To the editorial board of Solid Earth
Manuscript se-2012-18
by I.Koulakov et al.,
Nature of orogenesis and volcanism in the Caucasus region based on results of regional tomography

Dear Editor,
Dear Reviewers,

We are very grateful for your friendly and constructive comments. We took into consideration most of them which required considerable work to be done including some new calculations. In particular, as the problem of the resolution caused a lot of remarks of both reviewers, we have added two tests: one with a finer checkerboard (Figure 6) and another one with exploring the effect of vertical smearing of crustal anomalies (Figure 7). We have also done additional work on the literature search, as suggested by the reviewers. As a result, we find that the comments of the reviewers helped us to improve the paper.

We would be grateful if you further consider our corrected paper for publishing at Solid Earth.

The detailed answers to the comments of reviewers are given in the rebuttal letter. All the corrected parts in the manuscript are highlighted with red.

Best regards,

Ivan Koulakov, on behalf of the coauthors
10 of September, 2012
Novosibirsk, Tbilisi

Rebuttal letter on the paper by Ivan Koulakov, Irina Zabelina, Iason Amanatashvili, and Vladimer Meskhia "Nature of orogenesis and volcanism in the Caucasus region based on results of regional tomography"

All the author's answers are given in red and marked with "REP".

Anonymous Referee #1

The paper presents interpretation of a Caucasian part of the recently published seismic tomography model of Asia. Key features of the model are low P- and S-velocity anomalies in the crust and upper mantle below the highest mountains and volcanic centers. Based on this model authors suggest that mantle lithosphere and mafic lower crust beneath mountain ranges was delaminated, what in turn caused magmatic activity and heating of the crust. I'll attempt answering two major questions related to this paper. (1) How robust is seismological model? (2) How robust and innovative is its geodynamic interpretation?

(1) I think that the major features of the model that are high velocities related to Arabian and Eurasian plates and low velocities below highest mountains are quite robust. These features are visible in both P- and S- models and synthetic tests show that largescale features can be indeed resolved by the model. Correlation of lowest velocities and volcanoes also looks quite convincing.

To be on the safe side I would still check (by synthetic tests) if thick crust below the high mountains and very low velocities in the crust below young volcanoes could be smeared down to the mantle, thus significantly contributing to the observed low-velocity anomalies.

REP 1: We have performed a test exactly according to this suggestion (see Figure 7B). We can see that the inversion clearly resolves the bottom of the "low-velocity crust" and does not cause any vertical smearing. (see also Lines 215-222).

I'm not entirety convinced that smaller features of the tomographic model (like high Pwave velocity body at 800 km of Section 2 at depth 50-200 km, Fig. 5, that is interpreted as active delamination pattern in Fig. 8) are robust. This particular body is not so clear evident in the S-wave model. Moreover it is located right below the gap in the seismic network. To my opinion that feature may be or may be not real.

REP 2: In the new version we are more careful when describing these features. We honestly state that "*However, 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*".

Anyway, because of its possible importance for geodynamic interpretation this particular region deserves higher resolution seismic study.

REP 3: There are some new stations deployed in this area, a hopefully new data will appear soon. At the same time, when considering stations only in Caucasus, one cannot expect high resolution in the deep mantle. Regional earthquake data will only give the information on the crust and uppermost mantle. On the other hand, teleseismic data will not provide good vertical resolution. Thus, it is not obvious to us that new regional networks will significantly improve the mantle images provided by global data.

(2) I think that most reasonable interpretation of the robust features of the presented tomographic model and volcanic activity in the region is indeed delamination of the mantle lithosphere and mafic lower crust followed by the heating of the remaining felsic crust. So I support interpretation suggested by the authors. However, exactly the same process (tectonic shortening–crustal thickening–eclogitization of the lower crust that triggers delamination of the mantle lithosphere) was previously suggested based on petrological arguments (Kay and Kay, Tectonophysics 1993) and modeled (Sobolev and Babeyko, Geology 2005) for Central Andes. Rate of this process was analyzed by Jull and Kelemen (JGR 2001). I think that authors should clearly indicate that their interpretation is identical to that previously suggested for another orogen (Andes) and confirmed by geodynamic modeling. Actually this statement will even add credibility to their interpretation.

REP 4: In the new version we have accentuated the importance of previous studies on Andes for the Caucasian case (see Lines 267-271). All the mentioned references have been included

In general I think that this is an interesting paper, suggesting a reasonable geodynamic interpretation of the interesting seismological model for Caucasian orogen. However, authors should not interpret details of their model without thorough analyses of their robustness and they should clearly indicate that the geodynamic interpretation they suggest is not new but has been previously discussed in details in relation to central Andes.

Some minor issues: English should be improved. Show paper to the English native speaker.

REP 5: Unfortunately we did not find an appropriate person who could spend hours of his working time on editing our paper.

Page 648, line 17. Lithospheric thickness of 250 km should be typical for Archean cratonic lithosphere but not for the Arabian plate. Such thickness in your model is likely due to the vertical smearing.

REP 6: In the corrected version we are more careful about this (see Lines 235-238).

Page 650, line 3. I guess authors actually mean paper by Babeyko et al (EPSL 2002) discussing possible convection in the thick continental crust.

REP 7: This reference is included

Anonymous Referee #2

Received and published: 14 August 2012

The study addresses a topic of wide interest and it is of potentially great significance for better understanding Caucasian orogeny. The authors interpret a selected part of seismic tomography results obtained in another study and reported by the first author in another paper (Koulakov 2011, JGR).

The specific problems tackled by the study and reported in the manucript are nicely listed at the end of the introduction and regard the evolution of the „mantle part of the continental lithosphere during continent-continent-collision“ and „the nature of the active Cenozoic volcanism“ in the region. I appreciate chapter 2 as a good summary introduction to the „geodynamics and volcanism of Caucasus and surrounding areas“.

The chapter concludes with the sentence: „In this paper we will provide additional arguments for“ lithosphere delamination causing the Late Miocene-Quaternary volcanism „based on recent tomographic images of the upper mantle“. The problems I see with the manuscript result from the fact that, unfortunately, the seismic tomography images are obviously not of the requested resolution to address these questions. The authors are actually documenting this in Figures 6 and 7 with a checkerboard and with synthetic data testing.

REP 8: We agree with the reviewer that the resolution is not very high. At the same time, in the new version we present a checkerboard text with fine grid which shows that for some areas (which are the most interesting for us) we can resolve patterns of 100 km size and probably even smaller. We cannot expect much higher resolution for the mantle in cases of using alternative data sources and algorithms (for example in teleseismic or surface-wave studies).

In the region of interest, at best, the seismic data is able to resolve structure with dimensions of 150km*150km*150km and at least 3% average velocity variation. This should not come as surprise since similar resolution has been documented by various earlier studies for the ISC data set (e.g. Bijward & Spakman; Piromallo & Morelli). Such resolution, however, is insufficient to address questions of volcanism and even to address questions regarding the mantle lithosphere in the continent-continent collision zone. Note that the tomographic cross sections presented in Figure 5 exhibit minimum low velocity anomalies (-3%) in the depth range of the crustal root directly underlain (coinciding in lateral extent, hinting at a possible vertical leakage problem) by a large volume of relatively low velocity (-1.5%).

REP 9: Figure 7 shows that the problem of vertical leakage is not as strong as suggested by the reviewer.

Taking into account the significance level for the tomographic images –estimated by the reviewer as approximately +/- 1% based on synthetic test Figure 7- the two continental lithospheres involved in the collision are only in patches resolved outside the 400km to 600km wide collision zone.

In conclusion, the presented tomographic images could be interpreted (1) as documenting no mantle lithosphere at all beneath the Caucasus region and a mountain crustal root resting directly atop the asthenosphere upwelling.

REP 10: OK, in the new version of the paper we try to be more careful to avoid any overinterpretation

Alternatively (2), I would prefer to see additional local seismic data to be included in the tomography study Koulakov (2011) to significantly improve resolution and reliability of tomographic results before addressing the important questions raised in this manuscript introduction and chapter 2.

REP 11: The data of regional networks provide the information about velocities in the crust (for Pg and Sg data) and in the uppermost mantle (for Pn, Sn data). It does not give much information about the lithosphere interaction which is discussed in this paper. The stories based on crustal structure derived from regional data will be discussed in another paper.

