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Seismic Tomography from the Old to the New Millennium

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Abstract During the past two decades, seismic tomography has been landing from the blue sky of academic or pioneering papers to the hard ground of industrial processing over a large scale. Actually, this happened for a few specific applications, such as tomostatics and velocity modeling for prestack depth migration. Other more recent or sophisticated developments, involving full waveform inversion or interferometry, are still maturing in terms of theoretical refinements or viable implementations. In this paper, I review the major practical or theoretical impact. I also propose a list of weak or missing items in the state-of-the art technology that needs to be addressed, to cope with current challenges in exploration, monitoring and production of unconventional tight gas.

Keywords Seismic tomography · Traveltime inversion · Reservoir monitoring · Seismic imaging

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الخلاصة

خلال العقدين الماضيين هبط التصوير المقطعي الزلزالي من السماء الزرقاء للدراسات الأكاديمية أو الأوراق العلمية الرائدة إلى الأرض الصلبة للمعالجة الصناعية على مدى نطاق واسع. وقد حدث هذا في الواقع لتطبيقات محددة قليلة، مثل توموستاتيك ونمذجة السرعة لعمق الهجرة ما قبل المكدس. وآخر التطورات التي حدثت مؤخرا أو المتطورة التي تنطوي على انقلاب موجي كامل لا تزال تنضج من ناحية التحسينات النظرية أو التطبيقات القابلة للحياة.

وسوف نستعرض في هذه الورقة العلمية التقدم الكبير الذي شهده التصوير المقطعي الزلزالي خلال السنوات الخمس عشرة الماضية أو نحو ذلك، محاولين تسليط الضوء على المساهمات بتأثير أعلى من الناحية العملية أو النظرية. واقترحنا أيضا قائمة من العناصر الضعيفة أو المفقودة في دولة التكنولوجيا الحديثة التي تحتاج إلى معالجة، لمواجهة التحديات الراهنة في مجال الرصد وإنتاج غاز ضيق غير تقليدي.

1 Introduction

The goal of seismic tomography is to estimate a 3D Earth model of rock parameters such as P and S velocity and Q factor and possibly their anisotropic and time-varying behavior. Several different complexity levels exist in the literature, depending on the model choice, the type of waves considered and their modeling algorithm (e.g., traveltime versus full waveform). Different approaches are available to reduce the ambiguities due to multiple acceptable solutions, especially when the available data and the chosen Earth model do not match. In this paper, I review recent advances in seismic tomography during our new millennium and a few years earlier, while highlighting what needs to be done to meet the current challenges.

Seismic tomography has been used by earthquake seismologists quite earlier than exploration geophysicists [1–3]. A milestone paper for the latter ones was presented by Bishop et al. [4], who first tried to apply reflection tomography at a large scale for industrial purposes. Their paper underlines two key problems that, in my opinion, still need improvement in:

1. the mutual dependence of velocity model and reflectors' depth errors [5–7];
2. some kind of smoothing or constraints in the inversion to control the solution uniqueness.

The first problem has been partially solved by the interpretive processing of 3D pre-stack depth migration, and the related literature is abundant. A good tutorial and overview of this approach is provided by Fagin [8], based on a widely used commercial software. A 3D velocity macro-model is built by a layer-stripping method, which requires the interpretation of the main reflecting interfaces. Using interactive computer graphics, the main Earth's formations are imaged in sequence from the shallowest to the deeper ones. This method can provide 3D images of outstanding quality in depth, which is often the main structural model for exploration and production of hydrocarbon, CO_2 sequestration and gas storage. However, its precision is often inferior to what is expected or claimed, either because of near surface complexities (Vesnaver [9], among others) or because of inherent precision limits of the velocity analysis using the common-image gathers [10].

