

Abstract

In the paper we discuss the problem of continental collision and related volcanism in the Caucasus and surrounding areas based on analysis of the upper mantle seismic structure in a recently derived model by Koulakov (2011). This model, which includes P- and S-velocity anomalies down to 1000 km depth, was obtained from tomographic inversion of worldwide travel time data from the catalogue of the International Seismological Center. It can be seen that the Caucasus region is squeezed between two continental plates, Arabian to the south and European to the north, which are displayed in the tomographic model as high-velocity bodies down to about 200–250 km depth. On the contrary, a very bright low-velocity anomaly beneath the collision area implies that the lithosphere in this zone is very thin, which is also supported by strong deformations indicating weak properties of the lithosphere. In the contact between stable continental and collision zones we observe a rather complex alternation of seismic anomalies having the shapes of sinking drops. We propose that the convergence process causes crustal thickening and transformation of the lower crust material into the dense eclogite. When achieving a critical mass, the dense eclogitic drops trigger detachment of the mantle lithosphere and its delamination. The observed high-velocity bodies in the upper mantle may indicate the parts of the descending mantle lithosphere which were detached from the edges of the continental lithosphere plates. Very thin or even absent mantle part of the lithosphere leads to the presence of hot asthenosphere just below the crust. The crustal shortening and eclogitization of the lower crustal layer leads to the dominantly felsic composition of the crust which is favorable for the upward heat transport from the mantle. This, and also the factor of frictional heating, may cause to the origin of volcanic centers in the Caucasus and surrounding collisional areas.

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1 Introduction

Caucasus is a part of the Alpine-Himalayan orogenic belt which is the largest continental collision zone in the world. In the Caucasus segment of the belt, the collision occurs due to convergence of the Arabian and European continental plates in a zone located between two basins of presumably oceanic nature, Black Sea and South Caucasian Plate (Fig. 1). This collision determines active recent tectonic processes manifested in intensive mountain building, seismicity and Cenozoic volcanism. High level of seismic hazard in this densely populated region is one of the main reasons for vital interest to the tectonics of this region.

Mechanism of continental collision is presently not completely understood and it is actively discussed by specialists in different domains of geosciences. Considering most examples of continental collision (e.g. Dewey et al., 1986), one can see that convergence of continental blocks causes considerable crustal thickening which is roughly proportional to the value of shortening. At the same time, the fate of the lithosphere beneath the continental belts remains a disputable topic. While doubling the crust, the collision hardly results at thickening of the lithosphere: strong thick lithosphere would make impossible the observed active deformations in orogenic belts. Active mountain building and strong deformations imply that the lithosphere in the collision zones is weak, and this means that a part of the mantle lithosphere disappears. However the details of the mantle lithosphere recycling are still not well understood. Is it subducted to the mantle similarly as in cases of oceanic subduction or sink in another way? These questions are actively discussed in the scientific community. Seismic tomography, which allows imaging the structures at great depths, is one of the most powerful tools to clarify these and other geodynamical questions.

Deep seismic structure beneath the Caucasus region has been investigated in many geophysical studies, mainly using seismic tomography. Mantle structure beneath Caucasus and the surrounding areas has been studied using global and regional seismic modeling based on travel times of body waves (e.g. Neprochnov et al., 1970; Hearn

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and Ni, 1994; Al-Lazki et al., 2004; Gök et al., 2003), surface waves (e.g. Maggi and Priestley, 2005; Sandvol et al., 2001; Villasenor et al., 2001) and seismic attenuation (Sarker and Abers, 1998). Most of the studies display generally consistent features in the lithosphere depth intervals (50–250 km) with higher seismic velocities in areas corresponding to the continental blocks and low velocities beneath the folded belt. Here we base our discussion on a recent seismic model of Asia by Koulakov (2011) which enables higher frequency features compared to most of previously published regional and global tomographic studies. In order to verify several issues and to check the reliability of the proposed geodynamical scenario, in this study we provide additional synthetic tests oriented specially to the target region. Based on considering the tomographic model by Koulakov (2011) we will provide our answers to the following two questions:

1. What happens to the mantle part of the continental lithosphere during the continent-continent collision in Caucasus?
2. What is the nature of the active Cenozoic volcanism in Caucasus and surrounding areas?

