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Crustal structures beneath the seismogenic zones and lateral velocity contrasts across deep faults of Albania

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Abstract: *One-dimensional (1D) velocity models are computed for Albania using a database of events recorded during 2002-2006 by the Albanian, Montenegro, Thessalonica and FYRo Macedonia seismological networks. These velocity models indicate lateral velocity differences across deep faults and improve the hypocentral depths. Smooth velocity gradients with depth and low P- wave velocities are observed beneath the Albania Orogen. The interpretation of the obtained 1D velocity models and lateral velocity differences across deep faults of Albania allows us to infer interesting features on the deep structure of the Albania. These results represent a first step towards more detailed seismotectonic analyses.*

Key words: *Seismological network, Albania, velocity model*

INTRODUCTION

The Albanian seismic network and the seismological networks of Montenegro, Thessalonica and FYRo Macedonia consist of 29 permanent seismological stations that cover the entire Albania and surrounding regions (Fig. 1). Seismic phases recorded by the Albanian network, integrated with the ones from the Montenegro, Thessalonica and FYRo Macedonia networks, are used to prepare the database for this study. We defined reference velocity models for the Albanian seismogenic zones and lateral velocity differences across deep faults of Albania to better constrain the hypocentral depths determination. To improve earthquake location we used a reference 1D model close to the true earth model and station corrections that mitigate the effects of the structure close to receiver and deviations from the simple, laterally homogenous model (Zhi-xian et al., 2004; Claudio et al., 1997).

METHOD

The method calculates a (layered) 1-D velocity model and station corrections using the module VELEST of the software SEISAN, which is widely used for model optimization (Haskov, et.al., 2001). This module solves the forward problem by ray tracing from source to receiver, for direct and refracted rays passing through the 1-D model (Papazachos et al., 2002). The inverse problem utilizes the damped least squares matrix [A^tA+L] (A= Jacobian matrix, A^t=its transpose; L=damping matrix). Since the inverse problem is non-linear, the iterative solution involves ray tracing and a linear inversion for each iteration. In order to improve the stability of the inverse problem, a priori information on the model space may be used (Kissling, 1994).

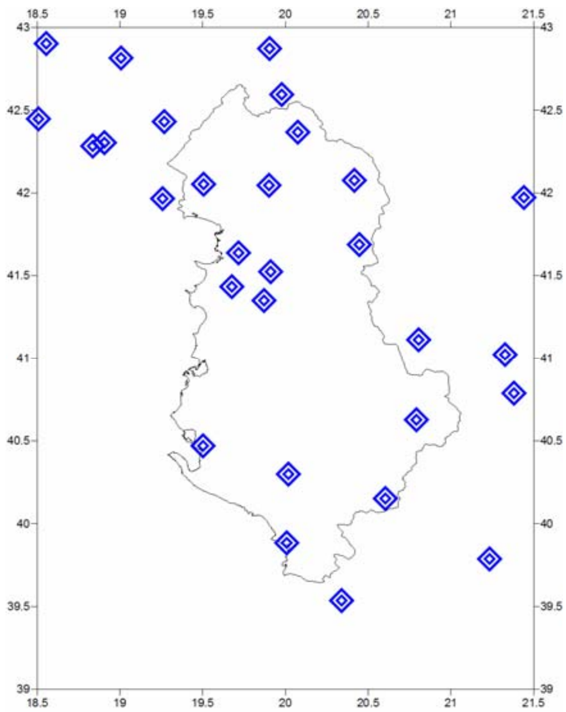

FIG.1. Map of 29 permanent seismological stations used for the inversion.