The second problem is clearly presented in the classical book of Nolet [3] by van der Sluis and van der Vorst [11]. The non-uniqueness of tomographic inversion can be reduced or eliminated by various terms that may impose local or global smoothness, but at the expenses of introducing a relevant personal bias or reducing the image resolution. These major drawbacks, unfortunately, are often presented as obvious and unavoidable, and rarely quantified. Adaptive models and a deep integration of all available data are much better remedies, but not popular, because they require more demanding processing and software development.

In the next section, I will review recent technologies for minimizing these two drawbacks and extend the information we obtain from geophysical data on the rock properties. I will deal mainly with traveltime inversion, although these two topics are merging into one over the years: the travel time inversion is becoming part of full-waveform inversion or pre-stack depth imaging, providing initial macro-models.

2 Tomostatics

The application of seismic tomography that has been most successful at the end of the past millennium is tomostatics. When the near-surface formations are highly heterogeneous and change laterally in both thickness and physical properties, the seismic signals emitted and recorded at the Earth surface are significantly distorted. If such a distortion is not recognized and removed, the image of the deeper formations and possible hydrocarbon reservoirs may be blurred or deceiving. As most oil and gas reserves are located on land, mitigating this problem has a major industrial impact.

The term tomostatics was coined by Zhu et al. [12], whose work can be considered a generalization of the classical refraction statics. A key advantage of this approach is that first arrivals are picked without assigning them to a specific refracting interface. Assuming for the velocity field a smooth, monotonically increasing trend, head waves (even from different interfaces) are approximated by diving waves, i.e., direct arrivals that are bent by such a velocity distribution (Fig. 1). Such Earth model approximates multi-layer refractions, so it is not surprising that better results are obtained than when using a simple one-layer or two-layer model. Unfortunately, tomostatics' approach reduces but does not remove the key weakness of refraction statics, i.e., its inability to estimate accurately low-velocity layers. Vesnaver [9] pointed out that when only diving waves are modeled or available, the

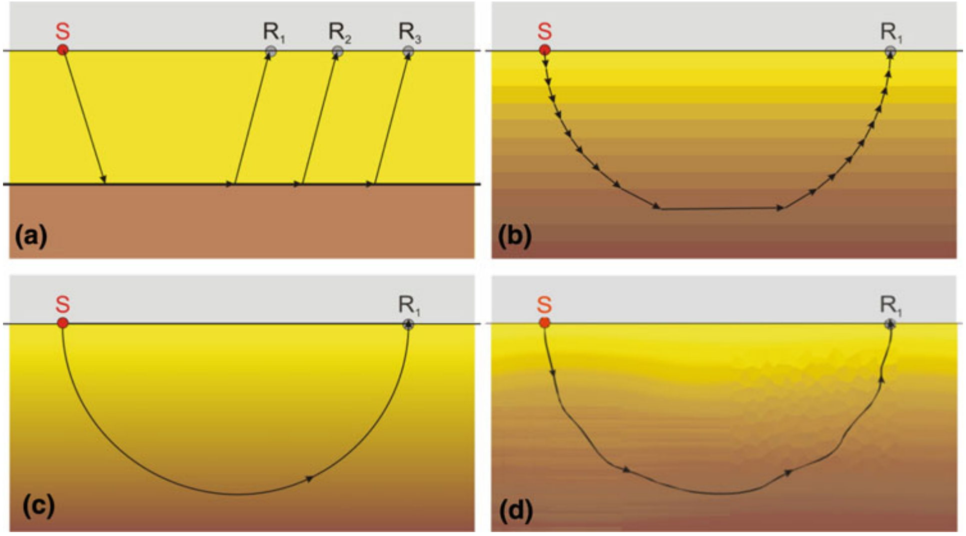


Fig. 1 Ray paths for head waves in medium with one layer (**a**) or multiple layers (**b**); a diving wave in a medium with a vertically increasing velocity (**c**) and the irregular path in a heterogeneous medium (**d**), which can be approximated by a diving wave

estimates may be severely biased by the initial model: different assumption about the vertical velocity gradient may provide different solutions.

