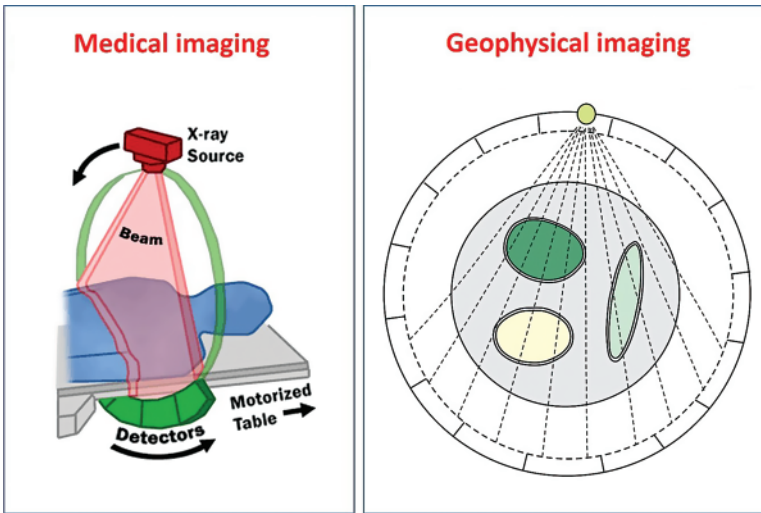


# 1

## Pioneering History

### 1.1 Introduction

Of all geophysical methods, the seismic method is the most promising one in terms of revealing the internal structure and composition of the Earth from a few shallow meters to a deeper few tens of kilometers. The delineation of the subsurface from the seismic method always depends on the type of seismic data acquisitions, which follows recording different seismic waves by a variety of geometries. The wide range of geometries includes seismic reflection, refraction, wide-angle seismic reflection, etc. as part of active-source seismic exploration and engineering applications and for local, global, and tele-seismic, etc. applications as a part of passive seismology. The low-angle seismic reflection data provides better structural information but lacks accurate velocity derivation, whereas the refraction/wide-angle reflection data provides better velocity information but with poor structural resolution of the crust and uppermost mantle. Thus, co-incident seismic reflection and refraction/wide-angle reflection experiments provide an accurate velocity-structure of a region. If the region is complex, such as is the thrust fold belt area or basalt covered province, it is rather difficult to image the subsurface by conventionally processing multi-fold seismic reflection data. Even state-of-the-art, pre-stack depth migration (PSDM) cannot be applied to the near-vertical reflection data without proper velocity information. On the other hand, seismic refraction/wide-angle reflection or ocean bottom seismic data can provide reliable velocity imaging of the subsurface even in a difficult terrain. The traveltimes of wide-angle seismic wave fields, recorded at the surface, are modeled or inverted through forward modeling or inversion theory to produce large-wavelength variations of seismic velocity structure, which can be broadly used for geo-tectonic implications or as an input for pre-stack depth or for reverse time migration for fine tuning subsurface images. Aki and Lee (1976) introduced the technique called seismic tomography, which is initially borrowed from medical imaging. It was used to reconstruct



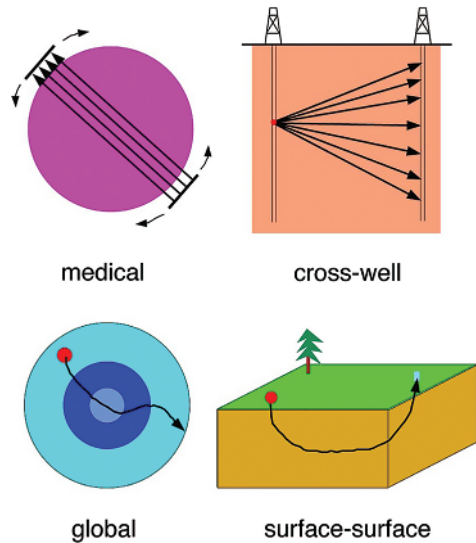
**Figure 1.1** Illustration of medical and geophysical imaging techniques. Left: The emitted X-rays travel through the human body and are detected by detectors; this will be processed to reconstruct bone density using X-rays absorption in medical imaging. Right: The generated seismic waves travel through the Earth and are recorded at different receiver locations surrounded by the Earth. The recorded data will be processed to reconstruct the seismic velocity in geophysical imaging.

the human body's density information through X-ray emissions and density-related absorption (Figure 1.1). The same principles are utilized in geophysical imaging to delineate the velocity from the emission of seismic waves and their components (traveltimes, amplitudes, frequencies, phases, etc.) related to velocity by solving it as an inverse problem (Figure 1.1). The term tomography is derived from Greek i.e., Tomography = tomo + graphy = slice + picture/section.