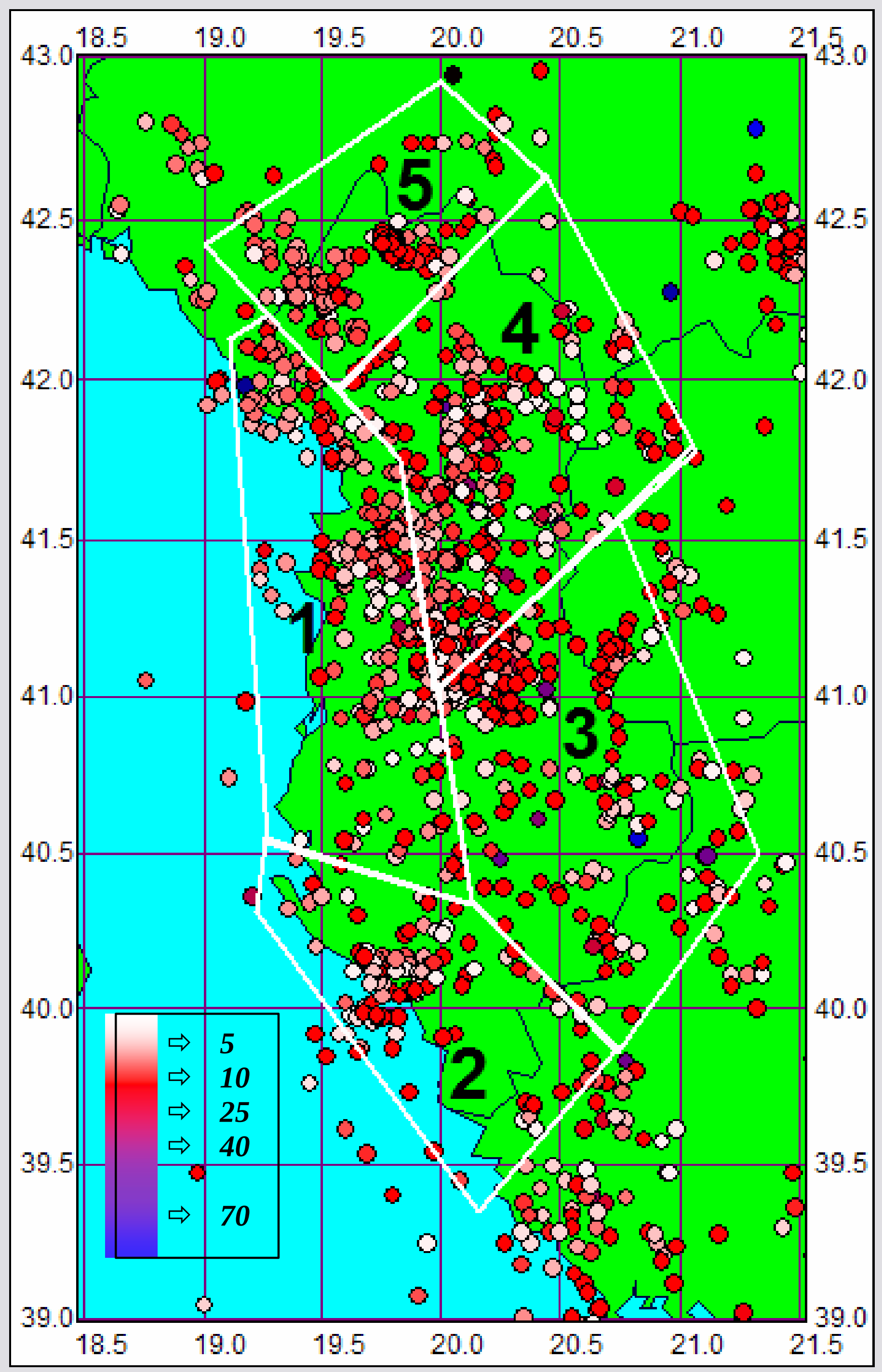

FIG. 2. The map of seismogenic zones and the earthquakes epicenter, for events during the period 2002-2006. Velocity models of the earth crust were calculated for each zone. The color scale denotes focal depths in km. Note that the Shkoder-Peje fault divides sub regions 5 and 4 and Lushnje-Elbasan-Diber fault devides sub regions 4 and 3.

DATA QUALITY

The data set includes earthquakes recorded by the Albanian network during 2002-2006, whose magnitude ranges from 2.0 to 5.2. Reading accuracy is about 0.02-0.05 s for P arrivals at epicentral distances less than 200 km, while reading errors of long traveling phases can be larger (Ormeni, 2007). For the inversion, we selected 1150 events located by HYPO 71. The focal distance errors were less than 4 km (horizontal and vertical), using at least 8 first arrivals. In order to derive 1D velocity models, Albania is divided into five main regions, according to its structural setting and earthquake distribution (Fig. 2): 1. Western Albania, 2. Southwestern Albania, 3. Southeastern Albania, 4. Northeastern Albania and 5. Northern Albania. For each sub-region we calculated, using Velest (Haskov et al., 2001), the station corrections and the damped least squares 1D velocity model. Figure 3 indicates that the stations near the Albanian seashore exhibit positive corrections up to 0.84 s.

