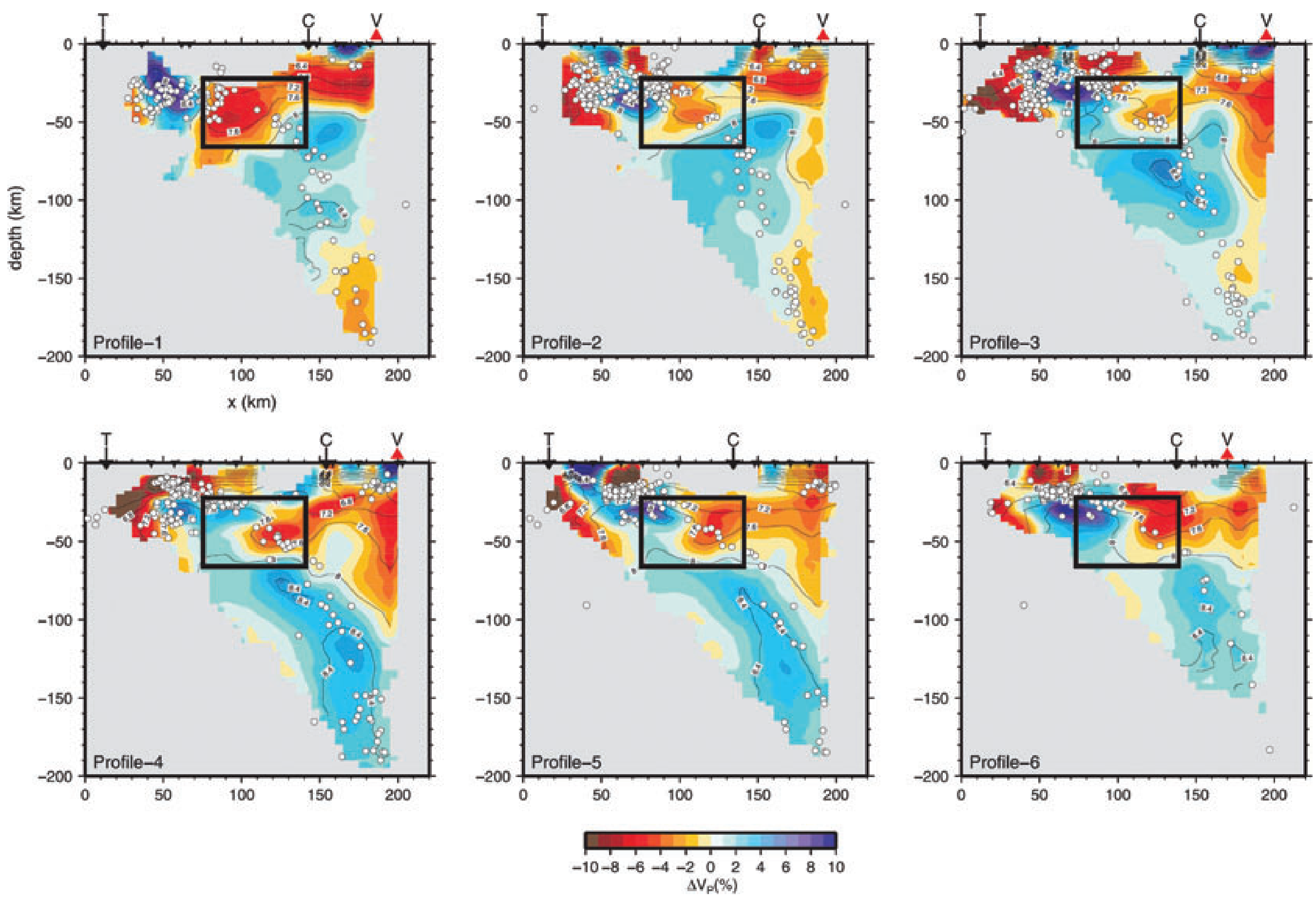

Figure 5. Vertical depth sections of V_p perturbations. Earthquakes (white circles), stations (black triangles), volcanoes (red triangles), trench (T) and coast (C) are projected on to the sections. Contour lines mark absolute *P*-wave velocities, the contour interval is 0.4 km s^{-1}. Profiles are shown in Fig. 2. The box indicates the mantle wedge corner.

Table 2. Reduction of traveltime residuals during five iterations of inversion procedure.

	One iteration	Two iterations	Three iterations	Four iterations	Five iterations
P-RMS (s)	0.36	0.28	0.24	0.228	0.219
S-RMS (s)	0.73	0.45	0.39	0.36	0.35

volcanic chain shows a displacement of *ca*. 30 km (dashed line in Fig. 7).

(iii) A slight difference of 0.05 in V_p/V_s is found between the N and S sections of the dipping oceanic mantle. Lower values are found in the south.