In addition, I would like to direct the authors attention to the following specific points:

Abstract, line 11. „.. supported by strong deformations indicating weak properties ...“ you mean weak lithosphere?, what deformations exactly do you mean – if uplift, what about isostasy?

REP 12: Here we are talking about horizontal deformation which causes crustal thickening and relief uplift due to the effect of isostasy. We have specified in the text this point (Line 40).

Abstract, line 22. „dominantly felsic composition of the crust which is favorable for the upward heat transport „ Why should the felsic composition promote the vertical conductive heat transport? Do you refer to extra heat source due to radioactivity?

REP 13: The radioactivity might be another candidate for the additional heat; this point has been added to the discussion. Actually we meant only the weaker mechanical properties of the felsic rocks which may lead to the convectional vertical movements in the crust which bring the heat from the mantle (lines 51 and 284-285).

Introduction, p.13-24. You seem to favour the model of somehow misteriously thickening the continental crust in the orogenic root zone without involving mantle lithosphere in a plate tectonic sense. Please add references to back this up and please add references where you refer to „actively discussed in the scientific community“.

REP 14. We have included some references which seem to us appropriate for this case (Lines 75-76).

Chapter 3, Figure 2 is not refered to in text (should be after Fig 1 and before Fig. 3).
REP 15: Corrected (See Line 160)

Also missing is important information on the data set: how many events, how many rays, how many unknowns/cells, what is your estimated observation uncertainty.
Page 646, Line 25

REP 16: We have added the paragraph with the description of all these parameters (Lines 158-162).

& page 647, lines 1-10. It is nice to caution the reader about „interpretation of absolute values of anomalies“ and to refer to the strong noise in ISC data. However, solution overdamping probably is the least of your problems and it can well be seen by the reader thanks to synthetic data tests. As documented by several previous glocal tomography studies using this data set (i.e. Spakman and coworkers in several studies), the real limitation of ISC data for such „local studies“ stems from strong inconsistencies and numerous blunders in the data.

REP 17: When performing the synthetic tests, we try to simulate the worst situation. For example, besides the regular random noise with the average RMS of 0.3, we add some outliers (in our case, the noise for 5% of data is multiplied by 10). Then we perform the same selection procedure as in the case of real data processing. As a result, the contribution of noise in synthetic tests is high, and we can see that the variance reduction is very low (for the finest checkerboard it was about 22%). Nevertheless we see that the algorithm is capable to resolve the synthetic pattern in case of large data amount. So, we believe that the problem of blunders in the data is not as sharp as stated by the reviewer (see Lines 191-201).

Page 647, line 29. „the shapes of all features are correctly reconstructed.“ In this general term this statement is certainly wrong. Take a look at your figure 7 and reconsider.

REP 18: This paragraph has been completely rewritten (Lines 206-214).

Page 648, line 17. „Arabian and European lithospheric plates is about 250km“ , this may not be deduced from these tomographic images and it should be discussed in the light of other information reported by previous studies.

See REP 6

Page 657, Figure 3. Mark volcanoes with clearly visible symbols.
REP 19: The volcanoes are now better highlighted in Figures 1, 3 and 4.

Color scale should
correlate with resolution power, with this noise in the data and with your cell size (you show lateral velocity variations of less than 100km extent) you will not be able to resolve reliably 0.3km/s velocity variations (see below remark on significance level).

REP 20: To be honest, we do not understand how the resolution power can be imaged with the same color scale as used for presenting the results; we have never seen such a way of displaying the tomography results. Usually, there are two colors (e.g., blue and red) which cover all the spectrum of anomalies. How can we add another parameter? In case of coloring the reliability lighter or darker, how can we distinguish areas with robust values of anomalies close to zero from unreliable results with large amplitude? Wouldn’t it be confusing? We believe that considering various synthetic tests together with real data results gives much more useful information for assessing the reliability of shapes and amplitudes than playing with colors. At least for the reviewer it was sufficient to assess correctly the values he mentioned.

Page 658, Figure 4. Same as for Figure 3 and 5, adjust significance level in color scale.
See REP 20

Page 659, Figure 5. Please calculate the significance level and adjust your color scale accordingly!
See REP 20

Page 660, Figur 6. Please use this figure in text to explain your resolution. From this image I suggest with P-velocity the smallest structure resolved must be of 150km size in all directions and possibly 2% or 3% anomaly. For S-anomalies I guess this would be 400km size and 4%. If you disagree, please add reasoning as more tests are needed to clearly define it.
REP 21. We still do not understand the term of resolution for anomalies and how it can be plotted. In any case, we present a new test with finer checkerboard structure and describe in more details the results of testing.

Page 661, Figure 7. In your synthetic model you show small separated volumes of light blue of about 1% amplitude and size of about 100km. These features are –not surprisingly- totally distorted or wiped clear in the recovered images since they are below the limits of resolution.
REP 22. We have added several sentences about smearing of the high-velocity drops (Lines 210-214).

In the central part of your model between 100km and

300km depth you introduce an extended approximately 2% negative velocity anomaly. In the recovered P-velocity image I notice an amplitude of 3% or more in the center part of this anomaly, an obvious artefact pointing toward a strong local (mostly vertical) leakage problem and suggesting a significant UNDER-damping (50% increase in amplitude!) of your solution. Note that in same figure and in same location the recovered S-velocity field remains OVER-damped. Finally, in either P- and S- velocity anomalies there is an obvious leakage between distance 1500km/depth200km and distance1800km/depth700km in the order of 1% anomaly! This points toward your significance level that for most parts in your cross section could be as high as +/-1.2% for 200km size anomalies, making it impossible in my opinion to interprete the tomographic images to the details that you desire in your study.

REP 23. The artifact related to the limited resolution are described in more details. We have included a new test in Figure 7B which considers the effect of the vertical smearing in the central part of the model for the patterns mentioned by the reviewer.

Nature of orogenesis and volcanism in the Caucasus region based on results of regional tomography

Ivan Koulakov (1), Irina Zabelina (1), Iason Amanatashvili (2), and Vladimer Meskhia (2)

(1) Institute of Petroleum Geology and Geophysics, SB RAS, Novosibirsk, Russia,
(KoulakovIY@ipgg.nsc.ru, zabelirina@yandex.ru)
(2) Ilia State University, Tbilisi, Georgia (iason.amanatashvili@iliauni.edu.ge)

First revision
Manuscript # SE-2012-18

Novosibirsk – Tbilisi
Submitted to Solid Earth
September 2012

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 horizontal deformations and crustal thickening 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 factors of frictional heating and the radioactivity of felsic rocks, may cause to the origin of volcanic centers in the Caucasus and surrounding collisional areas.

Key words: Seismic tomography, continental collision, Caucasus, delamination, volcanism

1. Introduction

Caucasus is a part of the Alpine-Himalayan orogenic belt which is the largest continental collision zone in the world. In the Caucasis 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 (Figure 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 (e.g., Dewey and Bird, 1970; England and Houseman, 1989, Ershov and Nikishin, 2004). 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 & Ni, 1994, Al-Lazki et al., 2004, Gök et al., 2003) , surface waves (e.g., Maggi & Priestley, 2005, Sandvol et al., 2001, Villasenor et al., 2001) and seismic attenuation (Sarker & 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 (Figure 1) mostly controlled by convergence of Eurasian and Africa-Arabian continental lithosphere plates. According to geodetic data, the total rate of the convergence is ~20 ‑ 30 mm/y (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 accretion of island arcs, intra-arc rifts, and back-arc basins etc. Thus, very large variety of arc volcanism age can be found in the collision zone around Caucasus (Adamia et al., 2011). Fold-thrust belts in the Great and Lesser Caucasus and, in between, the Transcaucasian intermontane depression were formed after definitive closure of Tethys in this segment of the collision belt during syn-collisional (Oligocene–Middle Miocene) and post-collisional (Late Miocene–Quaternary) stages of the Late Alpine tectonic cycle (Adamia et al., 2011). High intensity of the collision processes in Caucasus are possibly due to its location in a gap between two presumably oceanic type basins, Black Sea and South Caspian, which are thought to be the remnant parts of Tethys (see for example, Figure 21 in Adamia et al., 2011).