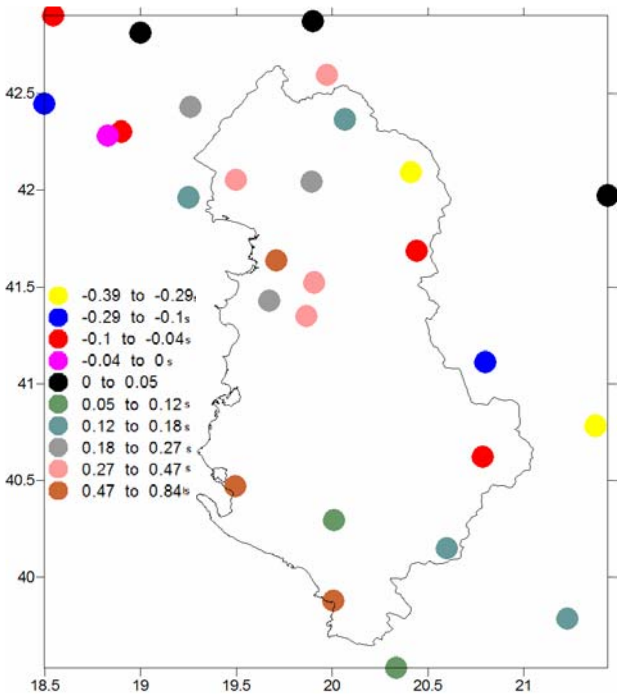

FIG. 3. Station corrections for the Albania seismological network. Positive values indicate low velocity and negative values reflect high velocity.

CALCULATION OF THE VELOCITY MODEL

Zone 1

In this region (Western Albania) the velocity versus depth curves (Fig. 4) become smoother at greater depths. The P wave velocity ranges from 5.4 km/s in the upper crust (0-10km) to around 6.0 km/s in the middle crust (10-25km). For the lower crust (25-40km) the P wave velocity reaches 6.5 km/s, suggesting the absence of strong velocity gradient with depth. At depths around 45 km the P wave velocity is 7.3 km/s. The events in the middle Albania (Zones 1 and 3) are sparse and exhibit large errors, due to the poor station coverage. Thus, we encounter difficulties in obtaining focal depths.

It is interesting to note that both Vp and Vs exhibit high positive gradient for the upper crust (Fig. 4). These velocity gradients become smaller and occasionally negative for the middle crust, lower crust and upper mantle.

Zone 2.

Positive corrections of stations are observed in South-western Albania (Zone 2), suggesting the presence of low velocities in the crust. P wave velocities slightly increase with depth ranging from 5.7 km/s in the upper crust (0-8km), 6.1 km/s in the middle crust (8-25km), close to 6.9 km/s in the deeper crust (25-40 km) and around 7.5 km/s below 45 km (Fig. 5).

The 1D model exhibits a low velocity seismic layer (Vp = 4.28 km/s) near the surface. In the middle crust, the velocity gradient is very small. Poor station coverage of this zone did not permit the estimation of the S-wave velocity model. The down-and-up going branches of Pn refracted phase exclusively probed the lower crust. The crust-mantle boundary, located at a depth of about 40 km under the Southwestern Albania, is considered relatively shallow.

Zone 3

Zone 3 covers the Southeastern part of Albania. P wave velocities range from 5.5 km/s in the upper crust (0-10km), around 6.05 km/s in the middle crust (10-20km), to 6.9 km/s in the lower crust (20-45 km) (Fig. 6). Below 45 km depth the P wave velocity is 7.3 km/s. The crust-mantle boundary located at a depth of about 50 km under the Southeastern Albania, is also considered relatively shallow, as in zone 2.

Zone 4

Negative corrections observed in php and puk phases for seismological stations in Northeastern Albania (Zone 4), suggest the presence of high velocities in the crust. The P wave velocities range from 5.4 km/s in the upper crust (0-10km), around 5.8 km/s in the middle crust (10-25km) to around 6.9 km/s in the lower crust (25-45km). Below 55 km depth the P wave velocity is 7.4 km/s (Fig. 7).

The Vp and Vs gradients in the upper crust are positive. For the middle and lower crust, both Vp and Vs gradients become smaller and occasionally negative. The Vp gradient exhibits higher values compared to the Vs gradient in the upper mantle. Thus, the Vp/Vs ratio increases in the upper mantle.