(iv) We find a zone of 4 per cent decreased *P*-wave velocity and increased V_p/V_s ratio, which starts at the mantle wedge corner and continues upwards until the volcanic arc. The width of the zone is 30 km and the angle to the horizontal is about 15°. The slowest mantle *P*-wave velocities correlating with an increased V_p/V_s ratio are found directly beneath the volcanoes. These anomalies indicate a zone of partial melting, extending to 100–150 km depth almost vertically (Fig. 5 and 6). The low velocity is more pronounced in the northern profiles and gets weaker towards the south suggesting a decrease in partial melting from north to south.

(v) Crustal thickness: Because of the spatial smoothing inherent in the tomography the Moho depth cannot be determined exactly form the vertical sections (Fig. 5). Therefore, we associate the crust–mantle transition with the zone between the 7.4 and 7.8 km s^{-1} velocity contours. Based on these contours the thickness of the continental crust seems to increase from Nicaragua to Costa Rica by 5–10 km. In the forearc region the velocity depth contours can be compared with a receiver function profile of MacKenzie *et al*. (2008). The comparative depth profile (Fig. 8) shows that the 7.8 km s^{-1} velocity contour deepens from NW to SE and that both 7.4 and 7.8 km s^{-1} velocity contours correlate with *P*-to-*S* converting interfaces of the receiver function profile. The 7.4 km s^{-1} contour agrees with interfaces found by seismic refraction profiling (Walther *et al*. 2000; Sallarès *et al*. 2001) and was previously identified with the Moho. This finding holds for S Nicaragua (NW), but appears questionable for N Costa Rica (SE) where *P*-wave velocities as low as 7.5 km s^{-1} were found beneath this interface (Sallarès *et al*. 2001; DeShon *et al*. 2006). This tendency to lower velocities is reflected in the deepening of the 7.8 km s^{-1} velocity of our study and, possibly, in the occurrence of a deeper interface in the receiver function image (Fig. 8). We interpret this structure as crustal thickening of N Costa Rica.

Onshore the average shape and size of the tomographic anomalies of our study agree well with the study of Syracuse *et al*. (2008). However, because of the higher station density and the availability of offshore data the resolution of the newly presented tomograms is