Late Cenozoic intrusive and extrusive volcanism is widespread throughout the collision zone from Anatolia to Iran. In Turkey the outcrops of calc-alkali volcanic rocks are observed along two suture zones in different sides of the Anatolian peninsula. The southern volcanic branch extends to Iran along the Urmieh-Dokhtar magmatic arc which is oriented parallel to the Zagros belt. The northern branch appears to be adjoining with intensive post-collisional magmatic manifestations in Caucasus.

Quaternary volcanism in Caucasus and surrounding areas is mostly represented by andesites-to-dacite series. The dacitic lavas were actively erupted in a time period from 760 000 a to 30 000 a in the Javakheti highlands (Lebedev et al., 2004). Products of the most recent and mostly uplifted segments of Caucasus including post-collisional volcanoes of the Elbrus, Chegem and Keli-Kazbegi are represented by lavas of calc-alkaline subalkaline andesite-basalt, andesite-dacite rhyolite composition (Tutberidze 2004; Koronovsky & Demina 2007). There are many evidences of Pliocene-Quaternary ages of eruptions for some of these volcanoes, for example, ~6000 years near the Kazbegi volcano (Djanelidze et al., 1982). It is interesting that some authors (e.g., Lebedev et al. 2008) observe a "dominoes effect" when the magmatic activity is migrated northward from one volcanic center to another.

Several geodynamic models have been proposed to explain the Late Miocene – Quaternary calc-alkaline volcanism of Caucasus, such as the detachment model of the last piece of subducted oceanic lithosphere (e.g., Innocenti et al., 1982) or the lithosphere delamination (Pearce et al. 1990; Keskin et al. 1998). In this paper we will provide additional arguments for the second concept based on recent tomographic images of the upper mantle.

3. Tomographic model

This study is based on analysis of P and S velocity models beneath Asia down to 1000 km depth computed by Koulakov (2011). This model was constructed using arrival times of seismic body waves reported in the worldwide ISC catalogue (ISC, 2001) in the time period from 1964 to 2007 based on the tomographic approach developed in Koulakov and Sobolev, (2006). All the data from the catalogue were initially reprocessed which resulted at relocation of the events and rejection of large amount of outliers.

The inversion was performed separately in 32 overlapped circular areas which covered most part of Asia. All data with ray paths traveling, at least partly, through the study volume, were considered in this study. This included, the data from events located in the study area recorded by the worldwide station network and picks from long-distant events recorded by stations in the study region. It is important that free inversion parameters were determined separately for each circular window based on the results of synthetic modeling. This allows minimizing a problem existing in global studies when the same damping parameter causes loss of information in densely covered areas and artificial instabilities in parts with insufficient data amount. In the presented model, for each window, the value of damping was separately tuned to enable the optimal reconstruction of a synthetic model.

For the selected area we used four circular windows of 8° radius with approximately 300000 rays in total. S-data took about 10% of the total amount. The distribution of stations and events used in this study is shown in Figure 2. Number of the parameterization nodes in each window varied from 6000 to 9000 for the P-data and from 4000 to 5500 for the S-data, depending on the data coverage

Here we provide several horizontal and vertical sections of the considered model shown in Figures 3, 4 and 5 which correspond to the Caucasus region. Note that one should be careful with the interpretation of absolute values of anomalies given in this model. The amplitudes of anomalies in seismic tomography studies are strongly affected by damping values which are used for the inversion. This problem is especially 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 Figure 6 we present a series of checkerboard models: two models for the P-data with the size of 2°x1.5°x300 km and 1.5°x1°x200 km and two models for the S-data (3x2.5x300 km and 2x1.5x200 km). In all cases, these models were finer than considered in tests in Koulakov (2011). When computing the synthetic data, we added the random noise with the rms of 0.3 s. Furthermore, to simulate the existence of blunders in the ISC catalogue, we also added 5% of "outliers" for which the noise was multiplied by ten. As a result, the variance reduction after the inversion for the synthetic data was about 25-35% which is significantly lower than in the case of real data (45-50%). Despite these "pessimistic" simulations, it can be seen that in areas with sufficient amount of data, the checkerboard patterns can be correctly resolved. For the coarser model, the resolved area covers the entire central part of the study area. For the finer board, having size of about 100 km, the satisfactory reconstruction is achieved only in areas of Turkey, Caucasus and Zagros; in most other areas the anomalies are not visible. Fortunately for us, the areas with the highest resolution are the most attractive from the geological point of view and mostly discussed in the next section.

Another test shown in Figure 7A consists in recovering of a model with realistic shapes of anomalies defined in vertical section 2. The conditions of synthetic modeling were the same as in the cases of the checkerboard tests. Because of larger size of synthetic patterns, close to the real anomalies, the value of variance reduction in this case was about 50%, which is similar to one observed for the real data inversion. The reconstruction results show that the shapes and locations of most features are generally correct both for P and S data. However, 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. For example, for the high-velocity “drops”, in the reconstruction results we cannot separate them and say exact the number of anomalies. At the same time, it is important for the interpretation that we can detect the existence of these drops in the mantle, though without resolving their details. This should be taken into account while constructing a geodynamical interpretation.

To check the possibility of vertical smearing and leakage of the crustal anomalies to the mantle we made another test shown in Figure 7B. The configurations of synthetic anomalies are the same as in the previous case, except for the low-velocity anomaly in the middle part of the profile defined down to 50-60 km which represents the thick crust. It can be seen that this anomaly is correctly resolved in both P and S velocities; no vertical leakage is observed and the lower boundary of the “crust” is reconstructed at the correct depth. From this test we can conclude that the low-velocity anomaly, which is observed beneath the Caucasus mountains, really represents the mantle structure.

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 200-250 km which is a little bit higher that estimated by other authors based on different methods (e.g. Artemieva, 2003). However it should be kept in mind that the lithosphere related anomalies might be smeared downward due to the limited vertical resolution. 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 Figure 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.

The obtained results allow us proposing mechanisms of the lithosphere recycling due to collision and origin of volcanism illustrated in Figure 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 & 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 press 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 Figure 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.

It is important to mention that a similar processes (tectonic shortening – crustal thickening – eclogitization of the lower crust that triggers delamination of the mantle lithosphere) was previously suggested for Central Andes based on petrological arguments (Kay and Kay, 1993) and numerical modeling (Sobolev and Babeyko, 2005). Rate of this process was analyzed by Jull and Kelemen (2001).

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, which can be considered as an integral layer for the crustal properties. It is known that the felsic layer is composed of mechanically weaker rocks which facilitate circulation of hot materials in the thick crust (e.g., Babeyko et al., 2002, Babeyko & Sobolev, 2005). This favors active heat transport from the asthenosphere to the surface that explains the existence of active volcanic fields in Caucasus and surrounding collisional areas. At the same time, additional heating can come from the frictional effects due to the strong compressional deformations. Some authors suggest that this factor cannot be ignored in the process of delamination (e.g. Schott et al., 2000) and in the origin of volcanism (e.g. Stüwe, 1998). Some contribution in heating can also be related to radioactivity of felsic rocks.

5. Conclusions

Based on our seismic model we can conclude that mantle lithosphere beneath the collision zone of Caucasus and surrounding areas is very thin or absent. That is why this segment squeezed between rigid Arabian and European blocks behaves as weak lithosphere and is strongly affected by tectonic shortening and orogenesis. Tomography results show that the continental lithosphere in the contact with the collision area is actively destroyed by the process of delamination and sink as separate drops. We propose that a big role in triggering the detachment of the mantle lithosphere and its more active descending is played by eclogitization in the lower crust affected by strong shortening. We believe that delamination mechanism of such type is the major candidate for the lithosphere recycling in all continent-to-continent collision zones of the world.

Important conclusion of this research consists in the definition of a collisional type of volcanism which is principally different of the intraplate and subduction types of volcanism. We propose that the volcanic activity in Caucasus and surrounding collisional areas is presumably due to direct heating of the crust from the asthenosphere which is possible due to lack of the mantle lithosphere and thinning of the mafic lower crust layer. This type of volcanism might be expected in most areas of continental collision, 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.