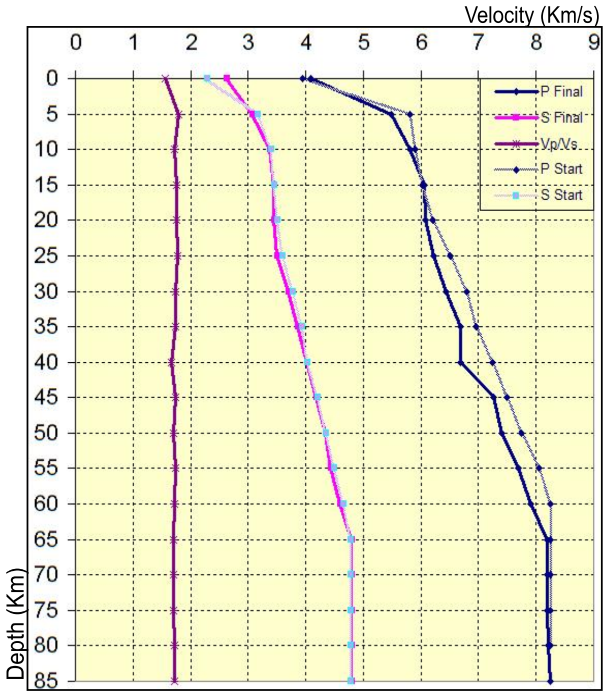

FIG. 4. Starting and final (bold) 1D P- and S-wave models with corresponding Vp/Vs ratio for Western Albania (Zone 1).

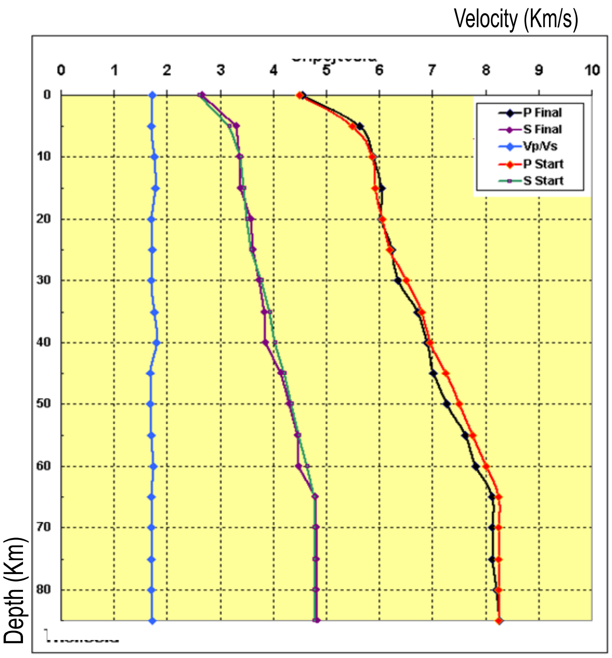

FIG. 6. Starting and final (bold) 1D P- and S-wave models with corresponding Vp/Vs ratio for South-eastern Albania. The P-velocity gradient decreases at the Moho and in the upper mantle (Zone 3).

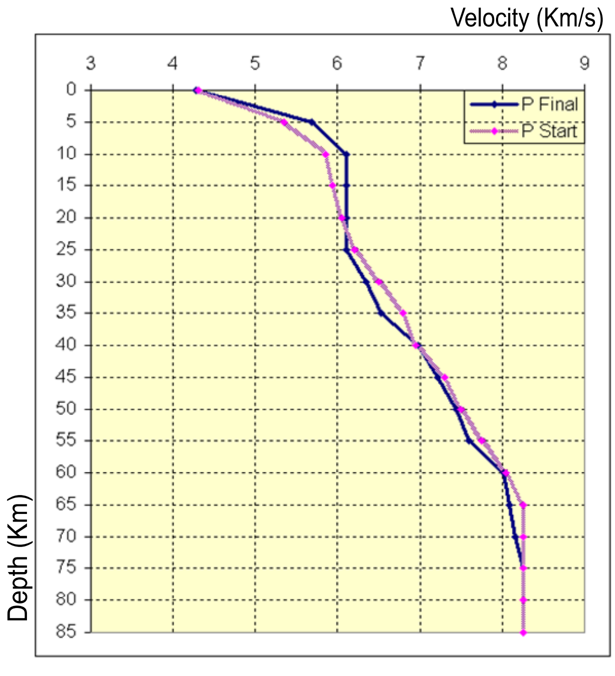

FIG. 5. Starting and final (bold) 1D P- or Southwestern Albania. The P-velocity gradient increases in upper and middle crust and decreases in the lower crust and upper mantle (Zone 2).