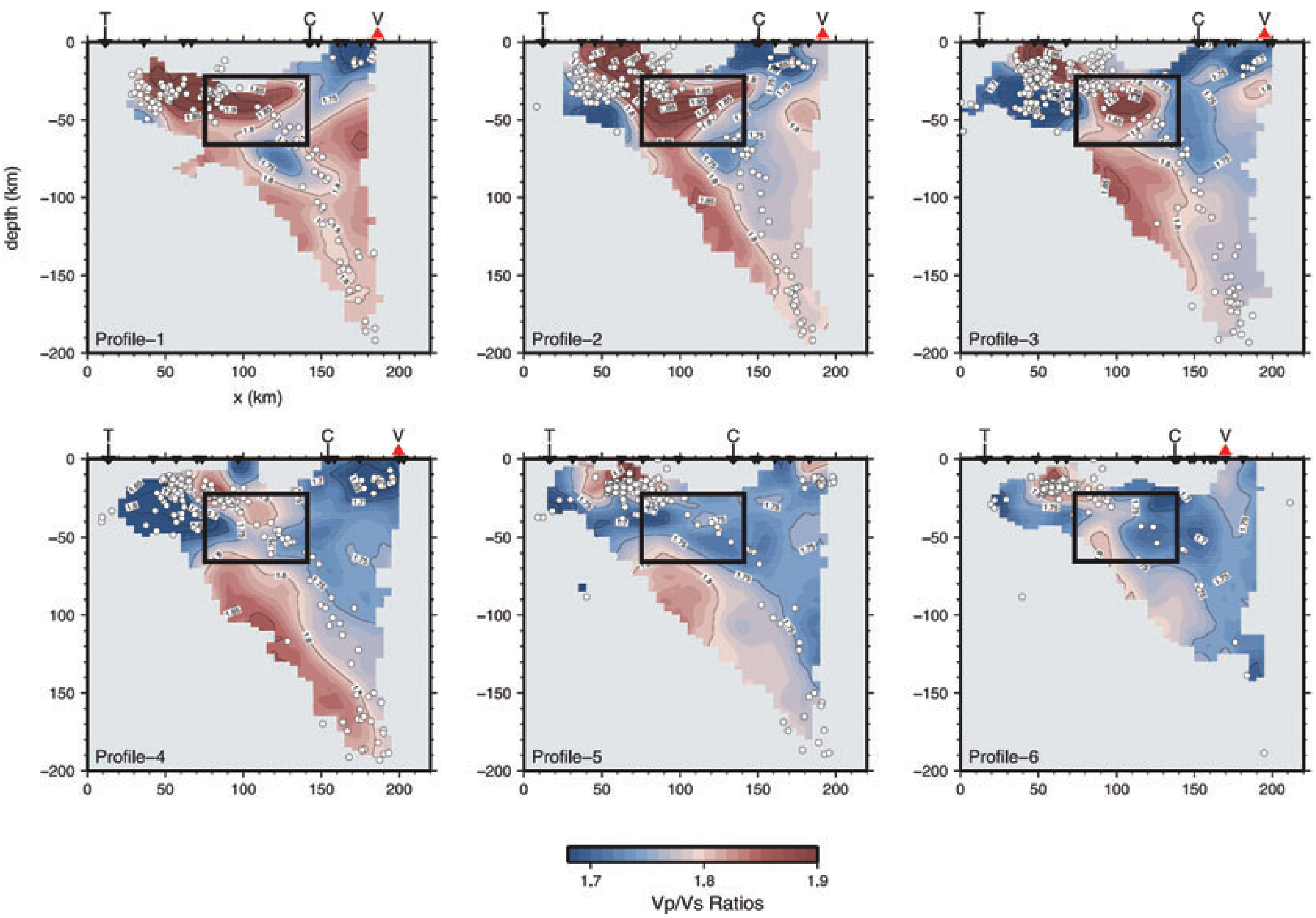

Figure 6. Vertical depth sections of absolute V_p/V_s ratios. Earthquakes (white circles), stations (black triangles), volcanoes (red triangles), trench (T) and coast (C) are projected on to the sections. Contour lines mark absolute V_p/V_s ratios, the contour interval is 0.05. Profiles are shown in Fig. 2. The box indicates the mantle wedge corner.