References:

Adamia Sh.A., T. Chkhotua, M. Kekelia, M. Lordkipanidze, I. Shavishvili, G. Zakariadze, (1981),Tectonics of the Caucasus and adjoining regions: implications for the evolution of the Tethys ocean, Journal of Structural Geology, Volume 3, Issue 4, Pages 437-447

Adamia, S., Zakariadze, G., Chkhotua, T., Sadradze, N., Tsereteli, N., Chabukiani, A., Gventsadze, A., 2011a. Geology of the Caucasus: A Review. Turkish Journal of Earth Sciences, 20, 489-544.

Adamia, Sh. 1975. Plate tectonics and evolution of the Alpine system: discussion. Geological Society of America Bulletin 86, 719 – 720.

Adamia, S., Mumladze, T., Sadradze, N., Tsereteli, E., Tsereteli, N. & Varazanashvili, O. 2008. Late Cenozoic tectonics and geodynamics of Georgia (SW Caucasus). Georgian International Journal of Sciences and Technology 1, 77 – 107.

Al-Lazki, A. I., E. Sandvol, D. Seber, M. Barazangi, N. Turkelli, and R. Mohamad (2004). Pn tomographic imaging of mantle lid velocity and anisotropy at the junction of the Arabian, Eurasian and African plates, Geophys. J. Int. 158: 1024–1040.

Allen, M., Jackson, J. & Walker, R. 2004. Late Cenozoic reorganization of the Arabia-Eurasia collision and the comparison of short-term and long-term deformation rates. Tectonics 23, 1 – 16.

Artemieva I.M., 2003. Lithospheric structure, composition, and thermal regime of the East European craton: Implications for the subsidence of the Russian Platform, Earth Planet. Sci. Lett., v. 213, 429-444, 2003

Babeyko, A. Y.; Sobolev, S. V. (2005): Quantifying different modes of the late Cenozoic shortening in the central Andes. Geology, 33, 8, 621-624.

Babeyko, A. Y.; Sobolev, S. V.; Trumbull, R. B.; Oncken, O.; Lavier, L. (2002): Numerical models of crustal scale convection and partial melting beneath the Altiplano-Puna plateau. Earth and Planetary Science Letters, 199, 3-4, 373-388

Burov, E.B., and Diament, M., 1995, The effective elastic thickness (Te) of continental lithosphere: What does it really mean?: Journal of Geophysical Research, v. 100, no. B 3, p. 3905–3928, doi: 10.1029/94JB02770.

Burov, E. B. and A. B. Watts, "The long-term strength of continental lithosphere: "jelly sandwich" or "crème-brûlé"?", GSA Today, 16, 4-10, 2006

DeMets, C., Gordon, R., Argus, D. & Stein, S. 1990. Current plate motions. Geophysical Journal International 101, 425 – 478.

Dewey, J.F., Bird, J.M., 1970. Mountain belts and new global tectonics. Journal of Geophyscial Research 74, 2625–2467.

Dewey, J. F., M. R. Hempton, W. S. F. Kidd, F. Saroglu, and A. M. C. Şengör (1986). Shortening of continental lithosphere: The neotectonics of eastern Anatolia—A young collision zone, in Collision Tectonics, M. P. Coward and A. C. Ries (eds.) London: Geol. Soc. London, pp. 3–36.

Djanelidze, Ch., Klopotovskaya, N. & Maisuradze, G. 1982. Holocene volcanites and lake beds near Goristsikhe settlement. International Union for Quarternary Research (INQUA), 11th Congress Guidebook for Excursion A-16, 28 – 31.

England, P.C., Houseman, G.A., 1989. Extension during continental convergence with application to the Tibetan Plateau. Journal of Geophyscial Research 94, 17561–17579.

Ershov A.V. and Nikishin A.M. 2004. Recent Geodynamics of the Caucasus-Arabia-East Africa Region, Geotectonics, Vol. 38, No. 2, 123-136

Forte, A., Cowgill, E., Bernardin, T., Kreylos, O. & Hamann, B. 2010. Late Cenozoic deformation of Kura fold-thrust belt, southern Greater Caucasus. Geological Society of America Bulletin 122, 465 – 486.

Gök, R., E. Sandvol., N. Turkelli, D. Seber, and M. Barazangi (2003). Sn attenuation in the Anatolian and Iranian plateau and surrounding regions, Geophys. Res. Lett. 30: doi:10.1029/2003GL018020.

Hearn, T. M. and J. Ni (1994). Pn velocities beneath continental collision zones: The Turkish-Iranian plateau, Geophys. J. Int. 117: 273–283.

Innocenti, F., Mazzuoli, R., Pasquare, G., Radicati F. & Villari, L. 1982. Tertiary and Quaternary volcanism of the Erzurum-Kars area (Eastern Turkey). Geochronological data and geodynamic evolution. Journal of Volcanology and Geothermal Research 13, 223 – 240.

International Seismological Centre, 2001, Bulletin Disks 1-9 [CD-ROM], Internatl. Seis. Cent., Thatcham, United Kingdom.

Jull, M. and P.B. Kelemen, 2001. On the conditions for lower crustal convective instability, J. Geophys. Res. 106, 6423-6446.

Kay RW, and Kay SM (1993) Delamination and delamination magmatism. Tectonophysics 219:177–189

Keskln, M., Pearce, J.A. & Mitchell, J.G. 1998. Volcanostratigraphy and geochemistry of collision-related volcanism on the Erzurum-Kars Plateau, North Eastern Turkey. Journal of Volcanology and Geothermal Research 85, 355 – 404.

Khain, V. 1975. Structure and main stages in the tectono-magmatic development of the Caucasus: an attempt at geodynamic interpretation. American Journal Sciences 275-A, 131 – 156.

Koronovsky, H. & Demina, L. 2007. Disappeared Pliocene volcanoes of the Main Caucasian Range and grandiose explosion of the Kazbegi at the beginning of Pleistocene (North Caucasus) Problems of Geodynamics, Petrography and Metallogeny of the Caucasus. Proceedings of the Scientifi c Sessions, Baki, 92 – 103 [in Russian].

Koulakov, I. (2011), High-frequency P and S velocity anomalies in the upper mantle beneath Asia from inversion of worldwide traveltime data, J. Geophys. Res., 116, B04301, doi:10.1029/2010JB007938.

Koulakov I. and S.V. Sobolev, (2006) A Tomographic Image of Indian Lithosphere Break-off beneath the Pamir Hindukush Region, Geophys. Journ. Int., 164, p. 425-440

Lavier L.L. and M. S. Steckler (1997) The effect of sedimentary cover on the flexural strength of continental lithosphere Nature 389, 476-479 doi:10.1038/39004

Lebedev, V., Chernishev, I., Dudauri, O., Arakelyants, M., Chugaev, A., Golzman, Y. & Vashakidze, G. 2004. Geochronology of Neogene – Quaternary dacitic volcanism of the Javakheti highland (Lesser Caucasus, South Georgia). Proceedings of Geological Institute of Academy of Sciences of Georgia 119, 535 – 544 [in Russian].

Lebedev, V., Bubnov, S., Dudauri, O. & Vashakidze, G. 2008. Geochronology of Pliocene volcanism of Javakheti highland (Lesser Caucasus). Article 2. Eastern part of the Javakheti highland. Regional Geological Correlation. Stratigraphy. Geological Correlation 16, 101 – 123 [in Russian].

Maggi, A. and K. Priestley (2005). Surface waveform tomography of the Turkish-Iranian plateau, Geophys. J. Int. 160: 1068–1080.

Neprochnov, Y. P., Kosminskaya, I. P., and Malovitsky, Y. P., (1970). Structure of the crust and upper mantle of the Black and Caspian seas, Tectonophysics, 10, (5-6),517-538.

Pearce, J., Bender, J., De Long, S., Kidd, W., Low, P., Guner, Y., Saroglu, F., Yilmaz, Y., Moorbath, S. & Mitchell, J. 1990. Genesis of collision volcanism in Eastern Anatolia, Turkey. Journal of Volcanology and Geothermal Research 44, 189 – 229.

Sandvol, E., K. Al-Damegh, A. Calvert, D. Seber, M. Barazangi, R. Mohamad, R. Gok, N. Turkelli, and C. Gurbuz (2001). Tomographic omaging of Lg and Sn propagation in the Middle East, Pure and Appl.Geophys. 158: 1121–1163.

