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Imaging with buried sources

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ABSTRACT

Because the shot-profile migration algorithm largely mimics the data acquisition process, simple thought experiments may extend its utility to image the subsurface with less conventional geometries and/or sources. Imaging with the forward- and backward-scattered wavefields in an elastically modeled earth from buried sources is easily implemented without the development of new tools. With this potential in mind, we identify several novel applications of this wave-equation imaging technique, detail the requirements and processing required for its success, and give an example of the process and results by applying these concepts to a crustal-scale imaging experiment using emergent teleseismic plane-waves as sources.

INTRODUCTION

Conventional seismic reflection surveys are largely constrained to sources detonated on the surface of the earth. Correspondingly, most of the advanced imaging techniques of proven value have been developed to migrate these types of data sets. One subset of sources generally excluded from the purview of seismic imaging is those originating at depth, including both active (e.g. VSP) and passive (e.g. micro-fracture) generated energy. The predominant reason for their omission is because of a lower applicability during the exploration stage. This is largely due to longer acquisition times, lower average source S/N ratios, the need for three-component data, and the irregularity of source distributions. However, the generality of wave-equation methods allows for the adaptation of exploration-oriented imaging techniques to novel non-exploration geometries. This fact provides the motivation for identifying a number of candidate experiments where buried sources may be used to image the subsurface using adapted imaging techniques.

Shot-profile migration shows an impressive adaptivity to acquisition geometries incorporating subsurface sources. One of this method's strengths is that reconstructions of source wavefields originating in the subsurface easily honor the geometry of individual experiments. These wavefields are used, in turn, to image components of both the forward- and back-scattered wavefields. This is accommodated by a proper selection of the sign of the exponential used to propagate the wavefields. Further, the ability to choose different velocity models by which to propagate each wavefield adds the ability to image with converted energy modes.

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We propose the application of seismic imaging methods to a suite of problems centered on the utilization of energy originating from buried sources. Geometries potentially suitable for imaging include both natural and induced fracture point sources, teleseismic plane waves, downhole VSP, similar to Harwijanto et al. (1987), and borehole tomography. All of these applications require a minor amount of pre-processing of the scattering wavefields contained in recorded data, the construction of appropriate source wavefields, and the generation of appropriate compressional and shear velocity models for use in the shot-profile migration algorithm.

To these ends, we present an overview of the processing flow, and point of some of the difficulties likely to be encountered when imaging with buried sources. After a general discussion of the methodology, we then apply the processing flow to the case of teleseismic imaging for a demonstration and to provide a proof of concept.

METHODOLOGY

In this section, we outline the steps for preparing data from buried sources for imaging. Figure 1 illustrates the work flow. Central to each of these new applications is the careful attention to the geometry and characteristics of the source wavefield. To be able to utilize these alternative sources, in many cases the first stage is determining when and where an event has occurred. The primary energy mode (i.e., P or S-wave) and the direction of first motion must then be determined to enable characterization of the available scattered phases. After this information is ascertained, an appropriate source wavefield is constructed for input to the migration.

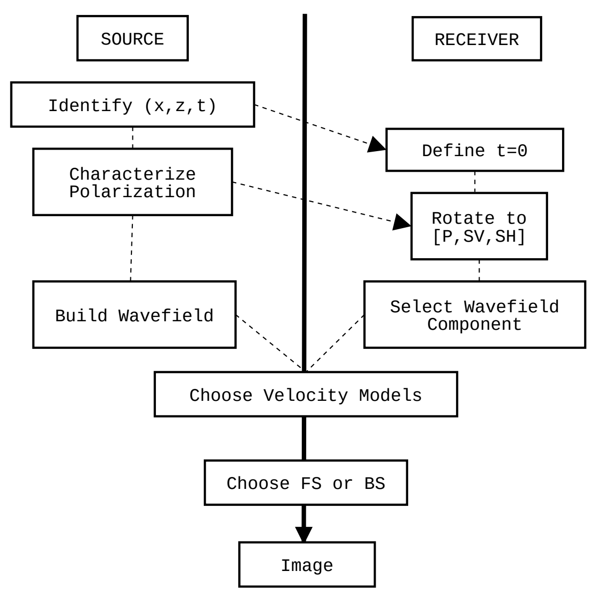

Figure 1: Flow chart illustration the steps to prepared data from buried sources for multi-mode migration. Solid line shows overall direction of processing flow. Dashed lines show dependancies. jeff2-Flow [NR]

After identifying source parameters, time zero and the total length of the record to be migrated is determined. Three-component receiver arrays are necessary to exploit the full range of wavefield scattering combinations in these experiments. With the introduction of vector displacements, a rotation of data components is defined that maps energy from the recording geometry $[Z,N,E]$ to an alignment with source wave vector axes $[P,SV,SH]$.

