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Seismic tomography of magmatic systems

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Abstract

Seismic inversion for three-dimensional variations of velocity and attenuation are often used to delineate magma bodies in the crust and upper mantle. Problems related to spatial resolution and data noise can obscure details relevant to investigating magma chambers, and the introduction of smoothing constraints, or damping, causes blurring. Tomographic inversions for P- and S-wave velocity/attenuation are summarized including large calderas, rift zones and smaller scale subduction zone volcanoes. While results vary considerably from place to place, most anomalies are found to be in the range of ±10% perturbation, a range often controlled by the method of smoothing or regularization imposed during analysis. At many volcanoes high velocity anomalies are observed in the shallow regions below active areas where conduits, dykes or sills are expected to be present. At other locations low velocity perturbations are seen and interpreted as magma accumulation. Resolution limitations and regularization play a significant role in determining the level of perturbation observed in tomographic studies, although there may be regions where diffuse accumulations of magma do not exhibit strong anomalies and their identification will be elusive.

Keywords: tomography; seismic velocity; attenuation; magma; magma chamber; melt accumulation

1. Introduction: What is tomography?

In this paper I review some of the basic methodology of tomographic inversion of seismic waves in a non-technical way, with the intent to reach a broad audience of non-specialists. There is general confusion about how this method is applied in seismic situations and often interpretation (or over interpretation) can be a problem. In many cases results are ambiguous and researchers seek explanations by invoking geological insight and *a priori* information as constraints. It is extremely important for readers and researchers, however, to emphasize the importance of the influence of incomplete and noisy data. These problems can only be overcome by raising the quality of data acquisition, data analysis and by increasing the total number and spatial distribution of seismic stations.

Tomography (literally, 'slice picture') originated in radio astronomy as a method to image aspects of remote regions of the universe. Later physicists and bio-physicists collaborated to create the first methodology and instrumentation that led to the first tomographic analysis of live tissue, especially human bodies. This approach was called "computer aided tomography" or CAT scans. Researchers who pioneered these methods received the Nobel Prize in physiology and medicine in 1979 (Allan Cormack and Godfrey Hounsfield). At the same time seismologists recognized that similar methodology could be applied to imaging the earth. Early papers on these approaches were not called tomography, but simply "three-dimensional

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analysis". It was not until the early 1980's that data sets large enough to actually mimic an approach similar to medical tomography emerged. An extensive collection of review papers about various aspects of tomographic analysis in seismology can be found in the compilation of Iyer and Hirahara (1993).

The basic idea is illustrated in cartoon form in Fig. 1. Earthquakes emit seismic energy that travels out to the stations at the surface. At first, we assume an intervening velocity structure, typically one dimensional, and use that to predict travel times to each station. If the model is correct the difference between predicted and observed arrivals will be small. If waves pass through anomalous structures, however, travel times will be perturbed and the differences will become significant. Seismic tomography often involves using the travel-time residuals to reconstruct anomalies where large numbers of raypaths overlap at varying angles. It can be shown that with complete coverage from all angles, the anomalous body can be reconstructed perfectly. This ideal situation is never achieved in real analyses, of course.

One main difference between medical tomography and seismic tomography is the simple fact that in the laboratory one can entirely surround the target body and thus get a complete, or nearly complete, view of the object studied. Under these conditions and geometries medical tomography can employ specially devised mathematical methods to perform the inversion, in particular the radon transform (the radon transform is a two dimensional integral, much like the Fourier transform, that allows one to convert line integrals of properties across a section into an image (Herman, 1980)). In local earthquake seismology this option is generally not available and other, more straightforward, methodologies (back-projection, for example) must be employed. Three dimensional seismic analysis usually invokes a very simple idea called "back-projection tomography". In this approach the difference between the predicted and

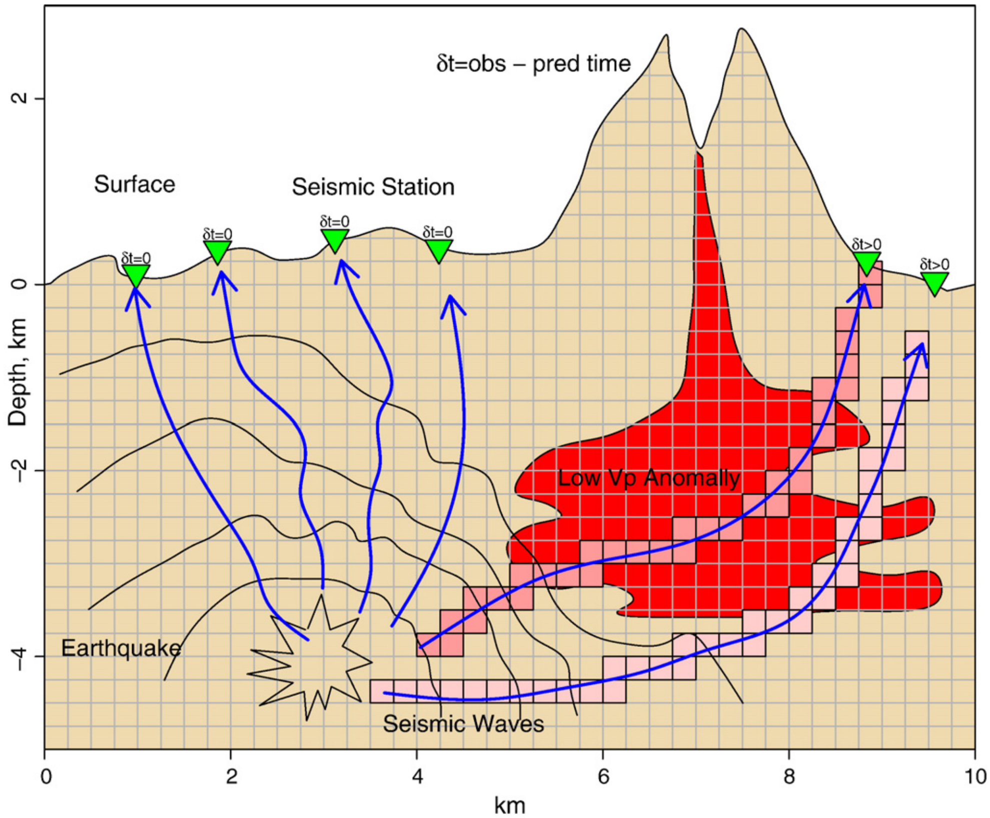

Fig. 1. Cartoon showing earthquake wave-fronts and raypaths used for a tomographic inversion. Raypaths that do not penetrate the anomalous body have a small residual and do not contribute significantly to changing the model. Those ray paths that pass through a low velocity magma region will have a positive anomaly, δt > 0. The travel-time difference can be projected back along the raypath by distributing the residual along the path. Colored blocks show two different rays intersecting the anomalous region, each with a different level of perturbation. Where paths intersect back-projections will constructively interfere and image reconstruction is attained. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)