Sarker, G. and G. A. Abers, (1998). Deep structures along the boundary of a collisional belt: attenuation tomography of P and S waves in the Greater Caucasus. Geophysical Journal International 133 (2), 326-340. doi: 10.1046 j.1365-246X.1998.00506.x,.

Sobolev, S. V.; Babeyko, A. Y. (2005): What drives orogeny in the Andes?. Geology, 33,8, 617-620.

Sobolev, S.V., Babeyko, A.Y., Koulakov, I. and O. Oncken, (2006). Mechanism of the Andean orogeny: insight from the numerical modeling, In: Oncken O et al. (eds) The Andes – Active Subduction Orogeny. Frontiers in Earth Sciences, 1, Springer, 513-535.

Stüwe K (1998) Heat sources of Cretaceous metamorphism in the Eastern Alps – a discussion. Tectonophysics 287: 251–269

Tutberidze, B. 2004. Geology and Petrology of Alpine Late Orogenic Magmatism of the Central Part of Caucasian Segment. Tbilisi University Publishers, Tbilisi, 1 – 340 [in Russian].

Villasenor, A., M. H. Ritzwoller, A. L. Levshin, M. P. Barmin, E. R. Engdahl, W. Spakman, and J. Trampert (2001). Shear velocity structure of central Eurasia from inversion of surface wave velocities, Physics of the Earth and Planetary Interiors 123: 169–184.

Zakariadze, G., Dilek, Y., Adamia, S., Oberhansli, R., Karpenko, S., Bazylev, B. & Solov’eva N. 2007. Geochemistry and geochronology of the Neoproterozoic Pan-African Transcaucasian Massif (Republic of Georgia) and implications for island-arc evolution of the late Precambrian Arabian-Nubian Shield. Gondwana Research 11, 97 – 108.

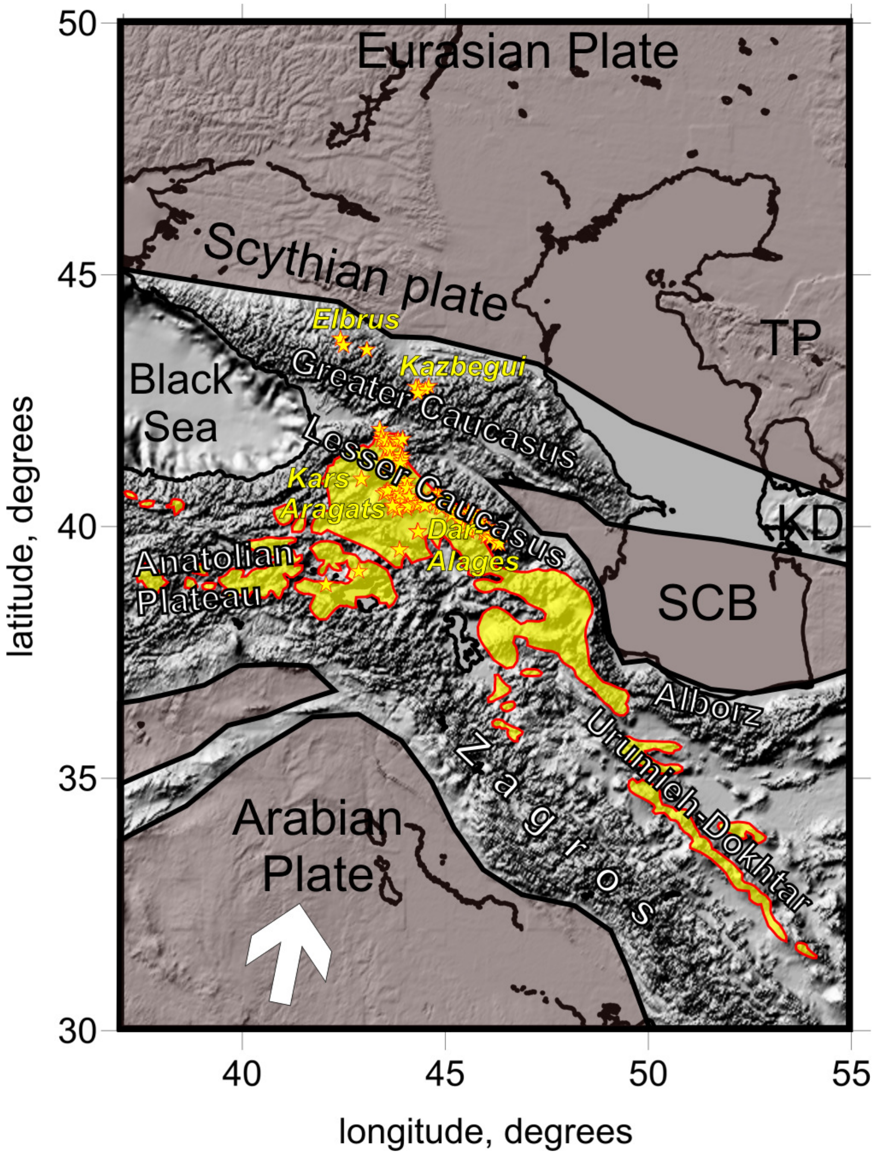

Figure 1. Main tectonic units in Caucasus and surrounding areas overlaid on a shaded relief map. Yellow stars depict the recent volcanoes in Caucasus (Adamia et al., 2011). Major volcanoes are named with yellow characters. Areas of Cenozoic volcanism in Iran compiled from Nezafati (2006), Verdel et al. (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.

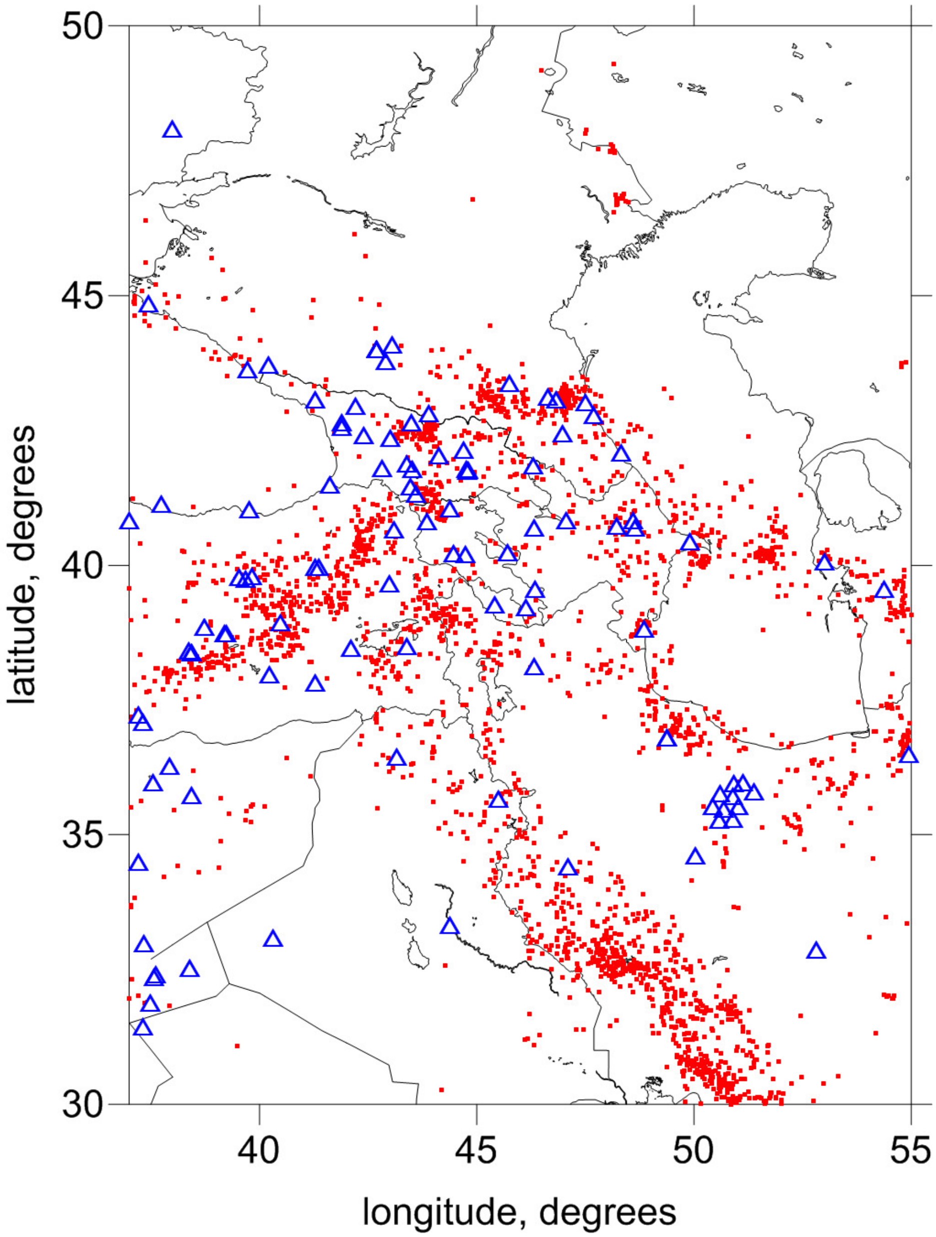

Figure 2. Distribution of data from the ISC catalogue: triangles depict stations, red dots are the events.