## 1.2 Applications

Seismic data contains one of the most valuable pieces of information for investigating the Earth's internal structure and composition. A number of methods exists for extracting subsurface structure from seismic data with different objectives in a wide range of geophysical applications (Figure 1.2). Here, we focus on the applications of seismic tomography using different components (traveltimes, amplitudes, frequencies, phases, etc.) of seismic data records. First and foremost, commonly known researchers Aki and Lee (1976) used the seismic tomography technique for local earthquakes delineate the 3D velocity structure beneath California from local earthquakes. The travelttime data was collected by 60 stations from 32 local

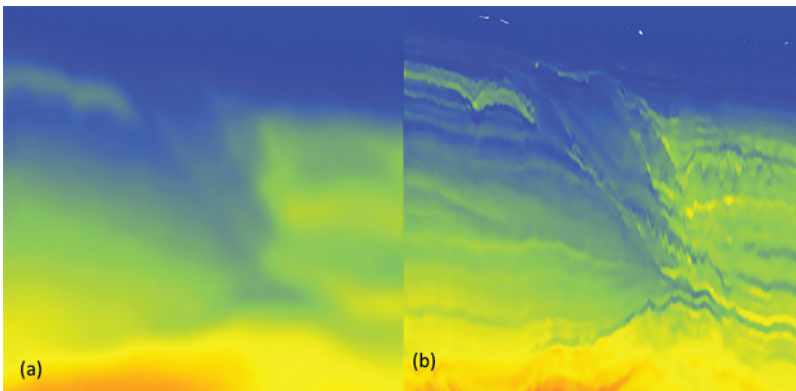
**Figure 1.2** The wide range of applications of seismic tomography includes cross-well studies for petroleum exploration, global studies for tectonic activities, earthquake risks studies for upper crustal faults and basin geometries in understanding geo-tectonics of the region and surface-surface studies for hydrocarbon exploration.



earthquakes. The data parameterized the subsurface into 264 constant slowness blocks and assumed that the inversion was linear because ray paths were assumed as a straight line through the homogeneous initial model. Later many researchers started to use the seismic data either in part or in full for the recorded seismograms for tomography; though it was named differently as traveltime, diffraction, full waveform tomography, etc. However, as traveltime tomography becomes conventional in delineating long-wavelength velocity structures, the other one, full waveform tomography, still challenges the community.

Bois et al. (1972) also implemented the technique for well-to-well recorded data, and their approach used a regular grid of nodes for the parameterization of the subsurface between two wells. In the late '80s and during the '90s, there were numerous studies developed in both raytracing and in wave equation modeling methods. Among those, the most popular studies were by Zelt and Smith (1992) and Zelt and Barton (1998), which used traveltimes by solving the eikonal equation in forward problems and in using the least square inversion methods to minimize the objective function. Zelt and Smith (1992) dealt with both reflection and refractions whereas Zelt and Barton (1998) dealt with refracted or diving, direct and diffracted phases alone except reflection traveltime data to develop the subsurface velocity structure. Taillandier et al. (2009) introduced the adjoint state method for using gradient calculation on traveltime tomography to avoid the ray tracing and estimation characteristic of the Fréchet derivative matrix. Lelièvre et al. (2011) introduced the fast marching method to avoid ray tracing the first arrival traveltime inversion by calculating the sensitivity of information through

an explicit symbolic differentiation of the forward modeling equations and by calculating directly during the forward solution. Huang and Bellefleur (2012) implemented the fast-sweeping method and adjoint-state method for joint inversion of both transmission and reflection traveltimes. The adjoint-state method required the two forward modeling solutions and thus circumvented the computation of the Fréchet derivative matrix estimation. This method also facilitates that the gradient can be calculated independently for each shot. Waheed and Alkhalifah (2015) extended the adjoint-state method to anisotropic media by taking advantage of the anisotropic eikonal solvers developed by Waheed et al. (2014, 2015). Afterward, Waheed et al. (2016) then introduced anisotropic first arrival traveltime tomography based on the adjoint-state method. On the other hand, in the early 1980s, the researchers started to develop numerical solutions for the wave equation for seismic exploration problems (Bamberger et al. (1982) and Tarantola (1984)). This helps exploit all types of seismic waves in synthetic seismograms to image the Earth's subsurface and is coined as full waveform tomography. Pratt and Worthington (1988), Pratt and Gouly (1991), Geller and Hara (1993), Song et al. (1995), Pratt and Shipp (1999), Pratt et al. (1998), and Pratt (1999) applied the full waveform tomography in frequency-domain, and Kolb et al. (1986) and Gauthier et al. (1986) applied in time-domain full waveform tomography. Further, Shin and Cha (2008) suggested an alternative Laplace-domain waveform inversion to sensitivity toward the initial model, which lacks in low frequency components. The wide-angle full waveform tomography is the main topic in advanced seismic imaging techniques, and the studies of Brenders and Pratt (2007a, 2007b) and Operto et al. (2006) from can be treated as benchmark.



**Figure 1.3** The sample derived velocity structure from (a) Traveltime tomography and (b) Full waveform tomography. (Kapoor et al., 2013).

However, we have very limited successful full waveform tomography applications within the field of seismic data due to various aspects like initial model, non-linearity of the problem, lack of low-frequencies, computational costs, etc. Alkhalifah (2015a, 2015b) analyzed the influence of scattering angles to the gradient model that propagates to update the model; we need to be cautious in the selection of scattering angles. Over the decades, tomography is a conventional method either by traveltimes alone or by full waveform for purposes of exploratively imaging the velocity model. Ray-based traveltime tomography gives the long wavelength structure, and this can be used as an initial model for full waveform-based techniques to delineate the sub wavelength structure of the subsurface (Figure 1.3).

### 1.3 Terminology

**Data:** The known direct measurements made by the observer from the real world with a specific objective.

**Parameter:** The unknowns that we want to answer in terms of numerical values of the specific properties of the world.

**Model:** The defined relationship between the data and parameters is referred to as the model. It is used for calculating the unknown properties from the known measurements of the world.

**Tomography:** It is a type inverse problem by which we determine the model structure by means of back projecting data along a path that connects a source and a receiver.

