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Descending lithosphere slab beneath the Northwest Dinarides from teleseismic tomography

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ABSTRACT

The area of study covers the marginal zone between the Adriatic microplate (African plate) and the Pannonian segment (Eurasian plate). We present a tomography model for this area, with special emphasis on the northwest Dinarides. A dense distribution of temporary seismic stations in the area of the Northern Dinarides along with permanent seismic stations located in the area, allowed us to construct this P-wave tomographic model. We assembled our travel-time dataset based on 26 seismic stations were used to collect the dataset. Teleseismic events were recorded for a period of 18 months and a set of 76 distant earthquakes were used to calculate the P-wave travel-time residuals. We calculated relative rather than absolute arrival-time residuals in the inversion to obtain depths of 0–400 km.

We imaged a pronounced fast velocity anomaly below the NW Dinarides which directly indicates a lithosphere slab downgoing beneath the Dinarides. This fast anomaly extends towards the NW direction to at least 250 km depth, and we interpreted it as a descending lithosphere slab. The thrusting of the Adriatic microplate may be brought about by sub-lithosphere rising movement beneath the Pannonian region, along with a push from African plate. In our interpretation, the Adriatic lower lithosphere has been detached from the crust, and steeply sinks beneath the Dinarides. A lithosphere model of the contact between the Adriatic microplate and Pannonian tectonic segment was constructed based on the tomographic velocity model and results of previous crustal studies.

1. Introduction

The Dinarides which are located at the contact zone of the Adriatic microplate and European plate, play an important role in the regional tectonics. We used teleseismic tomography, a method which can greatly contribute to a better understanding of the lithospheric structure and its interaction with the asthenosphere, in particular of the subduction related mechanism. In general, it is known that in the active tectonic region, low-temperature continental slab downgoing in the upper mantle are characterized by high seismic velocities, whereas the upwelling areas cause thinning of the upper mantle's top portion and the Earth's crust, and show low seismic velocities. Thus, in this particular study, teleseismic tomography was applied to offer a more reliable definition of present, active processes.

A subduction model for this contact region of the Dinarides and the Pannonian basin has been considered (Herak, 1986; Moretti and Royden, 1988) as a marginal zone of the Adriatic microplate and the Pannonian segment of the Eurasian plate. In such a model, the most common evidence is taken to be the geological development and magmatic activity in the area. It has been reported that initial subduction processes started in the Late Jurassic – Early Cretaceous periods, and was accompanied by ophiolite obduction (Tari and Pamić, 1998). This was followed by a strong compressive stress which occurred during the Eocene and the Oligocene periods, and resulted in the rising of the Dinarides and the termination of the subduction processes. The final stage of subduction is characterized also by sedimentary, magmatic and metamorphic formations of northern Bosnian Mountains, Pamić (1993).

If we consider the present situation, it is very doubtful whether a classic subduction occurred. Classic subduction is typically accompanied by a series of processes, where magmatic and deep seismic activities along a downwelling of a lithosphere slab are frequent. In the Dinarides, however, magmatism is not present, and most earthquakes are concentrated in the Earth's crust (Kuk et al., 2000). This may indicate that the slab collision model implies underthrusting of the Adriatic microplate underneath the Pannonian segment. Some models published recently apply the concept of escape tectonics to explain the incorporation of the Alpine and Dinaridic units within

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the Western Carpathians. These models considered absence of a lithosphere slab descending underneath the northwestern Dinarides (Brückl et al., 2007; Ustaszewski et al., 2008).

For studying the geological evolution of the Dinarides, there is a question of whether only one subduction should be considered (Tari and Pamić, 1998), or whether there are two subduction regimes, either interdependent or unrelated. In the case of two subductions, the first probably occurred in the Late Jurassic and Early Cretaceous periods and the second in the Late Cretaceous and Tertiary periods. The impact of the first subduction was probably neutralized by the upwelling in the Pannonian basin, as reported by the Sava ophiolite zone, which Pamić et al. (2002) considered the western part of the Vardar Zone ophiolites, whereas the impact of the second subduction might be related to the Dinaridic mountain range.

Despite several previous studies regarding these regions, where some include teleseismic data, both globally (Bijwaard and Spakman, 2000; Zhao et al., 2013) and regionally (Piromallo and Morrelli, 2003; Koulakov et al., 2009; Mitterbauer et al., 2011; Dando et al., 2011; Zhu et al., 2012), there was lack of information regarding the relationship between the subducting slabs beneath the study area. In these papers a shallow fast anomaly underneath the central and southern Dinarides was clearly imaged. However, the existence of a fast anomaly underneath the northwestern Dinarides could not be determined. For this reason, Mitterbauer et al. (2011), based on their own results and those obtained by Koulakov et al. (2009), interpreted that the "shallow slab" was limited to latitudes below 45° underneath the Dinarides, with no further extension towards the North. Thus, many regional tectonic maps were developed on the basis of these previous tomographic results (Handy et al., 2014; Ustaszewski et al., 2008; etc.). Consequently, this also affected other studies and models interpreting the geological history of this area. However, some of those previous teleseismic investigations were limited to the boundary areas of this region, which have a significantly lower data coverage and lower resolution (Mitterbauer et al., 2011; Dando et al., 2011). Others conducted sparse spatial data sampling which possibly resulted in smearing of any anomalies used as the basis for the conclusions about the relationships between the slabs (Koulakov et al., 2009Piromallo and Morrelli, 2003).

