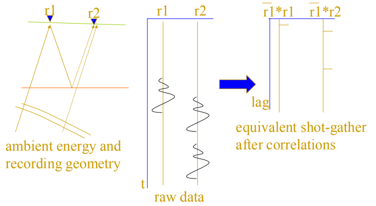
S11E
-0334

Passive Seismic Imaging

Brad Artman and Jeff Shragge, Stanford University
brad@sep.stanford.edu *jeff@sep.stanford.edu*

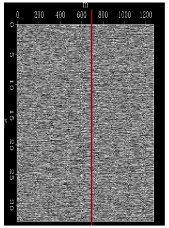
1. Imaging Passive Seismic Data

1a. Noise to data via cross-correlation

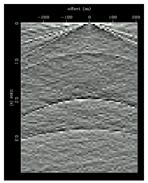


Every trace records both the incident source wave-field, and the energy returning from subsurface reflectors. Therefore, the correlation of every trace with every other builds hyperbolas from subsurface reflectors as well as removes the unknown time offset and phase characteristics of the probing energy.

Shot-gather from cross-correlation



passive transmission data



equivalent reflection data

Correlating every trace with every other squares the number of traces from the experiment. However, only the correlation lags corresponding to the depth of the deepest reflector of interest need be kept. This decimates the time axis by several orders of magnitude.

1b. Wave-equation migration

Wave-equation migration of reflection seismic data to produce images of the subsurface entails four basic operations:

- Summation of all shots
- Wave-field extrapolation (phase shift operator)
- Cross-correlation of source (U) with data (D)
- Zero lag extraction by $\Sigma R(\Re,z,\omega)$

Thankfully, all these operators commute which allows the correlation in migration to satisfy the correlation required to produce the reflection response of the subsurface from the transmission records. This is the case if the transmission records are used as both the source and receiver wave-fields.

Standard Migration

$$
\begin{aligned}
R_o &= U_o D_o^* \\
R_1 &= R_o e^{+i\,Kz\,\Delta z} \\
R_1 &= U_o D_o^* e^{+i\,Kz\,\Delta z} \\
R_1 &= U_o D_o^* e^{+i\,Kz(U)\,\Delta z\,+\,i\,Kz(D)\,\Delta z} \\
&= U_o e^{+i\,Kz(U)\,\Delta z} (D_o e^{-i\,Kz(D)\,\Delta z})^*
\end{aligned}
$$

This shows the commutability of the correlation and extrapolation operators (and coincidentally the equivalence of shot-profile and source-receiver migration) due to the seperability of the exponential operator.
Extracting the zero time of the wavefield R at any depth level gives the image at that depth.

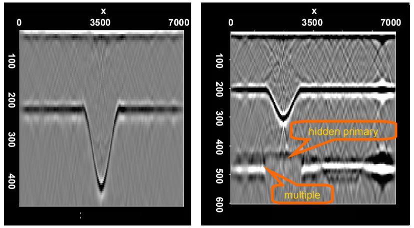
Passive Migration

The reciprocity theory tells us that another factorization of R, besides UD^* is the cross-correlation of T, or:

$$R_o = U_o D_o^* = T_o T_o^*$$

Direct migration of passive data uses the transmission wave-field, T, for both upgoing, U, and downgoing, D, wave-fields in the same structure.

2. Imaging synthetic data



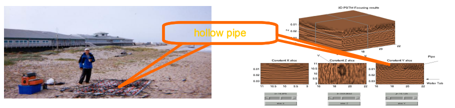
Synthetic passive data is generated by propagating many plane waves or impulses up through an elastic model from below the reflectors. These clean transmission panels are then convolved with long random noise sequences. Many panels thus generated are then summed. The quality of the resulting image is a function of how well the group of sources represents all possible azimuths and ray parameters.