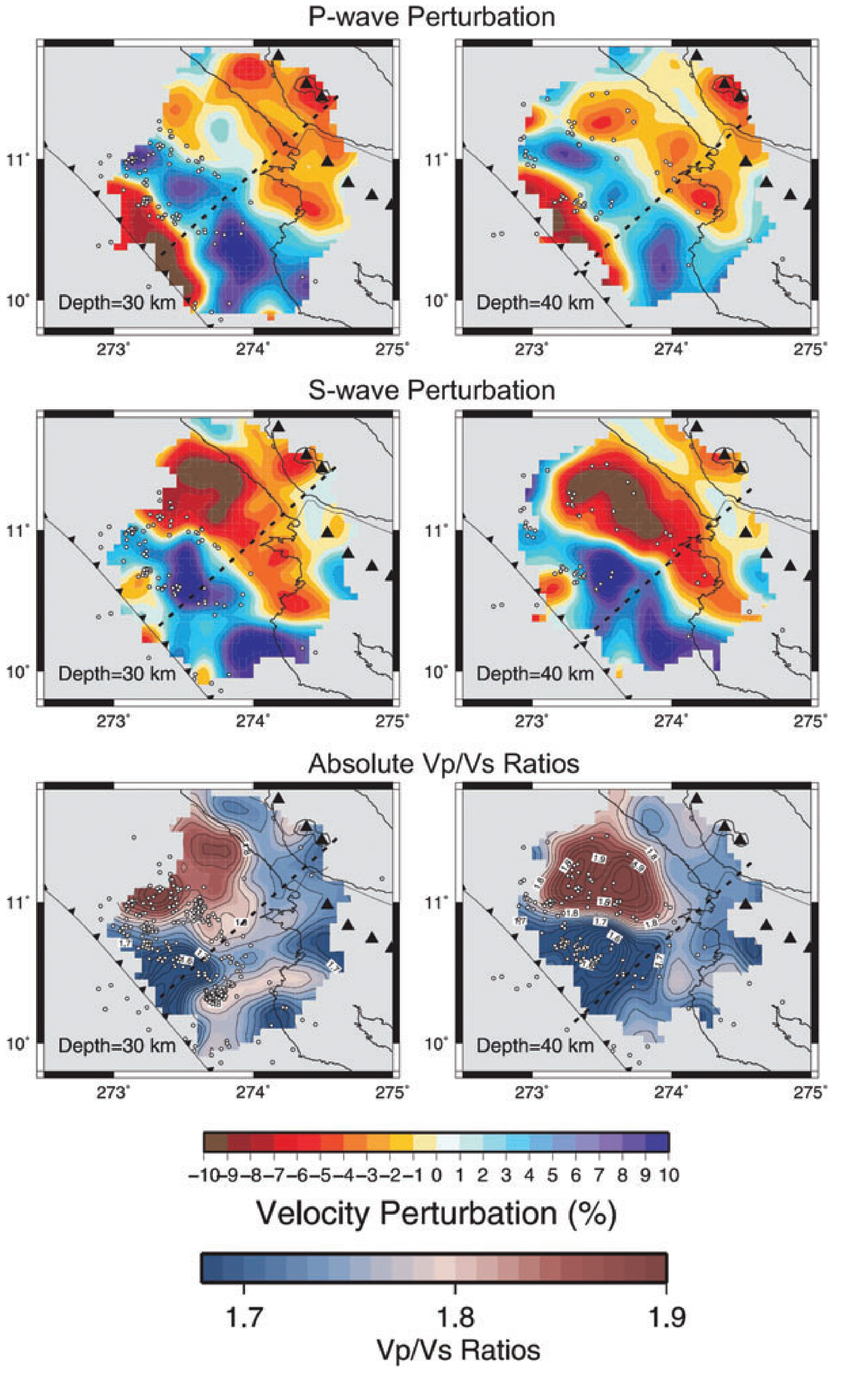

Figure 7. Horizontal depth sections for 30 km and 40 km depth. Upper row: V_p perturbations, middle row: V_s perturbations and lower row: V_p/V_s ratio after five-iteration inversion. The dashed line indicates the possible transition.

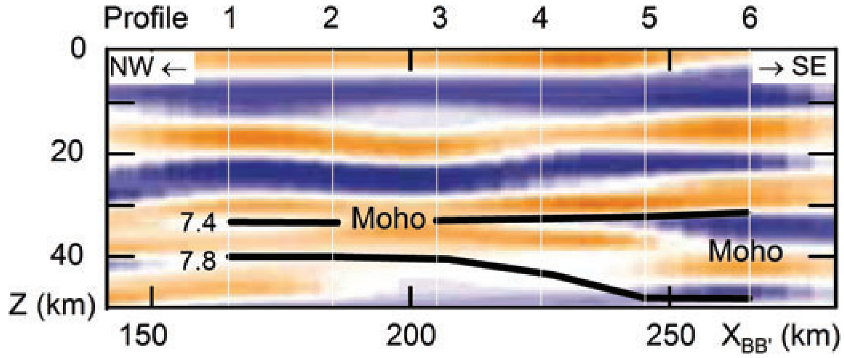

Figure 8. Crust–mantle transition along an arc-parallel profile in the forearc of S Nicaragua–N Costa Rica. The solid lines are the 7.4 and 7.8 km s^{-1} contour lines of *P*-wave velocity picked onshore halfway between the coast and the volcanic arc (coordinate 170 km see Fig. 5). The Moho is assumed to be located between these velocity contours. For comparison, a receiver function image is shown in the background. The receiver function image is a cut-out of profile BB' of MacKenzie *et al*. (2008) of which the depth axis was rescaled according to the *P*- and *S*-wave velocities found in our present study. Therefore, the receiver function depths shown here are 20 per cent smaller than in the study of MacKenzie *et al*. (2008). Crossing points with the tomographic profiles 1 to 6 are indicated on top of the figure (*cf*. Fig. 5), profile coordinates of MacKenzie *et al*. are shown at the bottom. We associate the Moho with the converting horizons located between the 7.4 and 7.8 km s^{-1} velocity contour lines. Note the abrupt deepening of these arrivals near Profile 5 where they step from *ca*. 30–35 km in Nicaragua (Profiles 1–4) to ≥40 km beneath Nicoya peninsula (Profile 6). The position of this change along the trench coincides with the lateral change in the V_p/V_s ratio (Fig. 7) and with the position where the 30 km displacement of the volcanic arc occurs (Fig. 2).

higher by a factor of two leading to a significantly improved image of the crust, the offshore area and the mantle wedge.

5 DISCUSSION

5.1 Effect of the overriding plate on the system

Down to 60 km depth the tomographic maps of *P*-wave velocity and V_p/V_s ratio show a zoning, which corresponds closely to the changes in geological structure observed at the Earth's surface. Within the segment considered in our study the incoming plate is almost homogeneous, meaning that it does not show any lateral changes of nearly comparative strength. Therefore, we favour the hypothesis that the structure and state of the overriding plate have a major influence on the subduction system of Nicaragua and N Costa Rica. This view appears contrasting to the widely accepted idea that the incoming plate governs the subduction zone processes (e.g. Ranero *et al*. 2003; Grevemeyer *et al*. 2007). Actually, setting more focus on the overriding plate does not lead to contrasting but to a more complete view of the processes: There is no doubt that the forcing comes from the subducted plate, but the outcome of the forcing depends on the subject exposed to the forcing, too. Regarding the investigated segment of the Central American subduction zone this statement is based on four groups of observations and arguments discussed in more detail below: The homogeneity of the incoming plate, the heterogeneity of the overriding plate, the variability of the stress regime of the overriding plate and evidences from modelling studies.