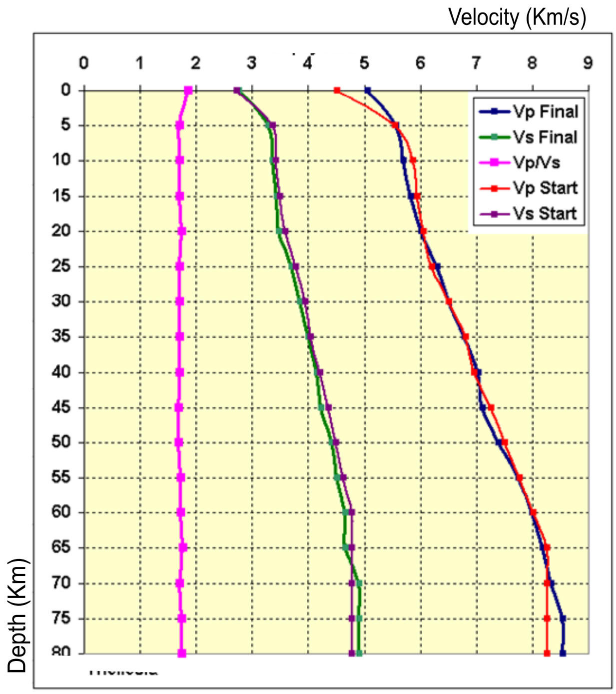

FIG. 7. Starting and final (bold) 1D P- and S-wave model with corresponding Vp/Vs ratio for Northeastern Albania between Shkoder-Pej and Lushnje-Elbasan-Diber Faults. Note the P-velocity gradient decrease in the crust (Zone 4).

Zone 5.

Zone 5 covers most of Northern Albania. The P wave velocities range from 5.6 km/s in the upper crust (0-8km), 6.1 km/s in the middle crust (8-25km), and around 6.8 km/s for the lower crust (25-45km), suggesting the absence of velocity gradient variation with depth (Fig. 8). Below 55 km depth the P wave velocity is 7.6 km/s.

The variation of Vp and Vs gradients is similar to the ones in Zone 4. The Vp/Vs ratio for zones 1, 4 and 5 exhibits significant variations, compared to its reference value of 1.73. For zone 3 this ratio is larger.

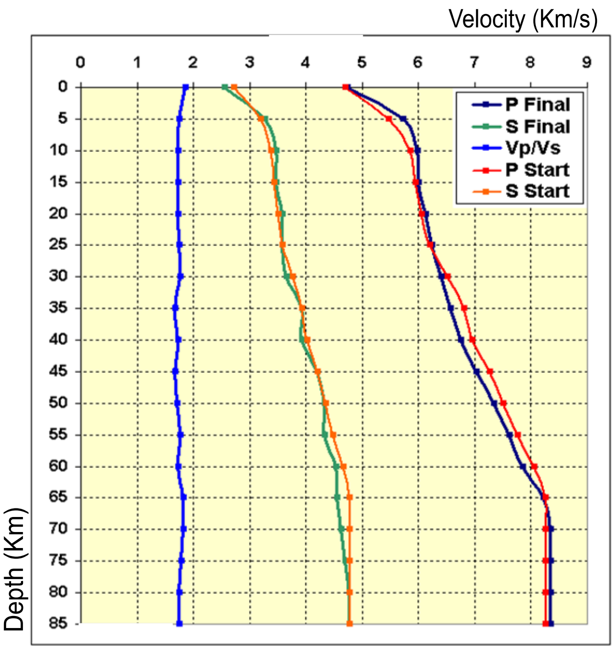

FIG. 8. Starting and final (bold) 1D P- and S-wave models with corresponding Vp/Vs ratio for Northen Albania. The P-velocity gradient increases in upper and middle crust and decreases in the lower crust (Zone 5).