The Table below summarizes all of the information required to generate images from various combinations of scattering modes for a source with an initial P-wave polarization. In the first column, FS and BS represent forward- and backscattering, respectively. Forward-scattered wavefields are introduced in a manner akin to the exploding reflector model of seismic imaging. The forward-scattered source wavefield propagates through the model space in the same direction as the data wavefield. This introduces the only substantiative modification to the shot-profile algorithm. This is implemented by a change in the sign of the exponential in the SSR equation (column 2). Additionally, the interaction of the primary source with the free-surface gives rise to downward reflected P- and converted S-wavefields that are, in turn, back-scattered in a manner similar to conventional reflection experiments. The second field in the first column indicates the various mode transitions available for use in migration. These are abbreviated by their source and receiver phases.

The third column contains the source and receiver velocities required to produce the desired image. The final column identifies the receiver component in which the individual scattering components are expected. Notice that there are a number of different modes in the P and SV sections and, accordingly, cross-mode contamination will occur.

Scattering Mode	Source Prop. Dir.	S. Velocity	R. Velocity	Rec. Component
FS P-P	-	P	P	$\overline{P}$
FS P-S	-	P	S	$\overline{SV}$
BS P-P	+	P	P	$\overline{P}$
BS P-S	+	P	S	$\overline{SV}$
BS S-P	+	S	P	$\overline{P}$
BS S-S	+	S	S	$\overline{SV}$
BS S-S	+	S	S	$\overline{SH}$

The ability to realize these conditions is highly dependent on the nature of the candidate buried source. Specifically, imaging with local earthquakes and induced micro-fractures requires a prior inversion for a source's nucleation location and rupture time. Additional issues are the correct identification of dominant energy mode and polarization, and perhaps a deconvolution of source functions of potentially significant complexity. In applications to reservoir monitoring or the imaging of a major fault zone (e.g. San Andreas), a proliferance of 3-C receivers at the surface and incorporation of existing velocity model provides background information to locate and characterize micro-tremor sources. Down-hole geometries make realizing these conditions somewhat easier since the spatial and temporal location of the source are known.

EXPERIMENTS

In this section, we present an example of the application of the shot-profile migration algorithm to a synthetic teleseismic earthquake data set. (For additional information regarding the synthetic data set refer to Shragge (2003)). The first step in imaging process is identifying the probing energy, and separating from all other phases emanating directly from the source. In teleseismic imaging, this is simplified by the fact that P- and S-waves are well separated in time at large epicentral distances due to differences in P- and S-wave velocity magnitude. In this case, we use P-waves because the provide a better S/N ratio than latter arriving phase. To characterize the teleseismic source, we exploit the fact that teleseismic arrivals are planar after traversing large distances (Shragge, 2003). Knowing the location of the earthquake, precise dip and azimuthal orientation of these plane waves can be calculated using standard 1-D reference earth models. Having thus characterized the source, we can construct a wavefield for use in the migration to come. An example of a modeled teleseismic source wavefield is presented in Figure 2a.

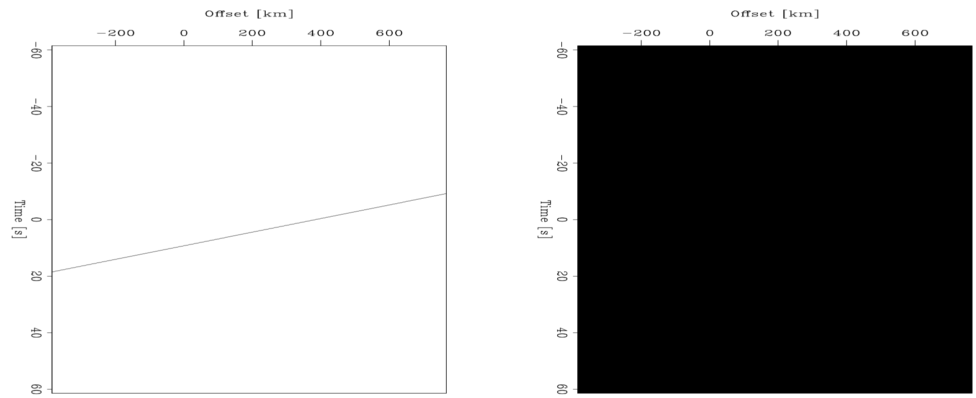

Figure 2: a) Constructed source wavefield; b) SV component of the (rotated) receiver wavefields. The data are immersed in a large field of zeros to allow for the correct migration of back-scattered energy that does not reflect from the free-surface within the length of the receiver spread. jeff2-sourcedata [ER]

The first stage in preprocessing the data is to identify zero time. Although this generally involves time-windowing about the estimated arrival time, with synthetic data it is a straightforward task. The dip and azimuth parameters from source characterization are used to define the appropriate receiver wavefield rotation from [Z,N,E] to [P,SV,SH]. Figure 2b presents one component of the rotated data.

We present the results of two different migrations in Figure 3. Figure 3a and 3c present the forward-scattered P-S converted mode and the backscattered P-P mode images, respectively. The model used to generate the finite-difference data is presented for reference in Figure 3b. The appropriate exponent and velocity models for are given in Table 1. The incorporation of $v(x,z)$ velocity models in the wave-equation migration leads to better positioning of model structure relative to other telseismic imaging techniques (Shragge et al., 2001; Shragge, 2003). This method also affords all the common advantages of wave-equation depth imaging in complex media.