2 Geodynamics and volcanism of Caucasus and surrounding areas

The geological evolution of the Caucasian region (Fig. 1) mostly controlled by convergence of Eurasian and Africa-Arabian continental lithosphere plates. According to geodetic data, the total rate of the convergence is $\sim 20\text{--}30 \text{ mm y}^{-1}$ (e.g. DeMets et al., 1990). More detailed analysis of regional deformations shows that about 60 % of this rate is taken by the Lesser Caucasian suture, and the rest is accommodated in crustal shortening in the Southern Caucasus (Allen et al., 2004; Forte et al., 2010).

Pre-Cenozoic evolution of this area was connected with closing of the Tethys Ocean between Eurasian and Gondwana continental parts (e.g. Khain, 1975; Adamia, 1975; Adamia et al., 2008; Zakariadze et al., 2007). Convergence of the ocean with continents during the Late Proterozoic–Early Cenozoic pre-collisional stage resulted at

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important in the case of using the ISC data which contain strong noise. To extract a coherent signal, one should apply strong damping which reduces the amplitudes of retrieved heterogeneities. It can be seen, for example, that in the presented results, the amplitudes of P-anomalies are stronger in shallow layers than those of the S-anomalies, and this can be explained by stronger noise level in S-data and, correspondingly, higher damping used in inversion. In most cases, true amplitudes cannot be achieved, as the reducing of damping causes the inversion instability. This is a fundamental problem which is actual not only for the model considered here, but for any tomographic studies. This should be taken into account when interpreting these results on a quantitative level, and especially, when converting P- and S-velocities into petrophysical parameters (temperature, composition, density etc). One of the approaches to estimate the realistic amplitudes of heterogeneities is synthetic modeling simulating realistic patterns, noise level and the main workflow used for real data processing. Comparison of the initial and recovered structures gives an idea about reduction of anomalies due to damping.

The model by Koulakov (2011) has been verified using many different tests. For example, the contribution of the random noise in the data was estimated based on the “odd/even” test with independent inversions of two data subsets with odd and even numbers of events. The spatial resolution was evaluated using several checkerboard tests with different sizes of patterns. In order to ground the approach with inversions in overlapping windows, the synthetic modeling was performed using a model with realistic shapes of structures. The travel times for this test were computed in the entire area, whereas the inversion was performed in separate windows.

Here we provide some additional tests. In Fig. 6 we present a checkerboard modeling with the size of anomalies of $2^\circ \times 1.5^\circ \times 300$ km for the P-model and $3 \times 2.5 \times 300$ km for the S-model, which is smaller than in Koulakov (2011). It can be seen that for the most parts of the area these anomalies are robustly resolved. Another test shown in Fig. 7 consists in recovering of a model with realistic shapes of anomalies defined in vertical Sect. 2. In general, the shapes of all features are correctly reconstructed. However,

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at greater depths, where amount of rays is much lower, the resolution of recovering is much poorer, the amplitudes of anomalies are much weaker than in the “true” model and they are strongly smeared, especially for the S-model. This should be taken into account while constructing a geodynamical interpretation.

4 Discussion

In shallower depth sections down to 220 km depth we can clearly observe higher P- and S-velocities associated to the south with the Arabian plate and to the north with the European plate which consists of several microplates in the contact zone, such as Scythian and Turan plates. Lower seismic velocities are observed beneath the collision zone in the areas of the major mountain belts. P- and S-models display generally consistent structures; however the amplitude of P-anomalies in the shallower sections is considerably higher. However, as was discussed in the previous section, this reflects rather the damping issues that the real relationships of amplitudes. It can be seen that all recent volcanic centers exactly fit to the low-velocity patterns of P- and S-anomalies in shallower sections.

In vertical sections, we can see that the thickness of high-velocity layers related to the Arabian and European lithospheric plates is about 250 km which is consistent to general knowledge on the continental lithosphere thickness (e.g. Artemieva, 2003). In the transition zones between high-velocities in continental blocks and low-velocities in collisional belt, the structure of anomalies is rather complex with alternating high- and low-velocity anomalies. It can be seen that high-velocity anomalies form drop-shaped bodies which seem to sink to greater depth mantle. Taking into account the results of synthetic test with vertical anomalies in Fig. 7, we can propose that the real data inversion smears and reduces the amplitudes of anomalies at greater depths. Thus, the true amplitudes of anomalies in these drops might be stronger than observed after inversion of real data.