EARTHQUAKE RELOCALIZATION IN ZONES DIVIDED BY DEEP FAULTS

There are systematic misallocations of the earthquakes in the Lushnje-Elbasan-Diber fault (between Zones 3.4, Fig. 2) and the Shkoder-Peje fault (between zones 4.5, Fig 2) due to strong lateral velocity contrast. The localization based on 1D velocity model, in the presence of velocity inhomogeneities, is systematically shifted towards the higher velocity zone (Manfred et al., 1992). The lateral velocity variation across Shkoder-Peje and Lushnje-Elbasan-Diber faults is as large as 3-9% in the crust and mantle, causing systematic misallocation and deviation of the fault location. Figure 9 shows schematically the apparent location of a vertically dipping fault, which separates two half-spaces with different wave propagation velocity $V_2 > V_1$. This is the case for a portion of the Shkoder-Peja fault where the lateral velocity variation becomes larger at depth 0-30 km (Fig. 10). Similarly, for the Lushnje-Elbasan-Dibra fault the lateral velocity variation becomes larger at depth 0-40 km (Fig. 11).

For stations S1 and S2 located at the same hypocentral distance from the events on the fault, since $V_2 > V_1$ the onset time t_2 at S2 is smaller than t_1 at S1. Running now the localization software and assuming a laterally homogeneous velocity model, the resulting hypocentral distances are $d_2(h) < d_1(h)$. The difference between the hypocentral distances increases with depth. Thus, the hypocenters are offset from the fault, defining a slightly inclined apparent fault (Borman et al., 2001).

In order to examine the effectiveness of this methodology in comparison with the routine earthquake localization, we applied Hypo71 on the whole re-picked data set using the computed minimum 1D models and station corrections.

Table 1 shows the average RMS of the P-wave arrivals. For the localization of earthquakes (period 2002-2006) we employed the:

1. Proposed velocity model and
2. The model by Muco et al. (2001).

This table shows that average RMS is smaller from the proposed model.

Table 1.

Model	*Average RMS (errors in s)*
Muco et al., 2001	*3.47*
Proposed Model	*0.78*

Figure 12 displays earthquake epicenters for the period 2002 – 2006, using two models. The relocated events exhibit reduced rms value (Table 1, proposed model). Larger residuals observed at stations more than 200 km from the epicentre are due mainly to phase picking or to lateral velocity variation.

The errors of the hypocentral distance for the relocated earthquakes are less than 4 km. The epicentral coordinates of the events are well resolved (error less than 3 km on average). Earthquake depths exhibit large errors, due to the sparse seismic network.

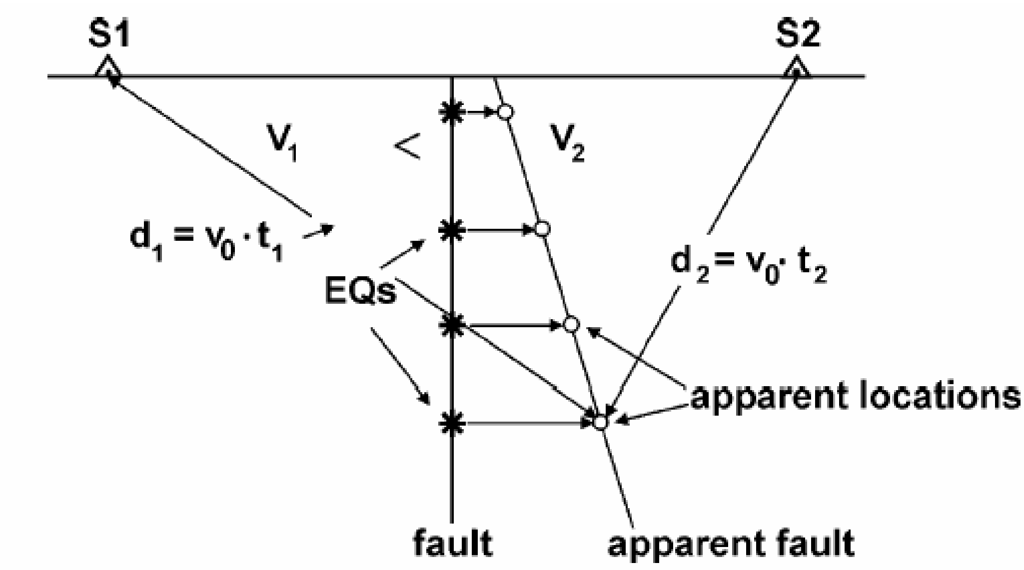

FIG. 9. Illustration of the systematic misallocation of earthquakes along a fault with strong lateral velocity contrast. The assumed model velocity is v_o with $V_2 > v_o > V_1$ (Borman, et al., 2001).