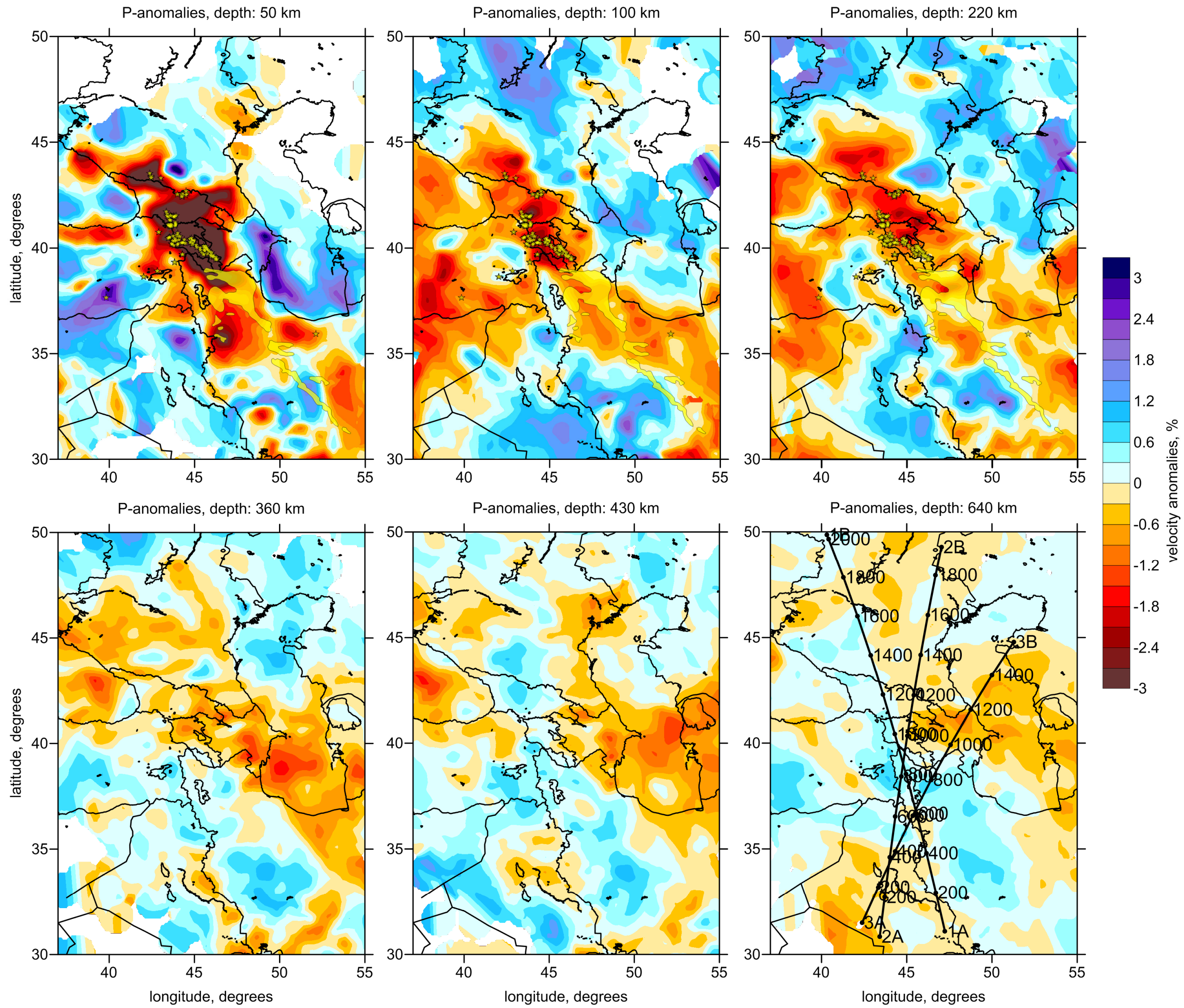

Figure 3. P-velocity anomalies in six horizontal sections, yellow stars and polygons mark the locations of recent volcanoes and folcanic fields in Caucasus and surrounding areas.