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The obtained results allow us proposing mechanisms of the lithosphere recycling due to collision and origin of volcanism illustrated in Fig. 8. It can be seen that the Arabian and Eurasian parts are represented by approximately similar lithosphere type of about 200–250 km thick. It can be proposed that the lithosphere of these plates have the standard continental type structure which includes upper felsic (granite) and lower mafic (basaltic) crustal layers and a rigid mantle layer which dominates in total strength of the lithosphere (e.g. Burov and Diament, 1995). When the plates collide, the crust thickens in the shortening areas between these plates. In this case, the lower mafic crustal layer appears at greater depth. Temperature and pressure increase lead to phase transformation of the mafic layer into denser eclogite (e.g. Sobolev et al., 2006). The drops of eclogite are united into larger bodies which, after reaching a critical mass, descend to the mantle. These changes in the lower crust may lead to detachment of the gravitationally unstable mantle lithosphere. The presence of dense eclogite drops may trigger the lithosphere detachment and accelerate sinking of separate pieces of the lithosphere as shown in Fig. 8. As proposed by Burov and Watt (2006), this may lead to the “crème-brûlé” behavior of the mantle lithosphere in the collision zone instead of “jelly sandwich” rheology which is characteristic for non-deformed continental lithosphere. This process abruptly decreases the total strength of the lithosphere and leads to its fast degradation through active delamination (e.g. Kay and Kay, 1993). According to this hypothesis, the mantle lithosphere at the edges of the collided continental plates should be gradually destroyed and delaminate together with dense eclogite produced in the lower crust. These sinking drops are probably visible as high-velocity bodies in vertical sections of our seismic model beneath the edges of the Arabian and European continental parts and beneath the collision zone.

After detachment of the mantle lithosphere, it is replaced by hot asthenosphere which may appear directly beneath the crust. Note that the crust in the collision zone is mostly composed of thick felsic rocks, whereas the lower mafic crust was transformed to eclogite and sank together with the mantle lithosphere. The existence of thick felsic crust is supported by the observed very low velocities in the collision zone at 50 km depth,

however in practice it is observed in a limited number of regions. This might be explained by a hypothesis that the collisional type of volcanism occurs only under the condition of complete detachment of the mantle lithosphere which is realized not in all cases of continental collision. However, this topic needs additional investigations based on thermo-mechanical modeling and analysis of geological data in different collisional belts.

Acknowledgements. This study is supported by the Multidisciplinary Projects SB RAS #76 (discussion on collision) and Project ONZ RAS #7.3 (part of the volcanism).

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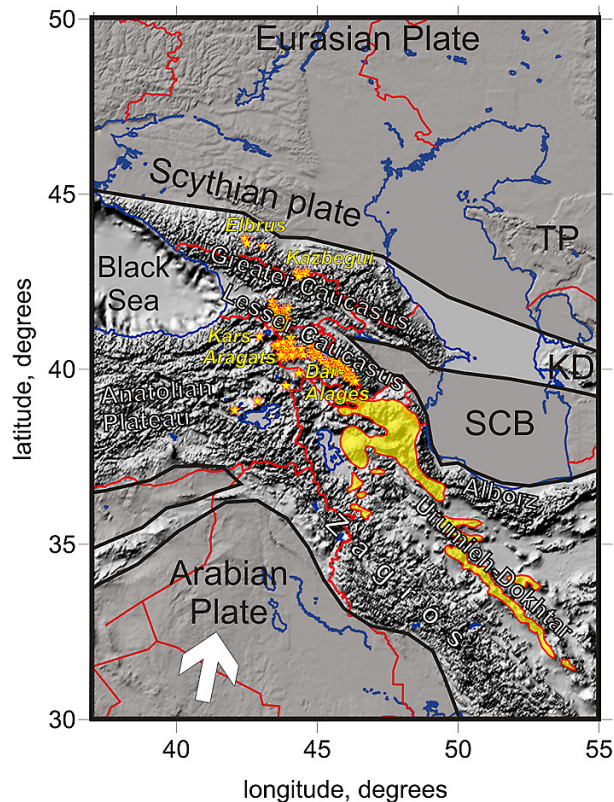


Fig. 1. Main tectonic units in Caucasus and surrounding areas overlaid on a shaded relief map. Yellow stars depict the recent volcanoes in Caucasus (Adamia et al., 2011). Major volcanoes are named with yellow characters. Areas of Cenozoic volcanism in Iran compiled from Nezafati (2006), Verdel et al. (2007) are marked with yellow. TP is Turan Plate; KD is Kopeth-Dagh; SCB is South Caspian Basin. White arrow marks the direction of the Arabian Plate displacement.