Zhang and Toksöz [13] introduced an algorithm to enhance the stability and convergence speed of traveltime inversion for refracted arrivals. They minimized the misfits of the average and the apparent slowness, i.e., respectively, the ratios of traveltimes to the corresponding ray lengths and the derivatives of traveltimes with respect to distance.

The joint inversion of refracted and reflected arrivals can improve the near-surface velocity estimation, reducing the ambiguities by feeding more data into the inversion process. Miller et al. [14] proposed a better model for the shallow layers to obtain more accurate static corrections and stacking velocities on land in 2D, and Bergman et al. [15] in 3D. Zhu et al. [16] exploited the increased data redundancy of 3D surveys to analyze possible apparent anisotropy in the near-surface velocity due to fault patterns.

Static corrections become critical when topography introduces major time delays within limited distances in the survey. Zhou et al. [17] introduced a robust method that parameterizes the near surface by a stack of quasi-parallel layers, whose shape is deformed iteratively to accommodate both the known elevation and some deep known reflecting interface.

3 Stereotomography

Stereotomography was introduced by Billette and Lambaré [18]. The initial motivation was to simplify the traveltime picking procedure, reducing or just eliminating the interpretation of coherent event. Normally, the signals from a reflector or refractor are picked in the pre-stack gathers and assigned to a specific interface. Especially for land data, where the signal/noise ratio may be poor, or in marine data contaminated by multiples, such an effort may be very demanding. So the idea was to (semi)-automatically detect coherent events, even sparse, and estimate a velocity model able to fit them. However, in my opinion, the main benefit of stereotomography is adding an effective constraint to the traveltime inversion by analyzing, in addition to the traveltimes, the slope of wavefronts in different pre-stack domains: common offset, common receiver, common source and common mid-point. Billette et al. [19], Alerini et al. [20] and Lambaré [21] presented this procedure for isotropic media, and Barbosa et al. [22] extended it to anisotropic media. The velocity model obtained in such a way can improve the pre-stack depth imaging.

A major "*caveat*" for this method is the possible contamination of multiple reflections. If the picking of coherent traveltimes is carried out before any multiple reduction procedure, reverberations may be mis-interpreted as primary reflections, especially if the velocity difference between adjacent events is small. In that case, the estimated velocities may be too low or even unstable.

4 Modeling and Inversion Strategies

Reducing the ambiguities in seismic tomography, i.e., the range of possible or acceptable solutions, has been pursued traditionally by introducing damping factors or smoothing operators in the inversion algorithm. An alternative to such approach is adapting the Earth model to the ray path distribution and the estimated velocity anomalies in sequence [23–25], using Voronoi polygons and Delaunay triangles instead of the more popular regular grids. Zhang and Thurber [26] extended such approach to tetrahedral voxels.

Staggered grids follow a different philosophy. Instead of increasing the resolution of the tomographic grid, so increasing the solution ambiguities too, they adopt low resolution regular grids, which differ to some extent for the grid origin position. Averaging the estimated velocities, we obtain a higher resolution image that is less contaminated by ambiguities [27,28].

Low spatial frequencies can be estimated using coarse tomographic grids, which are so populated by many ray paths and computationally well constrained. Starting the tomographic inversion with low-resolution grids and refining them at later iterations is the multi-scale strategy presented by Zhou [29], Operto et al. [30] and Delost et al. [31]. This approach has the relevant advantage of partly decoupling the estimation of well- and ill-posed parameters in the Earth model.

The core solvers for the traveltime inversion did not evolve significantly over the past decade, as a high level of computational efficiency was already available by sparse matrix inversion algorithms. A good overview of basic algorithms as Algebraic Reconstruction Technique (ART), Simultaneous Inversion Reconstruction Technique (SIRT) and conjugate gradient is provided by the classic papers of Lines and Treitel [32] and van der Sluis and van der Vorst [11], and by Michelena [33] for Singular Value Decomposition (SVD). Similarly, efficient implementations of minimum-time ray tracing were introduced by Moser [34], Asakawa and Kanawaka [35], Fisher and Lees [36] and Vesnaver [37]. This approach is more robust and efficient than algorithms based on the eikonal equation, which requires a smoothly varying medium [38–41]. However, in the presence of caustics and diffractions, the asymptotic ray theory may be preferred [42].