5.1.1. Homogeneity of the incoming plate

The Cocos Plate subducted beneath Nicaragua and Costa Rica has a complex history and shows segments of different age and structure along the trench (von Huene *et al*. 2000; Barckhausen *et al*. 2001). However, the slab subducted in the investigation area of this study belongs entirely to the EPR segment the isochrones of which are parallel to the trench (Barckhausen *et al*. 2001). The bathymetry shows bending-related trench-parallel faults that do not vary in density within the investigation area (Ranero *et al*. 2003). These faults have been considered as the cause and site of hydration of the incoming plate. Indeed, seismic refraction profiling performed along the outer rise showed a decreased *P*-wave velocity in the uppermost mantle indicative for fracturing and serpentinization (Walther & Flueh 2002; Berhorst 2006; Ivandic *et al*. 2008, 2010). This velocity decrease is uniform within the faulted EPR segments, and in particular uniform on those profiles located within the investigation area of this study (Walther & Flueh 2002; Berhorst 2006; Ivandic *et al*. 2010). The same applies to the seismic reflection structure of the downgoing plate (see data in Ranero *et al*. 2003 and McIntosh *et al*. 2007).

It may be argued that the already subducted part of the EPR segment could have shown more lateral heterogeneity than the not subducted part does today. Especially, the EPR-CNS 1-transition, which is found 30–50 km SE of our study area, could have induced lateral alterations of the oceanic lithosphere on regional scales at depth. However, we do not see a significant lateral change in the seismic velocities found along the slab between 50 and 100 km depth (compare profiles in Fig. 5). This can be interpreted as an indication that these hydro-thermal alterations may exist but apparently do not have a notable influence on the seismic velocity structure.

From Nicaragua to N Costa Rica we observe a small decrease of 8° in the slab dip in the uppermost 60 km. However, this dip change appears too small to significantly reduce the formation of bending-related faults and hydration of the downgoing plate. Indeed, no corresponding lateral velocity variation is found along the slab (Fig. 5).

5.1.2. Heterogeneity of the overriding plate

The overriding plate is composed of the Chortis Block in the north and the Chorotega Block in the south. The Chortis Block, forming Nicaragua, is considered as a splinter of the North American continent that moved along a strike-slip fault from west of Yucatan into its present position over the past 125 Myr. It represents a piece of continental crust. The Chorotega Block, forming north Costa Rica, is regarded as a thickened island arc that formed at the SW edge of the Caribbean Plate (e.g. Pindell *et al*. 1988; Meschede 1998).

The two blocks are supposed to be separated by a fault along which they finally docked to each other. The details of this movement are debated. The contact of the Chortis and Chorotega Blocks was suggested to represent a strike-slip continuation of the Hess Escarpment in the Caribbean Sea (Bowland 1993; Fig. 1). Astorga (1997) divided this fault system into the Santa Elena Fault in the north and the Bahia Tamarindo discontinuity further south. Our tomographic results (Fig. 5) together with the receiver functions of MacKenzie *et al*. (2008) and seismic refraction investigations (e.g. compilation of Flueh & von Huene 2007) show that the crustal thickness of these two blocks differs by 5–10 km. The thinner crust is found beneath Nicaragua and the thicker crust is located beneath N Costa Rica. The fundamental difference in the structure and composition of these two crustal blocks corresponds to a *ca*. 150 mGal change in the offshore gravity field, too, where the strongest lateral gradient coincides with the suspect terrane boundary (Berhorst 2006, based on Sandwell & Smith 1997).

The slowest mantle *P*-wave velocities, combined with increased V_p/V_s, are found beneath the volcanoes of Nicaragua. These anomalies are still present but much weaker in N Costa Rica. The observation that the velocity minimum occurs directly beneath the active volcanic arc makes it plausible to associate it with the up-rise of fluids and magma from the subducted slab. The decrease of the velocity minimum from NW to SE correlates with a decrease in volcanic activity, which has been quantified in terms of tephra volumes and erupted masses (Kutterolf *et al*. 2008).

The differences in volcanic productivity can be caused by differences in crustal thickness which influences the size of melting region in the mantle wedge by shortening or lengthening the ascent path of slab-derived fluids (Plank and Langmuir 1988). With regard to South America it has been argued that the dip of the slab correlates with volcanic activity. However, the observation from the South American margin cannot be transferred to Nicaragua–N Costa-Rica. Chen *et al*. (2001) have shown that the distribution of volcanic activity is basically bimodal at the S American margin: Volcanism exists for dip angles $>10^{\circ}$, and it does not where the slab dip is $<10^{\circ}$. The lack of volcanism seems to be caused by the shallow subduction of the Nazca Ridge and the suspected Inca Plateau. In Nicaragua and N Costa Rica the subduction angle is well above the threshold of 10°. A more plausible explanation of the variation of volcanic productivity, which may be alternative or complementary to the aspect of the crustal thickness, may lie in the varying stress conditions in Nicaragua and N Costa Rica. Compressional stresses do not prevent volcanism, but fluid pathways are more easily formed under extension.