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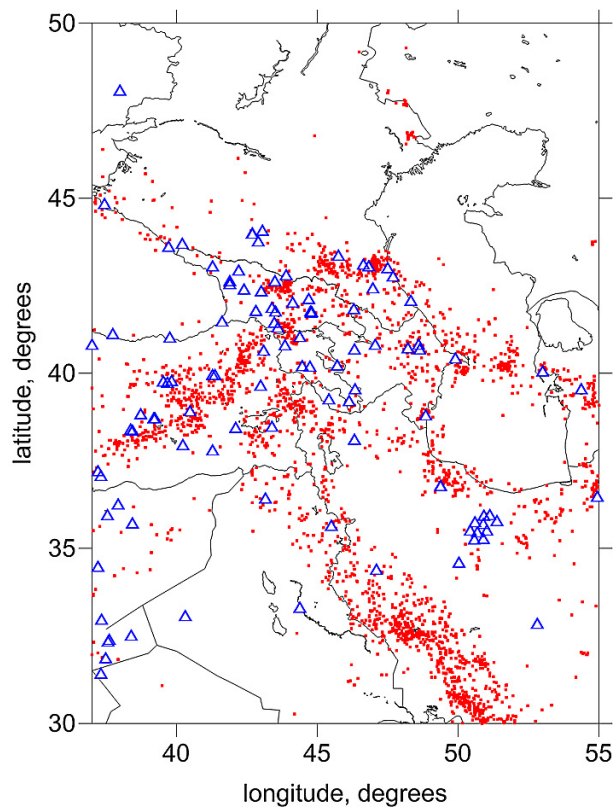


Fig. 2. Distribution of data from the ISC catalogue: triangles depict stations, red dots are the events.

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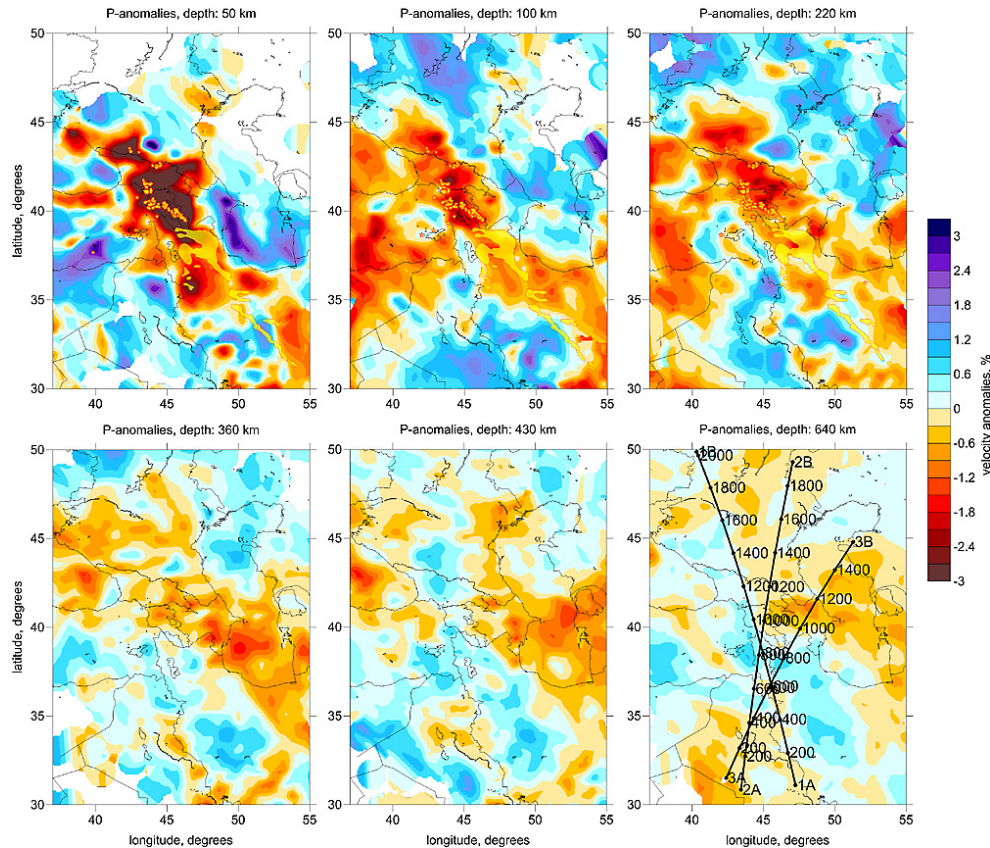


Fig. 3. P-velocity anomalies in six horizontal sections, yellow dots mark the locations of recent volcanoes in Caucasus.

