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Review

Studying deep sources of volcanism using multiscale seismic tomography

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ABSTRACT

This paper presents an overview of several examples of multiscale studies of different volcanic systems including intracontinental, collisional and subduction-related volcanic areas. Regional tomographic models of the upper mantle are presented for three regions with the Cenozoic intracontinental volcanism in Eurasia, namely Europe, Southern Siberia and Eastern Arctic. In all cases, recent volcanic fields correlate with low-velocity anomalies in the mantle. The modeling results show that these volcanic manifestations are related to large hot areas in the mantle and not to thin column-shaped contrasted plumes, as presumed by many. Collisional-type volcanism is discussed with an example of the Caucasus and the surrounding areas. The regional tomographic model for this region reveals a lack of mantle lithosphere beneath the collision zone. Volcanism in this area is most likely due to the direct heating of the thick crust by the hot asthenosphere. A dominantly felsic composition of the crust facilitates upward transport of the fluids and melts that leads to volcanic eruption. Subduction-related volcanic systems are discussed for three different scale levels. An example of a regional model of the mantle beneath the Sunda arc reveals the general configuration of the slab. Middle-scale tomographic models in areas of the Toba Caldera, Central Java and Central Andes display feeding paths of the arc volcanoes from the slab. The feeding paths are apparent in all of the considered cases but have different shapes depending on the unique features of the subduction regimes. An example of a detailed local-scale study of magmatic sources in the crust is discussed for the Kluchevskoy volcano group. It is found that the main volcano, Kluchevskoy, is fed through a complex three-layered system of magma sources. Another volcano of the same group, Bezymianny, seems to be connected with the mantle through a direct short-lived channel, which appears only during the eruption periods. A time-dependent tomography study performed for this group over a period of ten years clearly reveals the correlation between the changes in the seismic structures and the stages of the volcanic process, namely, preparation, activation and relaxation.

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1. Introduction

Since ancient times, people have wished to explain the nature of volcanoes and have tried to understand the mechanisms that are responsible for their activity. Only in the last few decades has the development of the branch of geophysics made such an endeavor a reality. One of the most powerful methods for studying the Earth structure in volcanic areas is seismic tomography, which has experienced a real breakthrough during the last twenty years. The 3D distributions of P and S velocities and, in some cases, the attenuation and anisotropy parameters obtained from the tomographic studies can be linked with petrophysical parameters of rocks, such as temperature, composition, density, fluid and melt content. Although these links are difficult to quantify, seismic tomography provides a valuable method to study the geodynamic processes beneath the volcanoes.

This paper considers three different types of volcanic activity associated with intracontinental areas, collision belts and subduction zones. In each case, different mechanisms of volcano feeding and activation are presumed.

The location of the volcano-generating mechanism is not limited by the structures situated directly beneath a volcano. Feeding of a volcano may occur at large depths and may cover broad areas. Therefore, multiscale approaches are necessary to achieve a comprehensive understanding of the origin of the volcanic activity. In this paper, I will review the different seismic models on scales ranging from a few to thousands of kilometers and pertaining to a few volcanic areas of the world. This series can be further expanded to smaller scales (up to meters and even centimeters), which can also provide interesting results. However, the smaller scale studies mostly relate to the consequences of volcanic activity and not to its origin. Therefore, they are considered as subjects of other reviews.

In this paper, I summarize the results of several studies related to different volcanic complexes of the world, published or planned for publication, and draw brief conclusions from each case. I avoid any technical details and special terms to make the material comprehensible to specialists in different areas of geosciences. I believe this treatment will make this paper useful for a wide range of volcano specialists.

2. Algorithms of tomographic inversion

Seismic tomography is a powerful tool for studying the sources of volcanism. In this section, I will briefly describe the algorithms that were used to obtain the results presented in the paper. Some other approaches that have contributed to the study of volcanic systems will also be mentioned.

In this paper, examples of seismic studies on scales of dozens of kilometers and larger will be considered. For such distances and depths, methods based on passive sources (earthquakes) appear to be most effective. In our studies, we mostly use methods based on the travel times of P and S body waves that have different configurations of sources and receivers. Below, I present some examples.

2.1. Regional tomographic modeling with global data

To perform regional scale studies of areas extending thousands of kilometers laterally and depth intervals down to approximately 1000 km, we use data from global seismological databases, which are mostly available in the catalogue of the International Seismological Center (ISC, 2001). This catalogue, which includes phase recordings from thousands of worldwide stations over approximately 50 years, provides an enormous amount of data that cannot be collected by a more transient network. However, the ISC catalogue contains a lot of erroneous data, and the quality of source locations is generally poor. Therefore, before using these data for tomography, they should be reprocessed. An important revision of the ISC catalogue was performed by Engdahl et al. (1998). The authors refined the locations of the most prominent worldwide events using more sophisticated location algorithms. However, the criteria for their data selection were rather conservative and resulted in a considerable reduction of the catalogue volume. A number of weak events in areas with moderate tectonic activity were rejected, which enlarged non-illuminated areas where body wave tomography cannot provide robust results.

We performed our own revision of the ISC catalogue based on similar approaches as those used by Engdahl et al. (1998), but we used more liberal selection criteria. All events between 1964 and 2007 were localized using the algorithm described by Koulakov and Sobolev (2006). The travel times were corrected for surface relief, the ellipticity of the Earth, and Moho depth (using the model *CRUST2.0*; Bassin et al., 2000). Furthermore, depth phases (pP and sS) were used to improve the depth locations of the sources. In this algorithm, special attention was paid to the problem of outlier rejection, which culled a considerable portion of the ISC catalogue (~25–30%). When reprocessing the ISC catalogue, we used only events with an azimuthal GAP of less than 180°. The residuals larger than 4 and 6 seconds for *P* and *S* data, respectively, were rejected. A minimum value of 30 recordings of *P* and *S* phases was fixed as the cutoff for all available epicentral distances for the events.

For the regional studies, we selected the data using different observation schemes. The first scheme used the stations located in the study region, which recorded teleseismic events at great distances. The second scheme, which is more appropriate for areas with low amount of seismometers, used the data from the earthquakes located in the study region recorded by worldwide stations at all available epicentral distances. The calculations according to these two schemes were performed using the tomography algorithm described in Koulakov and Sobolev (2006).

For some areas, the amount of data according to the mentioned schemes may appear to be insufficient for performing the tomography studies. For areas with low coverage of stations and seismicity (e.g., in platform areas), we used the travel times of reflected PP rays, which reveal information about deep structures in the areas below the reflection points. The algorithm for this scheme is described in (Bushenkova et al., 2002; Koulakov and Bushenkova, 2010).

For regional studies, the calculations are performed using a series of overlapping circular windows that cover the entire study area. The results of the independent inversions in each window are averaged in one model. For each window, the optimal values of the damping parameters are determined according to the results of the synthetic modeling. This helped us to avoid the problem of strongly heterogeneous data distribution in the global inversion scheme when one value of the damping parameter for the entire area might cause oversmoothing in one part and instability in another. The regional tomography algorithm has been tested in different areas of the world. Examples of regional tomographic studies from different volcanic areas are given in Sections 3, 4 and 5.2.