5 Elastic Inversion

The ratio between velocities of P and S waves is an important petrophysical attribute, as its anomalies can detect changes in the fluid saturation, thus potentially delineating reservoirs. Its estimation requires doubling the number of model parameters and triplicating (at least) the input data size, as three-component receivers become necessary to separate P, S and converted waves. However, a fully elastic traveltime inversion may become more stable and reliable than an acoustic one, i.e., based on P waves only. Rossi and Vesnaver [43] remarked the redundancy provided by converted waves: they add new information to that one from P and S waves without requiring additional parameters than P and S velocities. In addition, as the ray paths of converted waves are different from P and S waves, one can obtain a better ray coverage.

In marine surveys, Ocean-Bottom Cables (OBC) can record both P and S waves, although the seismic source emits P waves only into the seawater. Ursin et al. [44] developed the theory to model and invert the traveltimes and geometrical spreading of P and PS converted waves.

Foss et al. [45] were able to include both elastic and anisotropic parameters in the reflection tomography, exploiting the angular dimension in pre-stack seismic data with full-azimuth coverage.

The practical implementation of acoustic or elastic traveltime inversion is quite similar. When it comes to ray tracing for pure P or S waves, the only difference is that P or S velocity used to compute the traveltime along the ray path, as well as the ray path itself. When converted waves are modeled, the interfaces where the conversion occurs must be specified. For the inversion part, the size of the tomographic matrix is doubled, but the solving algorithms remain the same.

6 Anisotropy

Reducing the uncertainties in the estimation of P and S velocities in an isotropic Earth model is still an open challenge. However, when the signal quality is good and the ray coverage is well distributed in space, we can extract finer information from seismic data as azimuthal anisotropy or transverse isotropy [46–48]. The azimuthal dependence of velocities is often related to coherent fault and fracture patterns, while the dip dependence may be due to fine layering or just rock compaction effects. Pioneering work on seismic anisotropy dates back a few decades ago, mainly in mining or cross-well data [49]. More recently, case histories for hydrocarbon exploration took advantage of progresses in the recording geometry as 3D VSP [50,51], OBC or full-azimuth 3D surface surveys [52].

Ray tracing in anisotropic media is more complicated than in isotropic cases [53]. Dwornik and Pieta [54] generalized it to the anisotropic case for the technique of Fischer and Lees [36] based on graph's theory, but they used it so far only for direct arrivals.

7 Time-Lapse Tomography

Time-lapse (or 4D) seismic has been the last major breakthrough at the end of the twentieth century. The pioneering work of Nur [55] and Lumley [56,57] opened the way to a new era of research, technology development and commercial activities that is still flourishing and developing. The key idea was imaging a reservoir at different production stages and comparing the changes over time of the seismic response. Ideally, subtracting the images taken before the production start (base survey)—from others taken at later production stages (monitor surveys)—one can obtain an estimate of the fluids' flow in the reservoir. This simple concept, however, is very challenging when it comes to implement it in a real experiment. Coupling and position of sources and receivers may change significantly, thus reducing the survey repeatability.

A major challenge that involves seismic tomography is the velocity variation in the shallow layers due to seasonal factors, as discussed by Rossi et al. [58] and Bertrand and MacBeth [59]. At sea, this is due to temperature and salinity changes in the upper mixed layer, where thickness is a few dozens of meters. On land, the water table depth and the moisture saturation in the weathering can change significantly in areas with normal or significant rain seasons, but at some extent even in arid regions.