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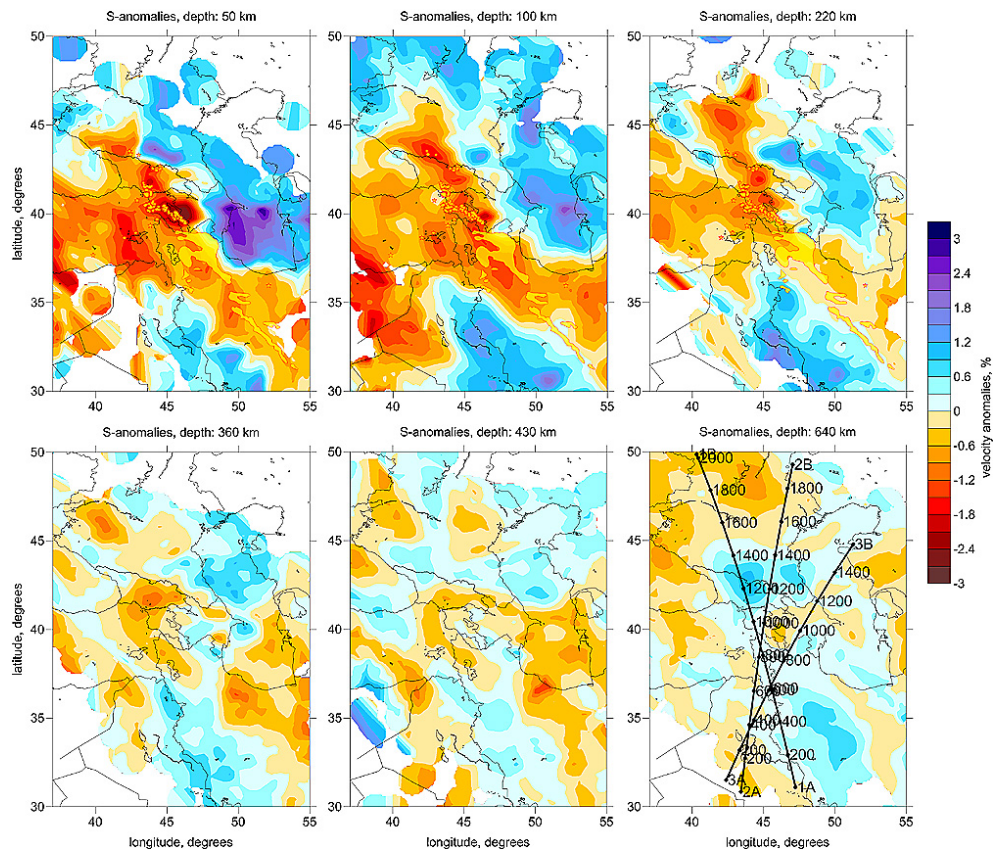


Fig. 4. Same as Fig. 3, but for the S-velocity anomalies.