5.1.3. Variability of the stress regime

The crusts of the Chortis and Chorotega Blocks may have been different in thickness right from their origin. However, it is evident that dynamic processes have played a significant role, too. The crust of Nicaragua seems to be thinned as a result of a tensional stress regime that finds its expression in back- and forearc depression fields such as the Sandino Basin. The origin of this large-scale extension is probably the roll-back or step back of the slab (e.g. Walther *et al*. 2000) connected with the oblique subduction and a steep slab (Fig. 7). This situation seems to change in the southern part of our study area, where the crust gets thicker and the recent uplift of Nicoya Peninsula indicates a compression. The uplift rate is *ca*. 4.5 mm yr^{-1} (Marshall & Anderson 1995).

A change in the recent stress regime in the overriding plate is also evident from focal plane solutions (Quintero & Güendel 2000; Correa-Mora *et al*. 2009), GPS measurements and related deformation modelling (Norabuena *et al*. 2004; Correa-Mora *et al*. 2009; La Femina *et al*. 2009): A locally compressional regime in N Costa Rica corresponds to an increased recent deformation rate of the Nicoya block and a significantly stronger locking of the plate interface than in S Nicaragua. The transition to a weaker plate interface locking seems to occur spatially near the transition from normal to increased V_p/V_s ratios in the mantle wedge. On the one hand, recent deformation rates and recent interface locking can be regarded as transient phenomena and are not necessarily related to long-term processes such as mantle wedge hydration. On the other hand, however, it has to be considered that the change of the overriding plate seen in the V_p/V_s distribution may imply significant rheological changes such as decreasing viscosity which may influence the temporal development of plate coupling and stress transfer also on geological timescales (e.g. Hilairet *et al*. 2007).

5.1.4. Evidences from modelling studies

Heuret *et al*. (2007) showed in their modelling study that the trench motion, slab geometry and the deformation style of the overriding plate (compression or extension) are closely related to the absolute motion of the overriding plate. Trench advance, steep dip, thin continental crust and backarc extension are observed mostly if the overriding plate is under extensional regime. A number of authors (e.g. Forsyth & Uyeda 1975; Chapple & Tullis 1977) invoked the existence of a trench suction force from slab pull, which would cause a trenchward motion of the arc and its divergence from the overriding plate. This could be the case along the Nicaragua segment of the Central American arc.

Seno (2005) stated that the stress regime of the mantle wedge controls the extent of hydration. Hydro-fracturing under extension can be considered as a mechanism to create fluid path ways. Therefore, the high V_p/V_s ratios of 2.0 observed in the tomographic sections of northern Nicaragua (Fig. 6) could be explained by a broadly hydrated mantle wedge, which was formed under extension of the overriding plate. Also, the forearc and intra arc depression occur along normal faults, which are cutting deeply into the mantle. They may provide additional pathways for fluids to migrate, to hydrate the mantle wedge, crust and to contribute to the melts beneath the volcanoes (Fig. 7).