Vesnaver et al. [60] introduced the time-lapse tomography. They imposed local constraints to velocity and structure variations among the Earth models estimated by different surveys, repeated over a producing reservoir over the years. At the reservoir and in the near surface (Fig. 2), the velocities may freely change over time, but elsewhere the possible differences (mainly due to estimation errors) are forced to be zero, by averaging the estimated local velocities over time among the different surveys. In most cases, by neglecting subsidence or uplift effects, one can average the local depth of the model interfaces (Fig. 3), thus reducing the errors in the estimated structure. A key advantage of this method is the increased data volume used to estimate the interfaces and the velocities outside the reservoir, reducing the near-surface contribution. The obtained velocity field can improve the prestack depth migrated sections. In Fig. 4, the reflections are more noticeable. In Fig. 5, in addition, one can see some structural differences both at the left and at the right sides.

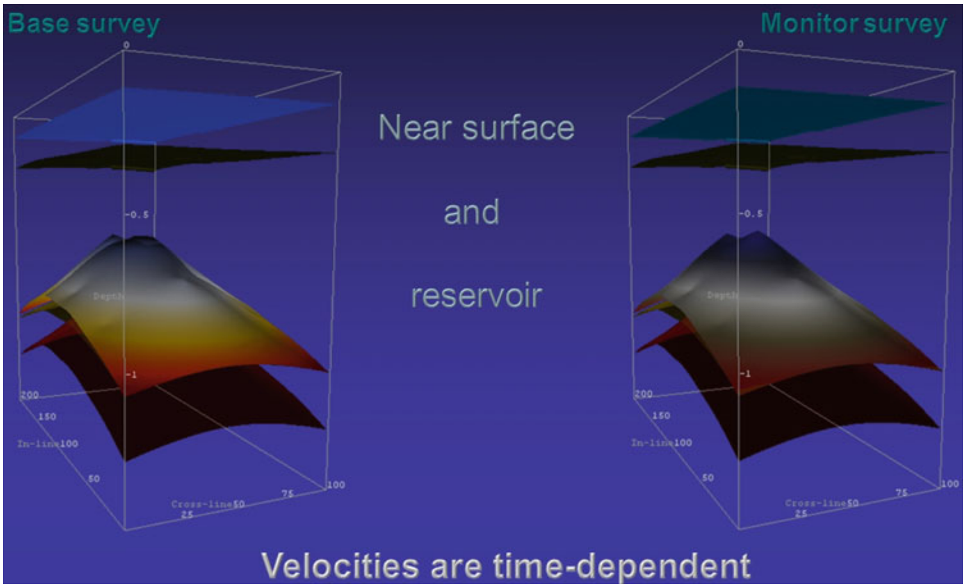


Fig. 2 In time-lapse tomography, the velocities of the near surface and at the reservoir are survey-dependent, while elsewhere they are constrained to be constant over time, for all available surveys