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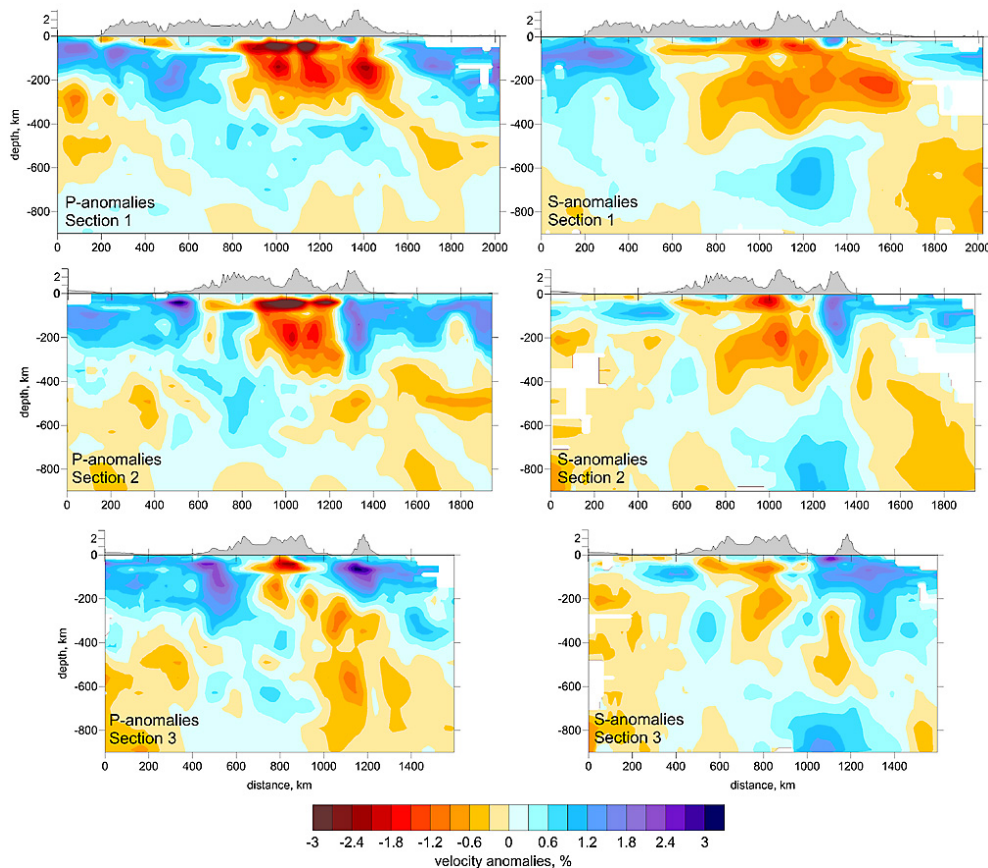


Fig. 5. P- and S-velocity anomalies in three vertical sections. The locations of the profiles are shown in maps in Figs. 3 and 4. Relief along the profile is shown above each plot.

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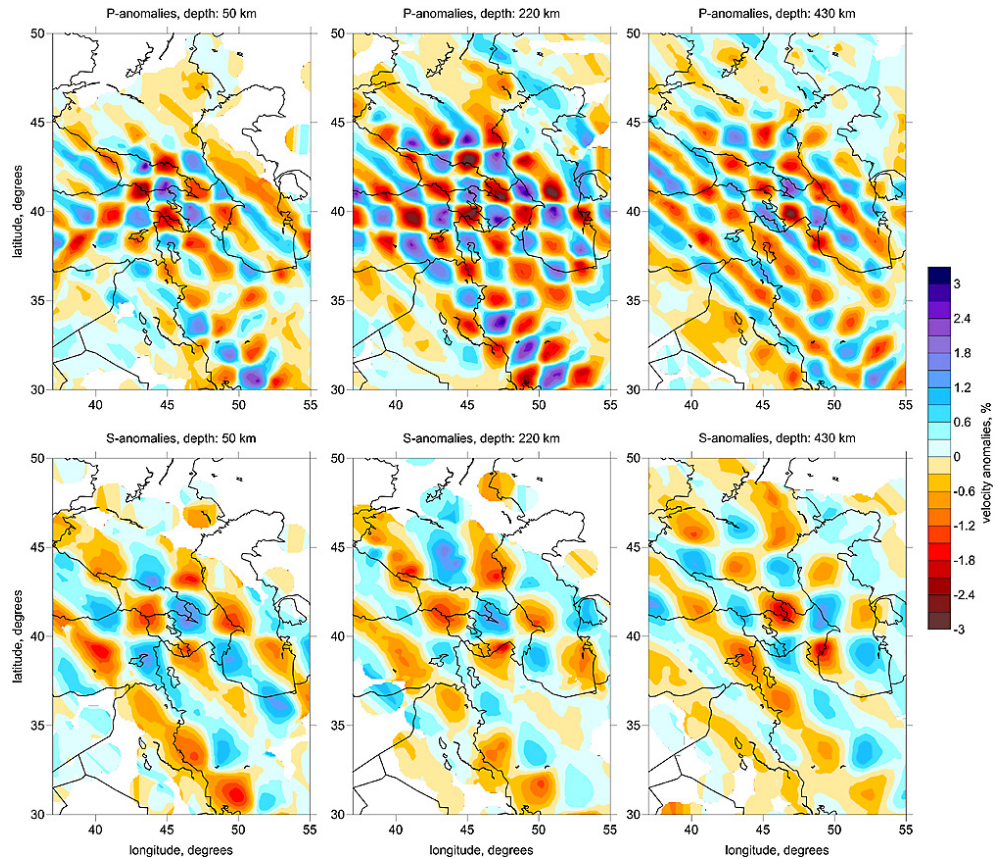


Fig. 6. Checkerboard test for P- and S-models in three horizontal sections. The sizes of synthetic anomalies are $2^\circ \times 1.5^\circ \times 300$ km for the P-model and $3 \times 2.5 \times 300$ km for the S-model.