5.2 Geophysical evidences of mantle wedge hydration

The increased V_p/V_s ratio of 2.0 and low *P*-wave velocity (Figs 5–7) observed near the mantle wedge corner (30–40 km depth) in the northern part of the investigation area can be regarded as an evidence for an intense hydration which is not found in the southern part. This variable degree in mantle wedge hydration correlates with the local maxima of geochemical trace elements found in the N Nicaraguan volcanoes, especially the maxima of 10Be concentration and B/La ratios indicative for oceanic crustal fluids (Noll *et al*. 1996; Patino *et al*. 2000; Carr *et al*. 2003; Hoernle & Hauff 2007). With increasing degree of hydration or serpentinization V_p/V_s is increased from 1.7 to a maximum of 2.4. In addition, the *P*-wave velocity is reduced from 8.0–8.2 km s^{-1} to a minimum of 4.5 km s^{-1} at 100 per cent transformation of peridotite to serpentinite (Christensen 1966; Carlson & Miller 2003). The *P*-wave velocities and V_p/V_s ratios found at the tip of the mantle wedge (box in Figs 5 and 6) are between 7.4–7.6 km s^{-1} and 1.95–2.00, respectively. These values would be compatible with about 20 per cent serpentinization and 2.5 wt. per cent H_2O. Serpentinite is stable up to temperatures of 600–700 °C, at depths between 30 and 150 km (Ulmer & Trommsdorff 1995). At higher temperatures it decomposes and water is set free (e.g. Zandt 2002). In the mantle wedge of S Nicaragua and N Costa Rica the estimated temperature is about 400 °C at 1 GPa (Ruepke *et al*. 2002; Peacock *et al*. 2005). Thus, serpentine should be stable. Similar results have been found for the central Japan subduction zone (Kamiya & Kobayashi 2000) and the central Cascadia subduction zone (Bostock *et al*. 2002). Serpentine shows stable-sliding behaviour in the laboratory. Therefore, it has been concluded that the plate interface between the slab and hydrated overriding mantle should be seismically silent (Peacock & Hyndman 1999). Indeed, we observe a local decrease in the seismicity in the around 40 km depth beneath Nicaragua (Profiles 1–3, see boxes in Figs 5 and 6). This local seismicity gap coincides with a zone of strong minimum of *P*-wave velocity (Fig. 5) and increased V_p/V_s ratio (Fig. 6), which occurs not only in the downgoing plate but extends also obliquely upward into the mantle wedge (best visible on Profiles 1 and 2 in Fig. 6, see also Fig. 9 top panel). This means that the anomaly may represent a zone where both downgoing and overriding lithosphere are serpentinized and mechanically weak or ductile. If so, the contact between both plates would only be weakly coupled because the reduced friction leads to a locally aseismic subduction (*cf*. Kamiya & Kobayashi 2000; van Keken 2003; Zhang *et al*. 2004). Indeed, this sort of a pronounced aseismic gap has been observed at the Central America subduction zone between 25 and 40 km depth also by other authors, but on a more regional scale (Protti *et al*. 1995; Walther *et al*. 2000). However, it was not paid attention to because it was regarded as an artefact of hypocentre localization. With the marine stations, our new data set covers the investigation area much denser than the previous studies, which were based on land stations only. Also, the joint tomographic and hypocentral inversion provides a location accuracy high enough for reliably discovering a gap of hypocentres of 20 km extent.

The approach to identify the V_p and V_p/V_s anomaly in S Nicaragua with serpentized rock volumes on both sides of the plate interface and with related low mechanical coupling is indirectly supported by GPS measurements and corresponding deformation modelling (La Femina *et al*. 2009, *cf*. also Correa-Mora *et al*. 2009). This modelling showed that coupling is indeed weak offshore Nicaragua, possibly extending no deeper than 20 km, and strongest in the Nicoya segment in N Costa Rica where the coupling of the seismogenic zone extends down to 40 km.

5.3 Fluid source for the hydrated mantle wedge

Dehydration and eclogitization of the subducting oceanic slab are most likely the source of water for the serpentinization of the forearc upper mantle (Bostock *et al*. 2002; Brocher *et al*. 2003; Hyndman & Peacock 2003). In addition, fluids are supposed to be introduced into the slab by the sediment filled half grabens, created by the