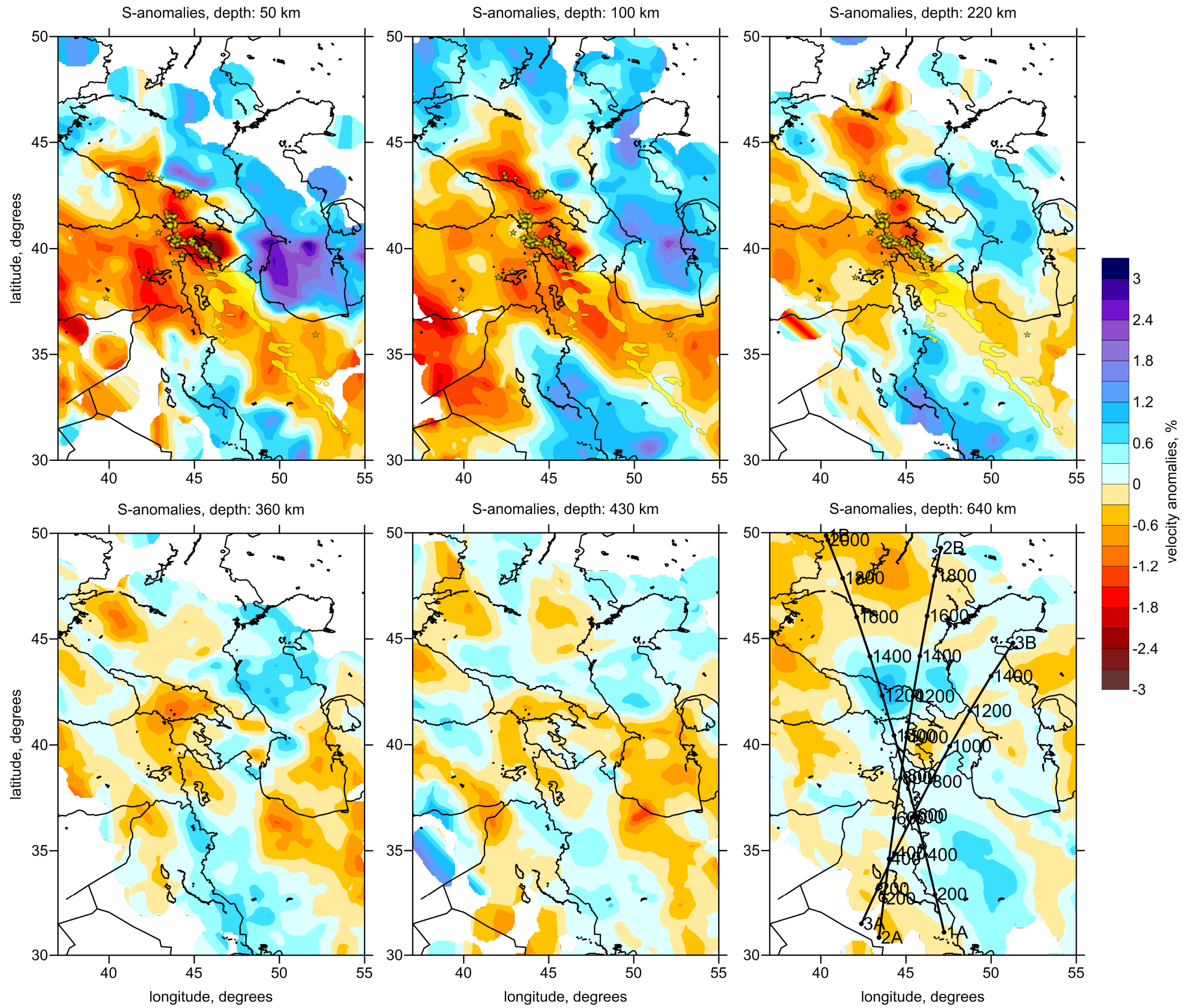

Figure 4. Same as Figure 3, but for the S-velocity anomalies

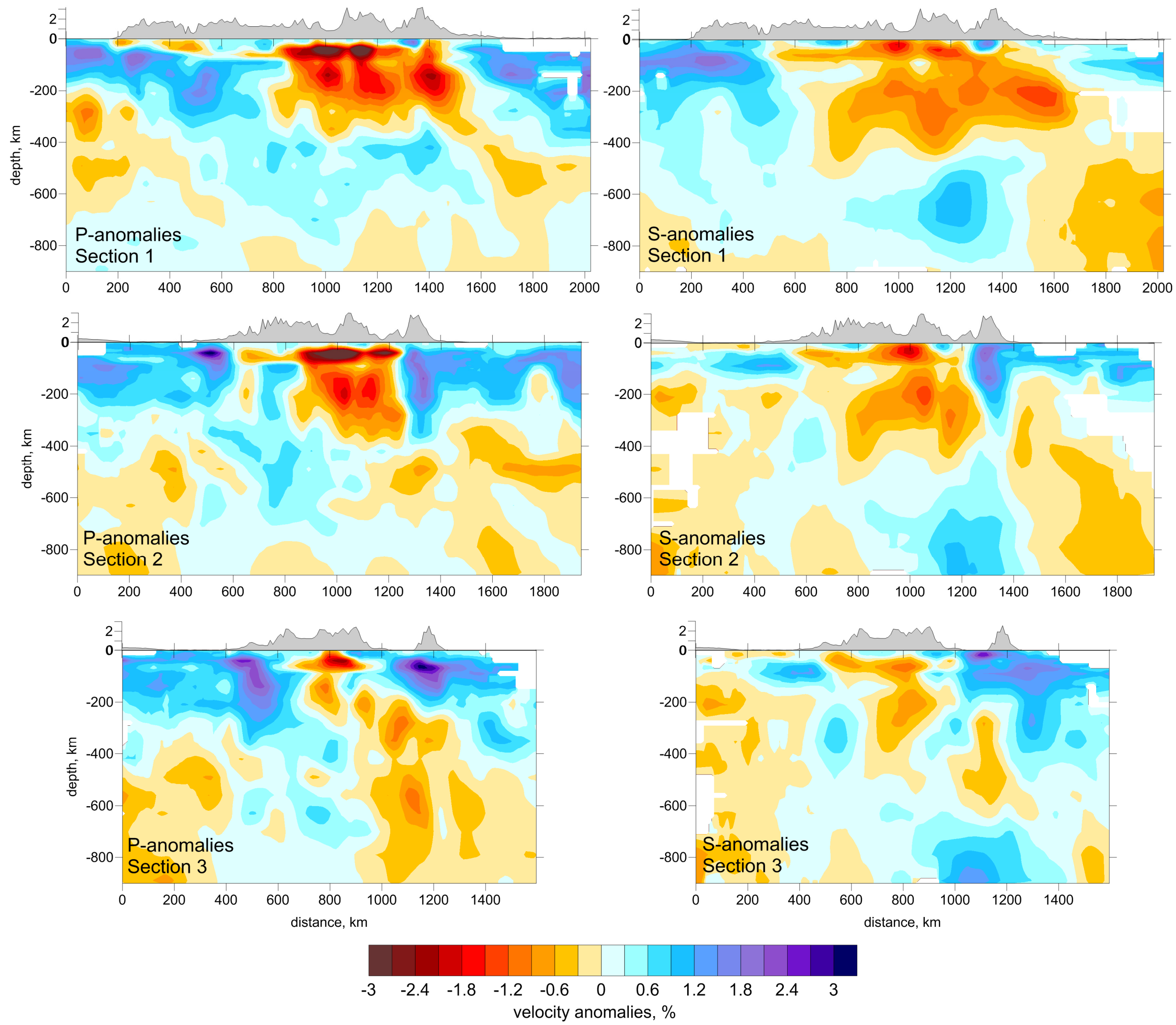

Figure 5. P- and S-velocity anomalies in three vertical sections. The locations of the profiles are shown in maps in Figures 3 and 4. Relief along the profile is shown above each plot.

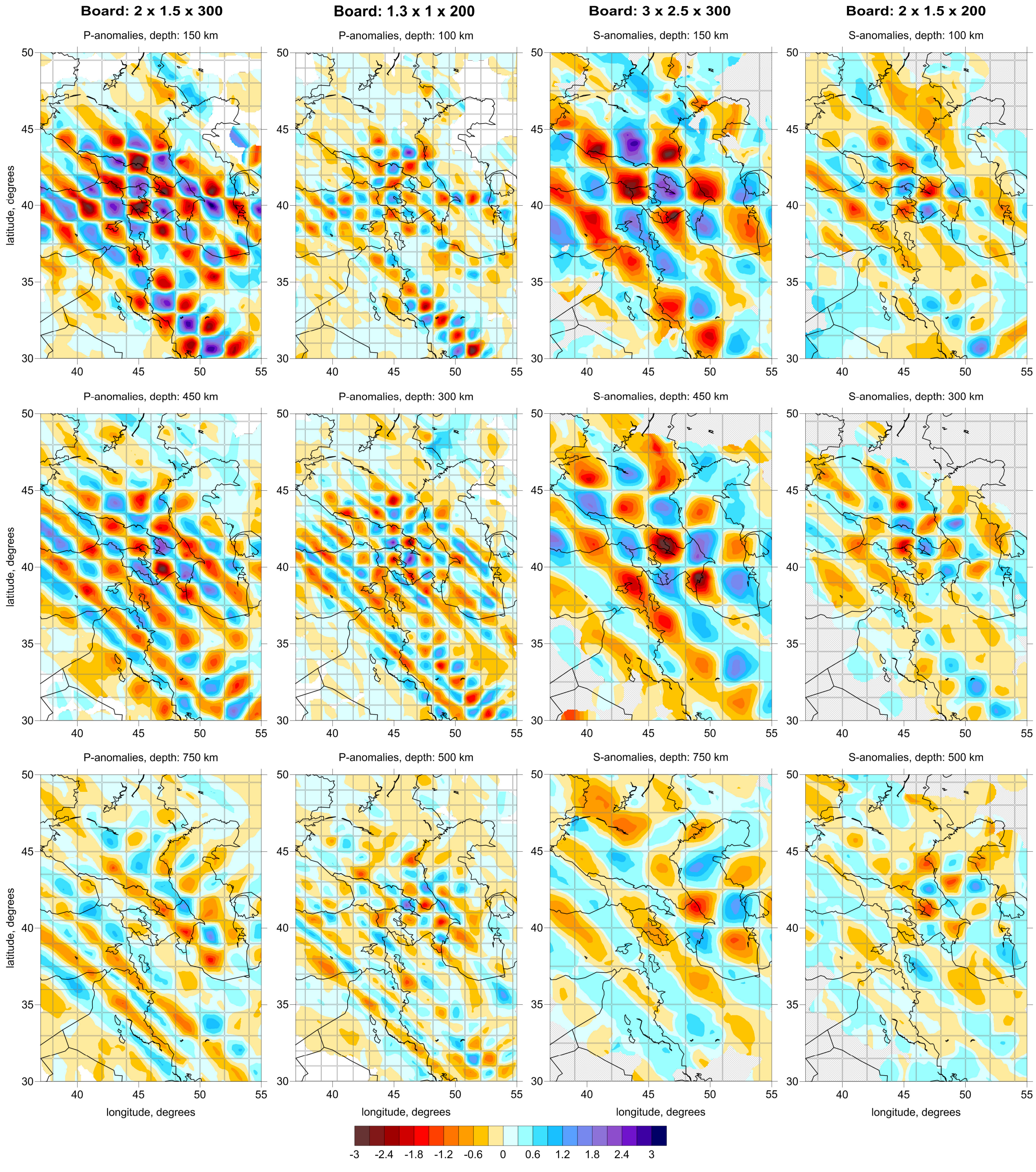

Figure 6 Checkerboard tests with different sizes of anomalies for P- and S-models in three horizontal sections. Depths of the sections correspond to the middle level of the checkerboard patterns. The sizes of synthetic anomalies are indicated above each column.