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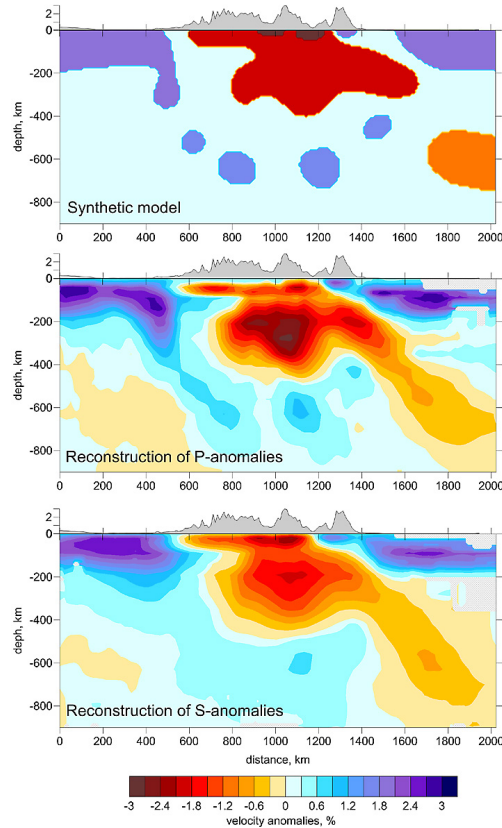


Fig. 7. Synthetic test with realistic patterns defined in a vertical Sect. 2, same as indicated in Fig. 5. Upper plot shows the configuration of the synthetic model; middle and lower plots are the reconstruction results for the P- and S-anomalies.

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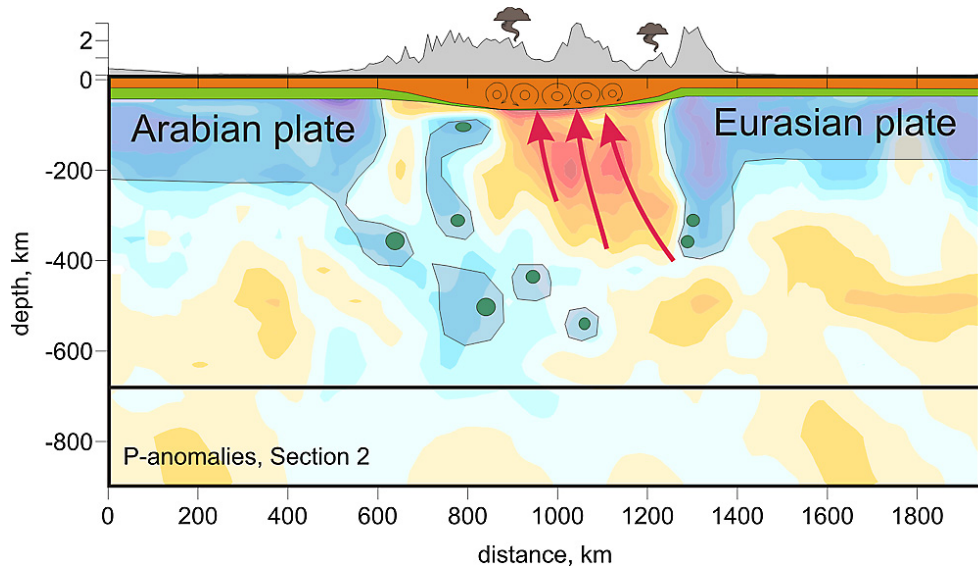


Fig. 8. Schematic representation of the delamination mechanism in the Caucasus region. The crust is composed of the upper felsic (orange) and lower mafic (green) parts. Blue areas indicate the mantle parts of the lithosphere. Background is the distribution of P-velocity anomalies in vertical Sect. 2, same as in Fig. 5. Relief along the profile is shown above the plot. Green ellipses schematically mark the possible locations of the eclogite drops which were transformed from the lower mafic crust in the shortening zone. Red arrows mark the asthenosphere upwelling.

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