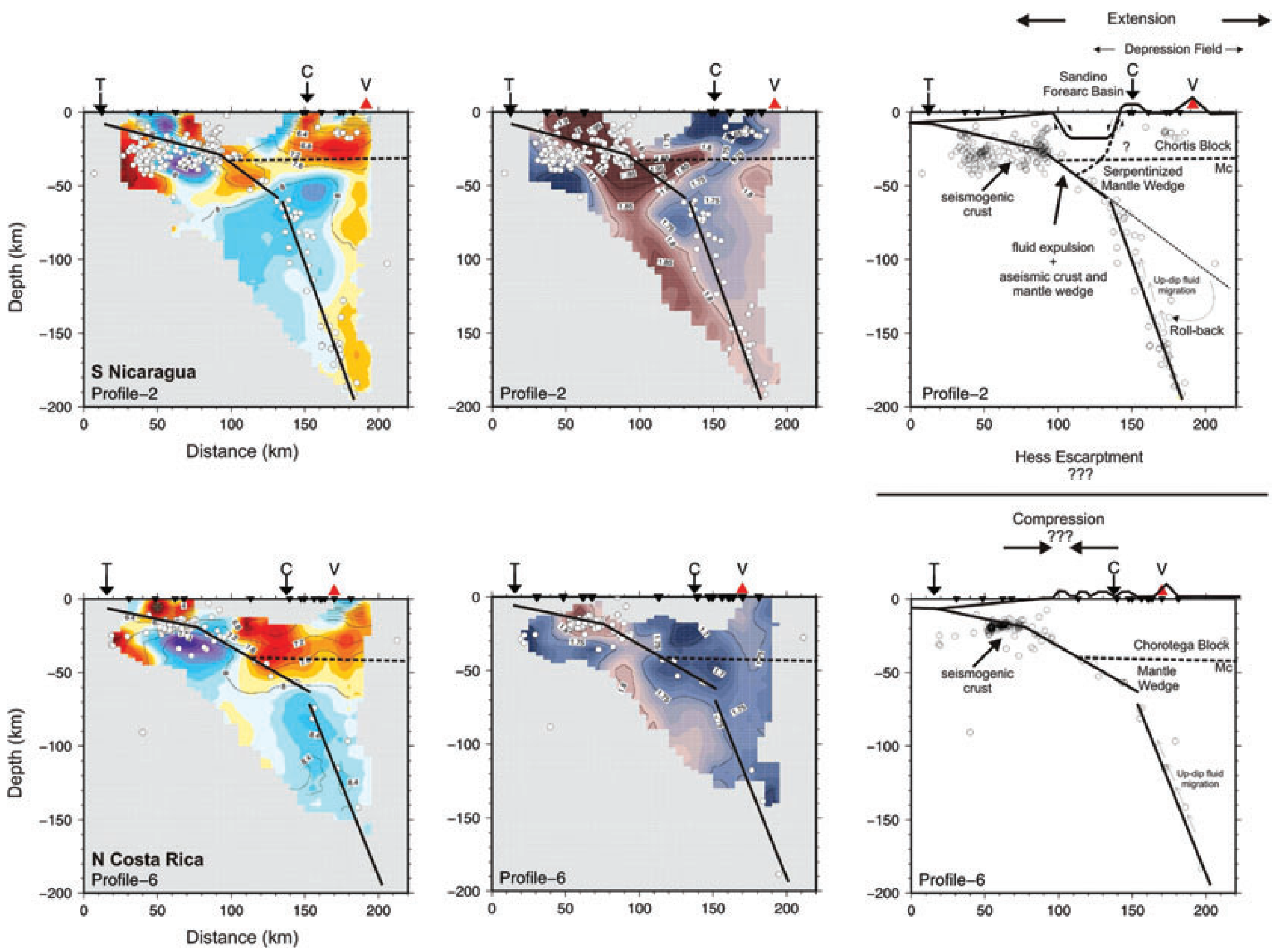

Figure 9. Schematic diagram of the proposed transition between S Nicaragua and N Costa Rica.

bend-related faults of the incoming plate. The bend-related faults offshore Nicaragua also facilitate plate hydration (Ranero *et al*. 2003; Grevemeyer *et al*. 2007). However, how can water penetrate into the overriding mantle? A comparative view of the situations in S Nicaragua and N Costa Rica is shown in Fig. 9. Most of the free water is expelled at shallower depths due to the compaction of subducted sediments and collapse of porosity in the upper oceanic crust, and most fluid is released beneath the forearc (Ruepke *et al*. 2002; Hyndman & Peacock 2003). Additional water is released by dehydration reactions starting at 75 km depth. It may migrate updip in the slab and hydrate subducted crust at shallower levels (Hacker *et al*. 2003). This process would require a pathway that allows fluids to ascend up the slab. The steep dip of the Nicaragua slab of *ca*. 80º may facilitate such a pathway. In addition, the *P*-waves of the intraslab events at 100–150 km depth in Nicaragua show a high-frequency late arrival, apparently trapped in a low velocity waveguide that could be explained by a high degree of hydration (Abers *et al*. 2003). This hypothesis is supported by our study through the slight increase of V_p/V_s ratios found along the subducting oceanic mantle offshore Nicaragua. For the water ascent into the overriding plate the extensional stress regime and related fractures seem to play an important role. Water accumulated at the depths of 30–50 km in the slab can escape into the overriding mantle wedge along these fractures (Seno 2005) causing hydration and related V_p and V_p/V_s anomalies in both overriding and downgoing plates. The situation is different in N Costa Rica (Fig. 9 bottom-panel) where the compressive stress prevents the upward channelling water from entering the overriding lithosphere and where V_p and V_p/V_s anomalies do not show any indications of serpentization.

6 CONCLUSIONS

Based on the analysis of *P*-wave velocity, V_p/V_s ratio and local earthquake hypocentres, the following conclusions can be drawn regarding the dehydration and hydration processes at the active continental margin of S Nicaragua/N Costa Rica.

(1) We find evidence for 2.5 wt. per cent mantle wedge hydration beneath S Nicaragua. In contrast, the mantle wedge beneath N Costa Rica is weakly or not hydrated. The hydration leads to local gap in the seismicity in Nicaragua.

(2) The lateral transition between the hydrated and non-hydrated areas occurs within a distance of about 10 km. This transition coincides with the significant structural changes in the overriding plate: in particular a change in the crustal thickness in the order of 5–10 km, thickening to the south, and in the tectonic regimes.

(3) The change in the tectonic regimes towards a stronger extension along the margin of Nicaragua could be the key for understanding the observed seismic structure: the extension supports the opening of pathways for wide zones of fluid migration and hydration through the overriding plate which are identified with areas of low V_p, high V_p/V_s and low seismicity.

(4) The extension has to be seen in the context of a large-scale slab roll-back starting in Nicaragua with increasing amplitude to the north. It finds its expression in a steepening of the subducted plate towards the north of the observation area.

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