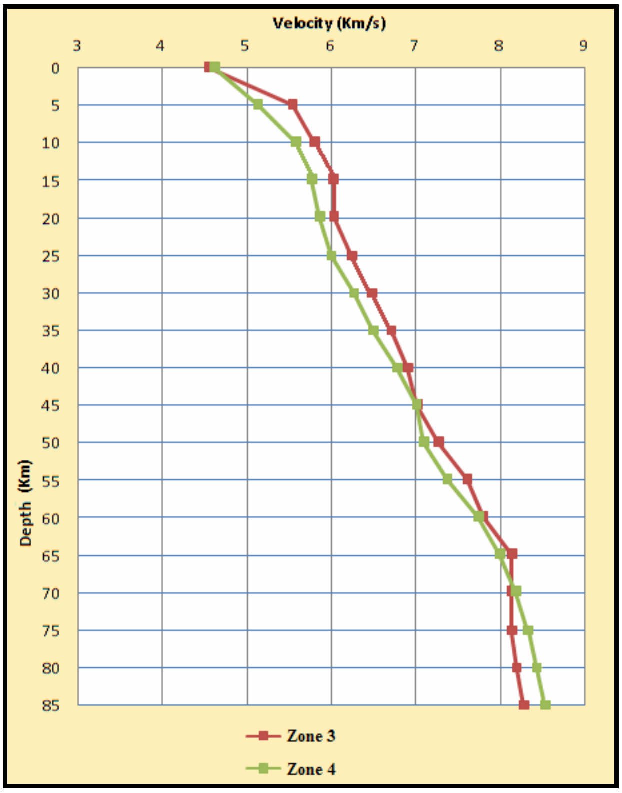

FIG. 10. Comparison of Vp models for Zones 3 and 4.

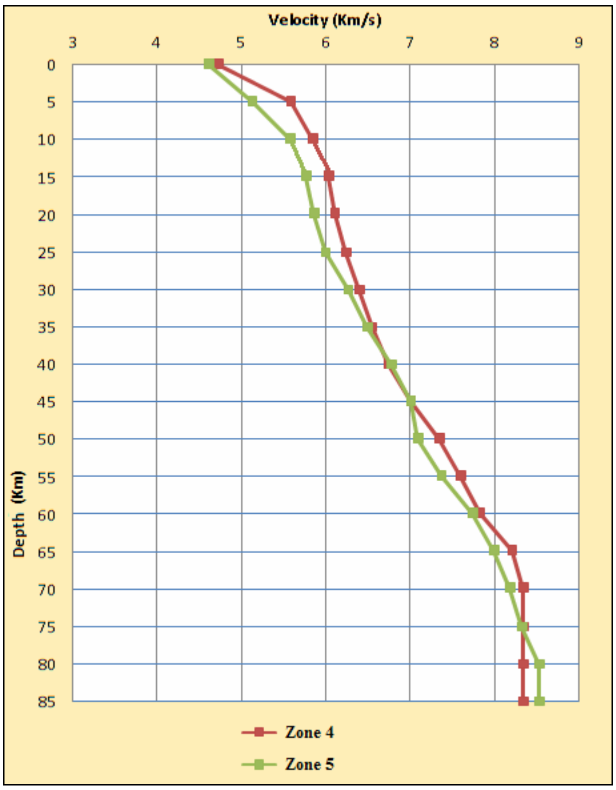

FIG. 11. Comparison of Vp models for Zones 4 and 5.