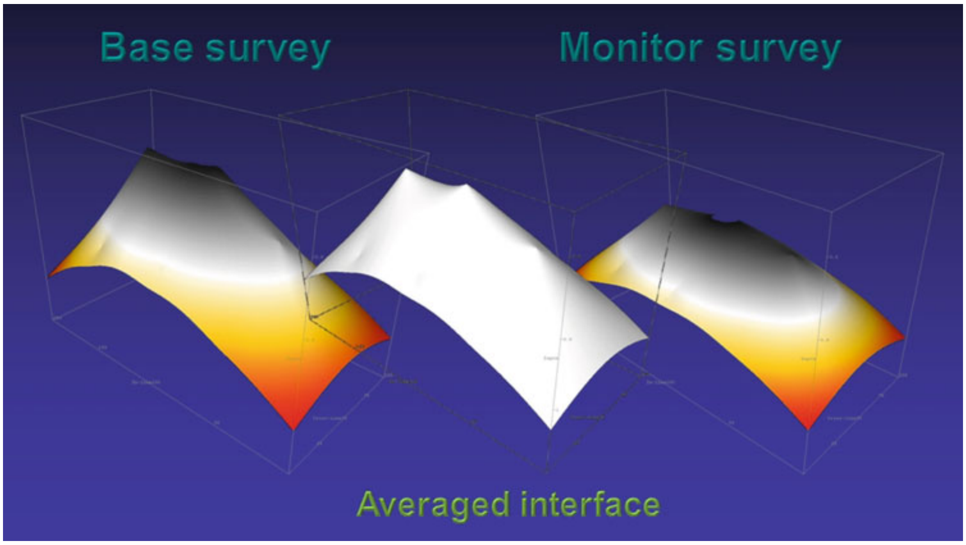


Fig. 3 Interfaces estimated by reflection tomography from the base and monitor surveys are averaged, if major uplift or subsidence effects are negligible

8 Passive and Active Seismic

Over the last two decades, petroleum engineers have used microseismic surveys to monitor the fracking operations and to stimulate production. Only in this century, microseismic has been used as a tool for reservoir monitoring, especially in areas where time-lapse seismic is not applicable. Micro-earthquakes can detect the areas where the injected fluids penetrated and displaced the hydrocarbons, either reactivating existing faults and fractures, or creating new ones. This procedure is an optimal production method, when brine is injected into the Earth to displace oil and push it towards the producing wells. In addition, monitoring the depth and location of micro-earthquakes is critical for seasonal storage of natural gas or for geological storage of CO_2: in both cases, one has to be careful not to damage the cap rock of the reservoir. Thus, the injection needs to be terminated if micro-earthquakes occur at shallow depth, i.e. close or even above the cap rock.

Micro-earthquakes are very weak events, mostly with a negative magnitude, which can be observed sometime only by deploying receivers in dedicated wells. In addition, the estimation of the hypocenter (i.e., the micro-earthquake coordinates) and its time origin depends heavily on the 3D velocity model for P and S waves.The only way to estimate reliable hypocenter locations is by well calibration using surface and borehole 3D active seismic at sources and receivers [61]. By combining active and passive seismic, one can improve the accuracy of hypocenter estimation. Furthermore, the micro-earthquakes become additional illumination sources, which improve the resolution and reliability of traveltime inversion [62].

Fig. 4 Pre-stack depth migrated sections using 3D velocity models obtained by conventional (**a**) and time-lapse reflection tomography (**b**) (modified from Vesnaver et al. 2003)

