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# Time-lapse seismic tomography of an underground mining zone

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## ABSTRACT

In this study, we determined P-wave tomographic images of the Yongshaba deposit, an underground mining zone in Guizhou Province, China, by inverting arrival-time data of micro-seismic events and blasts recorded by a passive seismic array consisting of 28 sensors during January to April 2014 using an event location technique and a travel-time tomography method that can handle complex seismic discontinuities. The damping parameter used in the damped least-squares method is determined with the help of trade-off curve. To reveal internal P-wave velocity changes of the study area under severe mining activities, a time-lapse data partition scheme is used. To assess the human influence on the underground structure, we introduce a parameter to measure the relative velocity changes in different periods. The resolution of the tomographic images and the robustness of the obtained features are examined by conducting a series of checkerboard resolution tests and a restoring resolution test. Our tomographic results obtained from the entire data set reveal a prominent low-velocity (low-V) zone and many obvious high-velocity (high-V) zones. These features match well with the geological setting and the excavation plan carried out in the mine, according to in-site surveys. The low-V zone may reflect empty volumes, stress releases and rock breaking and cracking caused by mining activities, whereas the high-V zones are probably the consequences of local stress concentrations caused by regional stress redistribution. The time-lapse tomographic images may reveal the process of stress concentrations caused by rock breaking due to the continuing excavations in the entire observation period, indicating that the mining activities influenced the rock property and caused complex changes of the underground structure.

## 1. Introduction

The propagation velocity of seismic waves is widely used in different scales and in various research fields such as seismology, geophysics and rock mechanics, as it is a comprehensive indicator of the rock property. Laboratorial experiments have provided sufficient lines of evidence for the strong correlation between seismic velocity and physical-mechanical properties of the rock medium, such as the Young's modulus, strengths, pore water, porosity, crack property and density, stress conditions, permeability, and joint fillings (e.g.,[1–7]). In seismological studies, velocity anomalies revealed by natural earthquake data are deemed to be important indicators of hotpots and mantle plumes in a global scale (e.g.,[8–10]), of subducting slabs and arc magmas in a regional scale (e.g.,[11,12]), and of active fault zones and source areas of large earthquakes in a local scale (e.g.,[13,14]). Whereas in engineering scales (e.g., tens to thousands of metres), seismic velocity is often investigated from induced seismic data and utilized for engineering purposes including mapping ore bodies, assessing rock qualities and investigating local stress fields (e.g.,[15,16]). In addition, some important properties can be directly derived from seismic velocities, such as the Poisson's ratio and bulk sound velocities (e.g.,[14–17]), which provide additional information on the rock medium.

The widespread adoption of wave velocity is not only due to its close correlation with the properties of rock medium, but also owes to the rapid methodological development of seismic velocity tomography. Since Aki and Lee[18] and Aki et al.[19] imaged 3-D velocity variations beneath seismic arrays using P-wave arrival times, seismic velocity tomography, especially travel-time tomography, has been popularly adopted and widely applied to studies using natural earthquake data, thanks to its robustness and reliability. So far, travel-time tomography is able to handle complex geological and geometrical models, e.g., those containing complex velocity discontinuities.[20,21] The capacity of travel-time tomography has also been extended to image 3-D seismic structure outside a seismic network (e.g.,[22,23]), and to invert different kinds of seismological and geophysical data jointly (e.g.,[24,25]), as well as to obtain fine-scale tomographic images.[26,27] During the past decades,

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travel-time tomography has proven its powerfulness and practical value in natural seismological studies. Similar to the successes achieved in seismological studies, seismic tomography has also proven to be a powerful tool in studies for engineering purposes with smaller scales, such as mining zones (e.g.,[28–33]). In the early 1970s, 2-D velocity images were obtained by inverting well-to-well data produced by artificial sources (e.g.,[34]). Since then, similar tomographic techniques have been frequently applied to mining zones (e.g.,[15,35–37]). The drawbacks of those techniques which utilize artificial sources are obvious, i.e., a large number of data are hard to be collected and the ray paths only crisscross well in a 2-D area, thus the 3-D structure is difficult to be evaluated. To obtain a 3-D velocity model, the US Bureau of Mines conducted a series of active seismic tomographic surveys at the Homestake and Lucky Friday mines using strikes of a 3.6 kg sledge hammer.[38,39] However, these surveys cost time and effort, and cannot keep a sustained growth of data. The passive tomography makes use of abundant micro-earthquakes induced by mining activities, which has been widely applied to mining zones (e.g.,[29,30,32,33,40]). Since the induced seismicity generates an increasing number of data with time, robust and time-lapse images can be obtained with the passive tomography (e.g.,[29]). Although the resolution of passive tomography is limited by issues such as a low source signal spectrum and less accurate source locations, it is still an efficient and effective method to detect the inner structure of underground mines. The result of passive tomography can also be used to detect hazardous areas for more detailed tomographic surveys, such as those using active sources.

Mining zones are typical human activity zones (HAZs), which are characterized by significant changes of the internal structure in a relatively short term, e.g., a few months. These changes are, for example, mining induced surface subsidence, stress redistributions of surrounding rock, and fault slipping, etc.,[41–46] which often show a continuous evolution with time in a limited period and are closely related to mining activities. Fortunately, the intense seismic activities caused by the changes provide abundant data, e.g., hundreds or even thousands of events per day,[30,47,48] making time-lapse tomography possible. Time-lapse tomography can not only reveal the property differences of rock medium in space, but also be able to unearth the influences of mining activities in time. With proper interpretations, the tomography of HAZs can assess the impact on surrounding areas of human activities from the viewpoint of environmental protection, and discover potential unsafe factors from the viewpoint of engineering safety. For both of the purposes, in this study we utilize the human induced micro-seismic data to image the internal structure of a mining zone, by applying a robust initial event-location method and a well-established travel-time tomography which has been successfully applied in the natural seismological field.