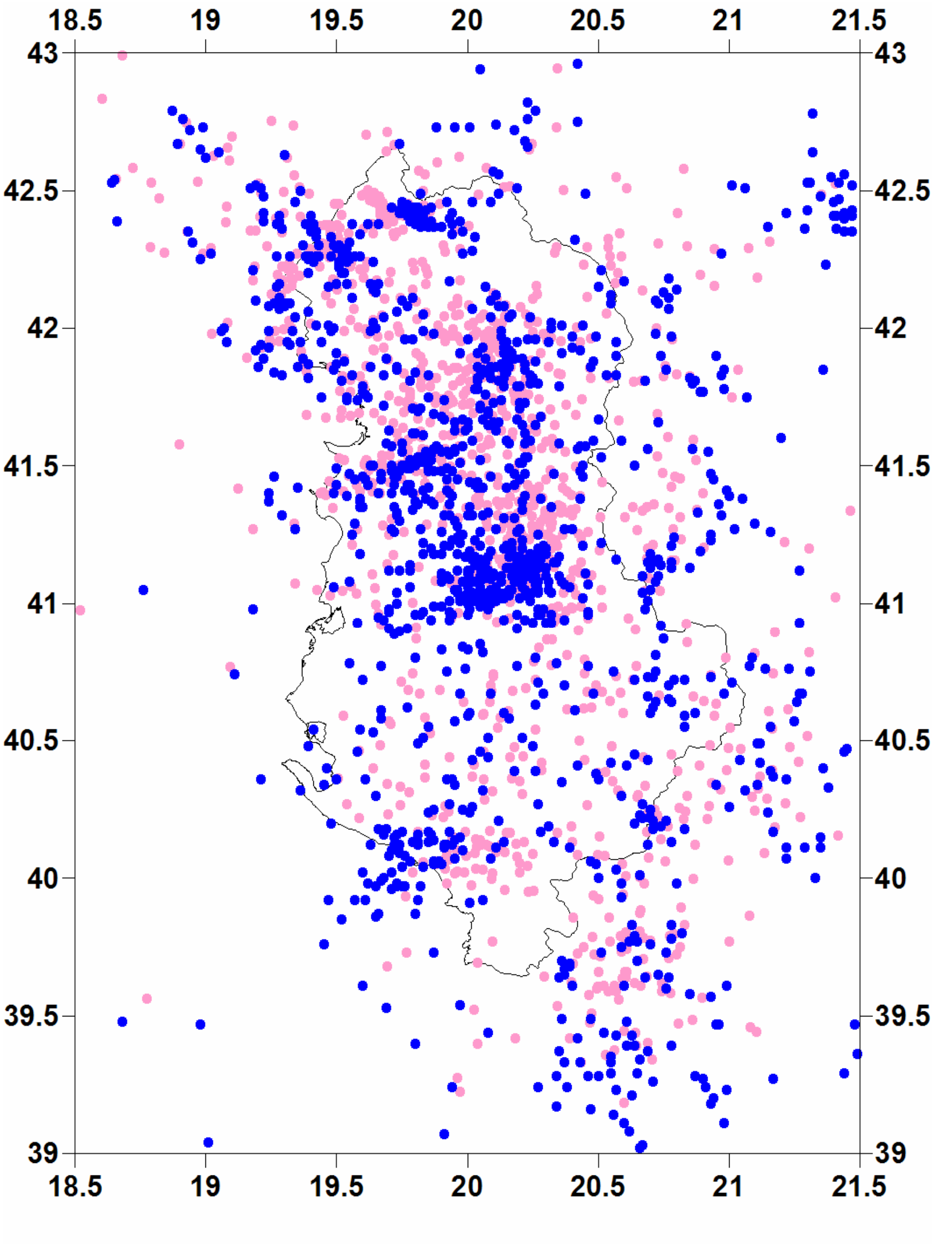

FIG. 12. The map compares earthquake epicenters 2002 - 2006 using two models.
● epicentres using Muço et al. (2001) model
● epicentres using the proposed model

Most earthquakes (about 92.6%, as shown in Fig. 2) occur in the upper and middle crust (hypocentral depth less than 25-30 km), defining the depth extent of the upper active seismic zone (Ormeni, 2007). However, a significant number of events occurs deeper in the crust and also below the Moho.

CONCLUSION

We calculated 1D velocity models for 5 zones in Albania. These models exhibit Vp=5.5 km/s in the upper crust and an increase to 6.0 km/s in the middle crust and to 6.8 km/s in the lower crust, produces a good fit of the P-wave arrivals. The P-wave velocity of about 7.5 km/s at 45 km depth is a feature that may be explained by a Moho depth greater than 45 km. The events occurred within the Albania in the past five years have been relocated using these models. The updated seismicity presents interesting patterns. While most of seismicity is confined within the upper crust, we note deep crustal and sub-crustal seismicity in the Western and Southern Albania. The comparison of the 1D velocity models for zones 3, 4, 5 shows that there are lateral velocity variations which indicate the deep structure of the Shkoder-Peja and Lushnja-Elbasan-Dibra active faults.

The lateral velocity difference across the Shkoder-Peje fault becomes larger at depths 0-30 km. The lateral velocity difference across the Lushnje-Elbasan-Diber fault becomes larger at depths 0-40 km. The lateral velocity difference across the fault Shkoder-Peje, Lushnje-Elbasan-Diber etc. is as large as 3-9% (0.18-0.35 km/s).

These results represent a first step towards more detailed seismotectonic analyses.

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