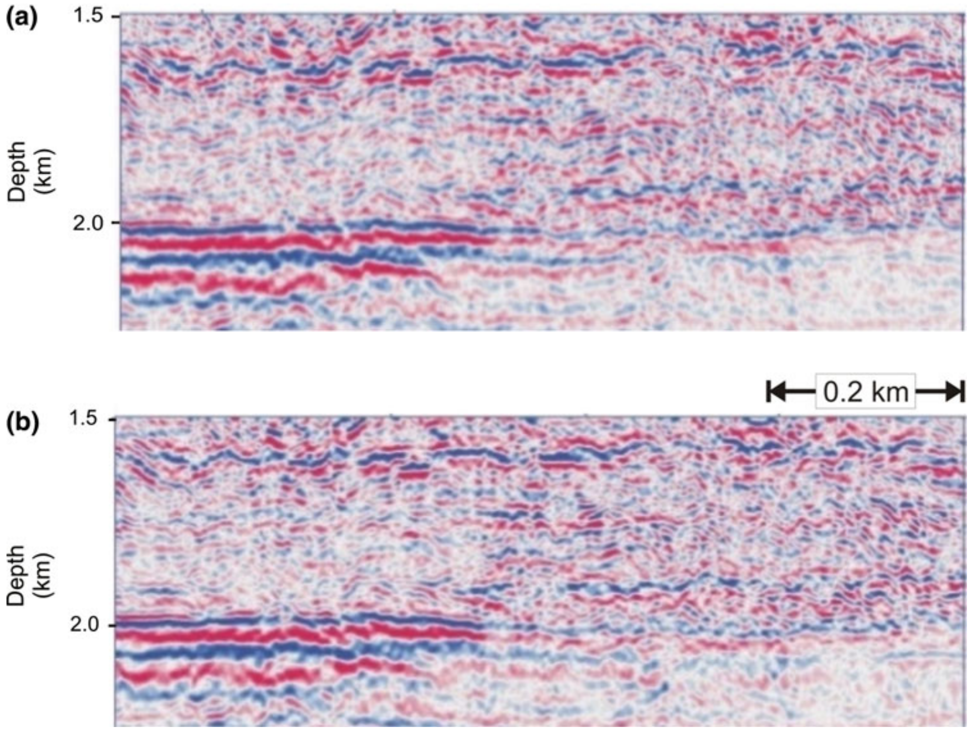
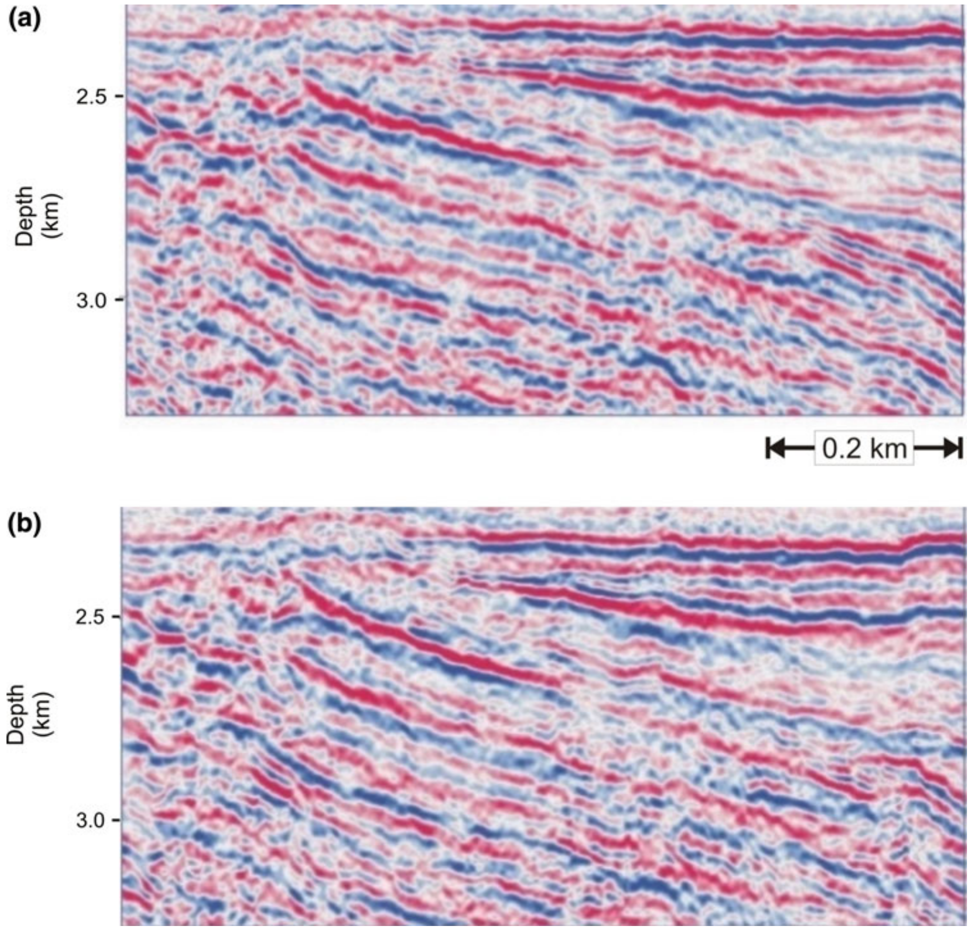


Fig. 5 Pre-stack depth migrated sections using 3D velocity models obtained by conventional (**a**) and time-lapse reflection tomography (**b**) (modified from Vesnaver et al. 2003)



The origin time of micro-earthquakes is an additional unknown that complicates the tomographic problem. Got et al. [63] and Zhang et al. [64] applied the double-difference method to passive seismic, adapting it from global seismology. They achieve better inversion stability, but less accurate in estimating absolute hypocenter location.