## 2. Methodology

### 2.1. Initial locations of seismic events

The initial locations of seismic events are of key importance in local tomography studies, in particular, when the initial velocity model is uncertain. Locating weak seismic events faces another problem: the signal-to-noise ratio (SNR) of the waveforms is often very low, which leads to large picking errors (LPEs).[49,50] The LPEs are likely to bring severe location errors to the initial locations, especially when the seismic array is sparse or the event energy is not large enough to trigger many sensors.[51,52] We employed a LPE-tolerant location method called virtual field optimization method (VFOM) to locate the events in this study.[53] The VFOM establishes a continuous and smooth objective function using travel-time equations of sensor pairs, and searches the space for the event location that makes the objective function maximum. Furthermore, the method contains a filtering mechanism that can recognize and delete the unreliable data automatically, ensuring a high quality of seismic data for the subsequent tomographic analysis.

### 2.2. Travel-time tomography

We applied the tomographic method of Zhao et al.[20] to invert the local earthquake arrival times for a 3-D P-wave velocity (Vp) model of the study area. The tomographic method uses a 3-D ray tracing technique combining the pseudo-bending algorithm[54] and Snell's Law to compute theoretical travel times and ray paths, which has been confirmed to be very robust and efficient by a number of studies (e.g.,[10,55,56]). This tomographic method was originally developed for a study of the Japan subduction zone and adopted the spherical coordinate system.[20] In this work, we adopt the following observation equation in the Cartesian coordinate system:

$$T_{ij}^{obs} - T_{ij}^{cal} = (\frac{\partial T}{\partial x_{ij}})_{ij}\Delta x_{ij} + (\frac{\partial T}{\partial y_{ij}})_{ij}\Delta y_{ij} + (\frac{\partial T}{\partial z_{ij}})_{ij}\Delta z_{ij} + \Delta T_{0i} + \sum_{n=1}^{N}\frac{\partial T}{\partial V_n}\Delta V_n + e_{ij} \tag{1}$$

where $T_{ij}^{obs}$ and $T_{ij}^{cal}$ are the observed and calculated travel times from the $i$th event to the $j$th station, $x_i$, $y_i$, $z_i$ and $T_{0i}$ are the hypocentral parameters of the $i$th event in the Cartesian coordinates, and $\Delta$ denotes the perturbation of a parameter. $V_n$ is the velocity at the $n$th node of a 3-D grid which is set up in the modeling space for expressing the 3-D Vp structure. $e_{ij}$ represents higher-order terms of perturbations and data error. Following Thurber [57], the partial derivatives in Eq. (1) are given by

$$\begin{cases} \frac{\partial T}{\partial x} = -\frac{1}{V_e}\frac{dx}{ds} \\ \frac{\partial T}{\partial y} = -\frac{1}{V_e}\frac{dy}{ds} \\ \frac{\partial T}{\partial z} = -\frac{1}{V_e}\frac{dz}{ds} \\ \frac{\partial T}{\partial V_n} = \int_{source}^{station} -(\frac{1}{V(x,y,z)})^2\frac{\partial V(x,y,z)}{\partial V_n}ds \end{cases}, \tag{2}$$

where $(\frac{dx}{ds}, \frac{dy}{ds}, \frac{dz}{ds})$ are components of the unit vector tangent to the ray path at the hypocentre and pointing in the direction of ray propagation, $V_e$ is the velocity at the hypocentre, and $s$ is the parameter of path length. $V(x, y, z)$ is the velocity at $(x, y, z)$, and is expressed by a linear interpolation of the velocities at the surrounding eight nodes as follows:

$$V(x, y, z) = \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} V(x_i, y_j, z_k)\left[\left(1 - \left|\frac{x - x_i}{x_2 - x_1}\right|\right)\left(1 - \left|\frac{y - y_i}{y_2 - y_1}\right|\right)\left(1 - \left|\frac{z - z_i}{z_2 - z_1}\right|\right)\right] \tag{3}$$

where $x_i$, $y_j$ and $z_k$ are the coordinates of the surrounding nodes.

A distinct advantage of the tomographic method[20] used in this study is that complex-shaped velocity discontinuities can be considered in the model, such as the Conrad and the Moho discontinuities, and the upper boundary of a subducting slab (e.g.,[14,20]). Such an advantage is utilized to consider a thin orebody in this study, which is a natural velocity discontinuity that is located between two different rock strata. A 2-D grid is used to express the discontinuity and its elevation can be expressed as follows:

$$H(x, y) = \sum_{i=1}^{2}\sum_{j=1}^{2} h(x_i, y_j)\left[\left(1 - \left|\frac{x - x_i}{x_2 - x_1}\right|\right)\left(1 - \left|\frac{y - y_i}{y_2 - y_1}\right|\right)\right] \tag{4}$$

where $x_i$ and $y_j$ are the horizontal coordinates of the surrounding four nodes of the 2-D grid, and $h(x_i,y_j)$ denotes elevations of the four nodes, which are derived from geological data.

The system of observation Eq. (1) is solved using the damped least-squares method and the parameter separation technique[20,58].