CONCLUSIONS

Imaging the subsurface with wave-equation migration algorithms can be extended in exciting ways to encompass new experiments. Combinations of natural or induced seismicity, and sur-

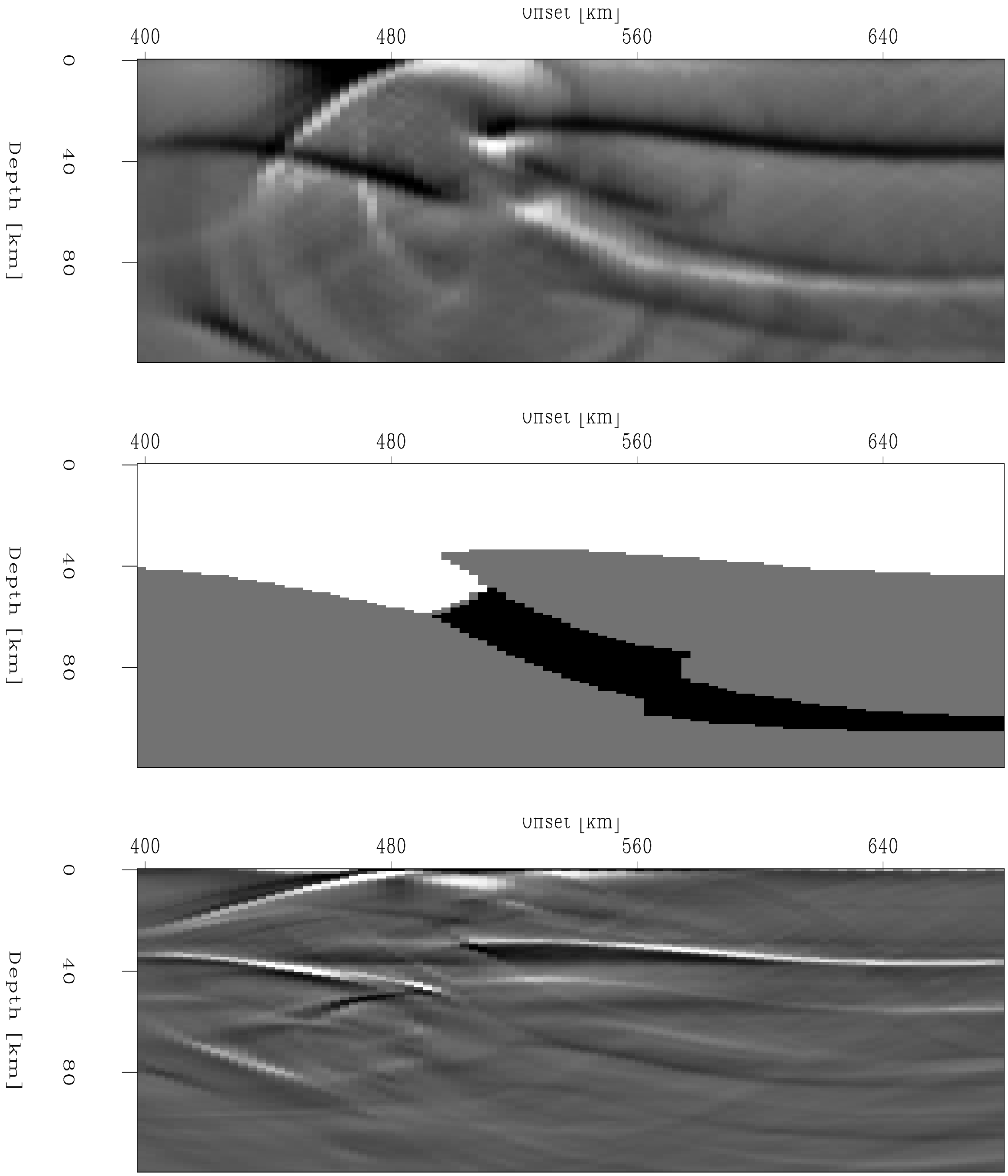

Figure 3: a) Forward-scattered P-S mode image; b) Synthetic Model; c) Backscattered P-P mode image. jeff2-fsbs [CR]

face and down-hole sources and 3-C receivers has the potential to greatly extend the scope of imaging techniques. To demonstrate the generalized processing flow, we have used a synthetic buried source to generate two complementary images of model structure. By extension, the same methodology can be used to produce five additional images using other scattering modes extant in the teleseismic section. Buried sources closer to our array undergo a transition from plane-waves to point-like sources. We speculate that these can also be utilized for imaging by following the procedures outlined above. The application of these ideas would be most readily accomplished in cross-well tomography and VSP experimental geometries. The potential for reservoir monitoring using pressure-change induced micro-fracture sources during exploitation or CO_2 sequestration is also extremely intriguing.

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