In this study we focus on the northwestern Dinarides and their contact with the Pannonian basin. Available Croatian permanent seismic stations were used together with temporary stations within the ALPASS-DIPS project to achieve satisfactory spatial sampling. The primary objective of the investigation was to construct a new velocity model by teleseismic tomography, which is used in conjunction with crustal structure information from previous studies. We believe that this approach provides a more reliable model of the collision between the Adriatic microplate of the African plate and the Pannonian segment of the Eurasian plate. Our tectonic model provides new insights into the dynamic relationship between lithosphere slabs, i.e. the downwelling of the Adriatic mantle lithosphere in the area of the northwestern Dinarides.

2. The study area and regional geological setting

The study area covers a contact zone of the Pannonian segment and the Adriatic microplate (Fig. 1). It is located in the marginal zone between the African and Eurasian plates that includes the Dinarides and the Pannonian basin, thereby encompassing several different geotectonic units. There are two ophiolite zones towards the Pannonian basin, the Dinaridic and Sava zones that are actually suture zones between the Adriatic microplate and European plate. The ophiolites of these two zones differ in their origin, structure and age (Pamić et al., 2002). The study area was bounded to the southwest segment of the Tisza block in the Pannonian basin. The Mid-Hungarian zone (MHZ) is considered to be boundary of the Tisza block, as a part of Eurasian plate, and the Alcapa, as a part of the African plate.

The Dinarides, which stretch about 700 km, merge with the Southern Alps in the northwest, and the Hellenides in the southeast. Mesozoic carbonates are dominant in the Dinarides. Outcrops of Paleozoic and older rocks can be found in this area as well. Paleogene rocks (carbonates, clastics and flysch layers) can be also found, particularly in the coastal part of the Adriatic, but also in some inland karst fields (Geologic Map of SFRY, 1970).

There are two significant reverse faults in coastal region of the Dinarides: the Ćićarija fault (CF; Fig. 1), and the Velebit fault (VF), that are located at the front of the Adriatic collision. The Ćićarija fault is found at the edge of the Dinarides whose location can be very well defined in the mainland, but not further to the south, in the Adriatic Sea.

The Pannonian basin is characterized by extending structures (Posgay et al., 1995). The Pannonian basin and its origin are most frequently considered in relation to the Carpathian range in terms of a "back-arc" basin (Stegena et al., 1975; Royden et al., 1983). However, marginal areas of the southern Pannonian basin are influenced by events in the Dinarides (Pamić, 1998; Tari and Pamić, 1998). Several previous works dealt with the concept of "escape tectonics" in the geodynamic modelling of the Pannonian basin, which was suggested to explain the transport mechanism of Alpean fragments included in the north Pannonian basin and the Internal Carpathians (Kazmer and Kovacs, 1985; Ratschbacher et al., 1991; Csontos et al., 1992; Csontos and Vörös, 2004). This concept discussed the crustal structure of Eastern Alps and the surrounding regions (Brückl et al., 2007, 2010).

Neogene and Quaternary sediments are predominant in the southwest part of the Pannonian basin. There are depressions filled with Neogene deposits that vary in their dimensions and depths, but also several mountains in the investigated part of the Pannonian basin, which consist of Paleozoic-Mesozoic rocks.

3. Previous geophysical investigations

A Gravity map of Yugoslavia (1972) which includes the study area was developed in the 1950′s at a scale of 1:500,000. Bouguer corrections were performed with a density of 2.67 g cm^{-3} (Bilibajkić et al., 1979). The lowest gravity in the study area stretches in a NW to SE direction below the Dinarides; therefore the deepest Mohorovičić discontinuity, "the Moho" (Mohorovičić, 1910), could be expected there (Fig. 2). Using these data, gravity modelling was carried out by Šumanovac (2010,2015) and has provided new information about the structure of the crust and lithospheric mantle.

A deep seismic sounding (DSS method), using refraction surveying, was performed in a framework of deep lithosphere research for the study area covered. Two basic discontinuities were mapped; the Mohorovičić discontinuity and the basement beneath the sedimentary cover. The results were published in many publications: Dragašević and Andrić (1968), Andrić and Zeljko (1971), Joksović and Andrić (1982, 1983), and Skoko et al. (1987). They mapped the greatest Moho depths beneath the Dinarides (40–48 km) and the lowest depths beneath the Adriatic and the Pannonian basin (22 km).

A new geophysical exploration was commenced, with a seismically controlled source experiment ALP 2002, "Seismic Exploration of the Alpine Lithosphere" (Brückl et al., 2003, 2007; Šumanovac et al., 2009), which covered the areas of the Eastern Alps, the northwestern Dinarides, the eastern part of the Pannonian basin and western part of the Bohemian massif. The longest profiles in the