When first-order problems are resolved (as velocities and hypocenter locations), one can start analyzing higher order problems, as detecting anisotropy. Verdon and Kendall [65] observed S wave splitting in microseismic data, getting a clue about the fracture pattern in a reservoir. Gei et al. [66] quantified the accuracy needed, and proposed a star-like acquisition geometry to observe the vertical transverse isotropy in a dedicated observation well.

9 Towards the Full-Waveform Inversion

Moving from traveltime to full-waveform inversion is a natural evolution from a simplified to a more accurate Earth model. The early work by Woodward [67] and Zhou et al. [68] highlighted the advantages of such approach, but the computational capacity allowed at that time just 2D applications as cross-well imaging [69]. Over the years, the increasing computational power at affordable costs has been paving the way to a wider use of full-waveform inversion [30,70]. Instead of reducing the need of traveltime inversion, practical experience shows that the macro-model provides an ideal initial model for the full-waveform algorithms [52]. If such an initial model is poor, the full-waveform inversion may never converge to an acceptable solution.

In principle, full-waveform inversion allows extraction of more information from the seismic data. In addition to traveltimes (for P and S velocity) and amplitude decay (for Qp and Qs factors), the phase rotation of wavelets and the Amplitude Versus Offset (AVO) may be estimated, providing constraints about the density contrasts at the layer interfaces. Density anomalies may be related to gas reservoirs, in an exploration framework, or may be induced by hydrocarbon production or CO_2 injection. The information extracted from full-waveform inversion is, therefore, very important for industrial applications.

10 Towards a Shared Earth Model

Although P and S velocities are the key parameters that traveltime (and full-waveform) inversion is going to estimate, other parameters may be included into a shared Earth model to better characterize the rocks. Besides anisotropy and micro-earthquakes hypocenters, the anelastic absorption may give us a clue about possible saturating fluids. The signal amplitude allows estimating the Q factor, if a sophisticated and challenging amplitude-preserving processing sequence is adopted. Quan and Harris [71] introduced a less demanding approach, further developed by Rossi et al. [72], based on the frequency analysis of seismic signals.

The integration effort for the joint or coupled inversion of seismic, electro-magnetic and gravity data has been continuing over the years, but is becoming more and more accurate and efficient [73,74]. Antonelli et al. [75] presented a cross-well experiment where both direct and reflected seismic arrivals were inverted and correlated with gamma ray and density logs, whereby obtaining a good correlation between seismic and petrophysical properties. Herwanger et al. [76] used seismic and electrical measurements jointly in an attempt to link the observed anisotropy to rock fractures and fabric.

Seismic-while-drilling provides an unusual synergy between conventional seismic surveys and drilling operations. Rossi et al. [77] and Eidsvik and Hokstad [78] showed that the joint inversion of active and drill-bit data can extend the illumination area and make more robust calibration between conventional seismic data and well logs.

11 Conclusions

During the last decade or so, seismic tomography moved its focus from traveltime inversion to an integrated, full-waveform approach, able to reconcile data from different origin into a shared Earth model. In my opinion, such a trend is likely to consolidate and continue in the future. This is the major strength of seismic tomography.

Relevant challenges are posed by the availability of large dataset [79]: acquisition systems with 100,000 channels are operational today, and new ones with 1 million channels are being built. Multi-component receivers may increase the data size by a factor of 3 or 4 (for OBC data, including an hydrophone), or even by 9 when both P and S seismic sources are used. This huge amount of data could force full-waveform inversion to remain unpractical and unaffordable tool unless efficient and reliable algorithms for automatic picking become readily available.

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