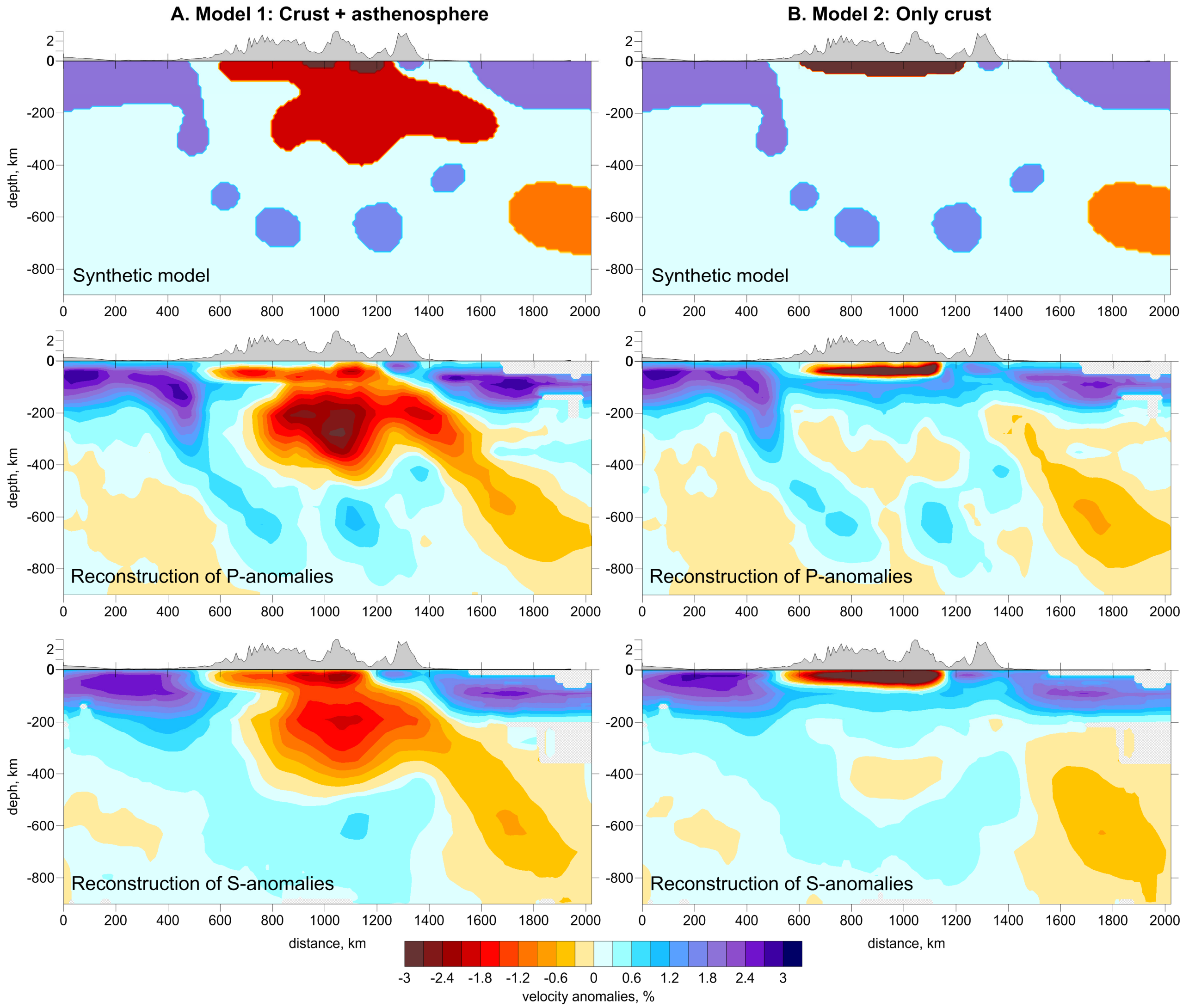

Figure 7. Two synthetic tests with realistic patterns defined in a vertical section 2, same as indicated in Figure 5. Upper plots show the configurations of the synthetic models; middle and lower plots are the reconstruction results for the P and S anomalies.

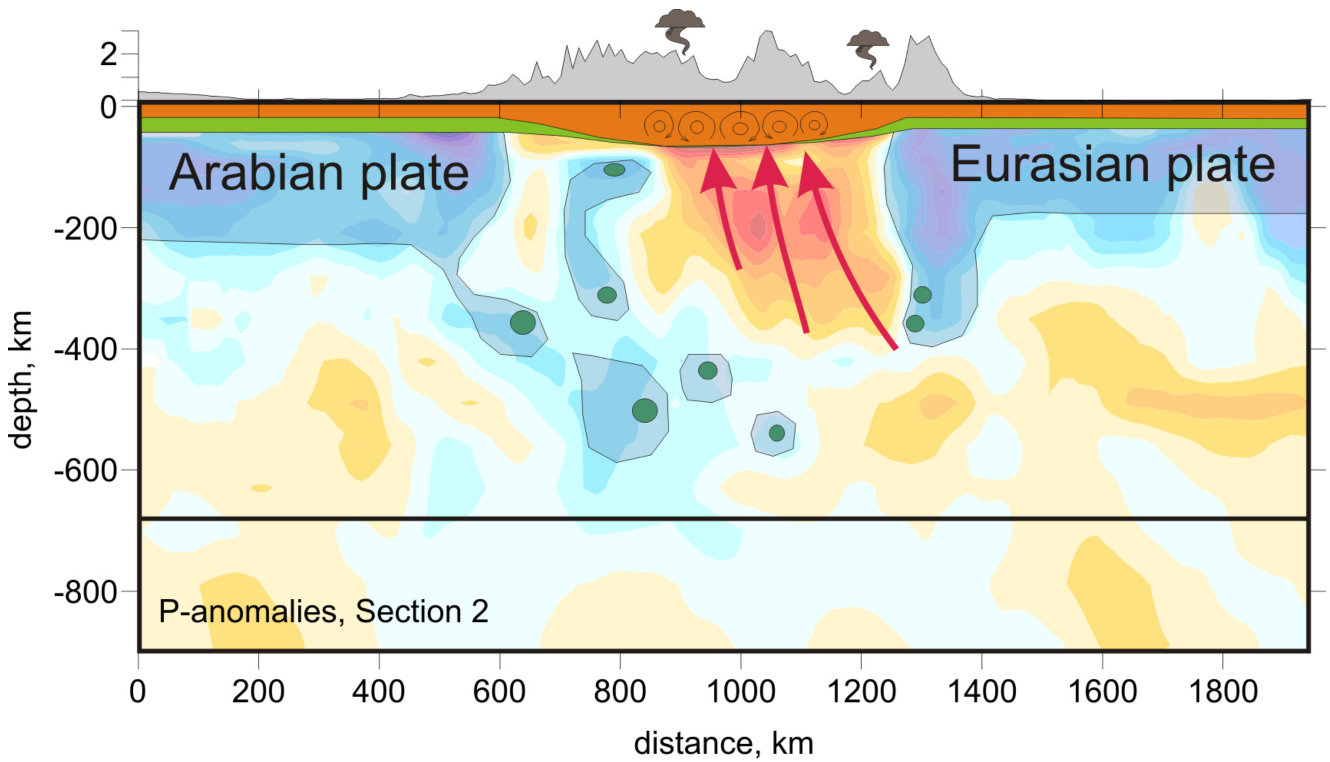

Figure 8. Schematic representation of the delamination mechanism in the Caucasus region. The crust is composed of the upper felsic (orange) and lower mafic (green) parts. Blue areas indicate the mantle parts of the lithosphere. Background is the distribution of P-velocity anomalies in vertical section 2, same as in Figure 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.