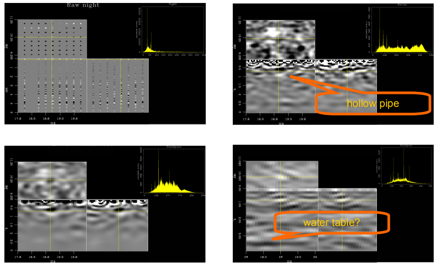
A passive data set can be imaged directly, or expanded into shot-gathers and migrated. Migration correctly images energy in the data and allows for the introduction of 3D velocity models to map subsurface structure.

Images from two synthetic passive data sets are shown at the left. While migration after generating shot-gathers yields an equivalent result, it takes at least 10 times more computer time to generate due to the extra very long Fourier transforms.

However, if the location is subject to difficulties such as inter-bed multiples, inappropriate energy can mask the true reflectors just like conventional reflection.

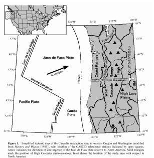
3. Application to the shallow subsurface



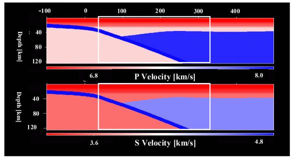


72 channel acquisition on the beach of Monterey, CA. Too few channels in any direction leads to an inability to find hyperbolas. Migration with in-filled zero-traces provides an interpolation that aids interpretation. Shallow depths suffer however as zero-traces acquire energy. Deconvolution prior to migration as well as simple band-pass versions of data were used from several different times of the day.

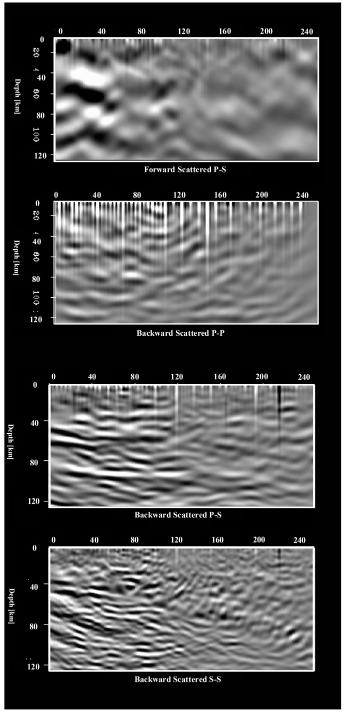
4. Application to CASC93



from Rondenay et al. [2001]



White box shows area in imaged sections below.



CASC93 Highlights

All images are directly comparable to those of S11E-0335, Wave-equation Imaging of Teleseismic Body-wave Coda. Instead of the classic migration strategy, the entire P-wave data was used as both source and receiver. Thus, the backscatterd P-P image is equivalent to the passive experiment explained in panel one. Apologetically, we admit to not using the raw data for this work, but undoing (as best we could) the processing sequence described on S11E-0335. For this reason, the results are not as high quality as they could be (see you next year with more images).

The use of multi-component geophones provides many more imaging possibilities heretofore unthought of in the conventional framework of passive seismic imaging.

Direct migration of raw data does not allow for the construction of a velocity model from the data. However, focusing of events via migration has thus far proved very stable, and allows for velocity update techniques common to exploration seismic processing. Interestingly, this process can also output the reflection experiment data as if collected with a shot-point at every receiver location.

5. The Truly Passive Teleseismic Experiment

I use the word passive with a more rigorous definition than is the norm within the community of seismologists. The cross-correlation process allows us to manipulate transmission records into equivalent shot-gathers without any knowledge of source energy. Further, when large array acquisition strategies are employed, imaging the subsurface with complicated 3D velocity models is mandatory, and easily implemented with this framework.

Migrating raw data without imposing (incorrect) assumptions during pre-processing steps such as deconvolution or rotation can provide more accurate images as human intervention is limited. Further, multiple scales of resolution can be realized as local seismicity extends the bandwidth of the total source energy envelope.

The extension of this technique to the teleseismic context has also expanded its possibilities. Imaging forward-scattered mode conversions is not included within the traditional scope of passive seismic imaging. The same ideas of allowing the wave-equation to propagate energy into the subsurface without pre-processing holds.
Lastly, the computational cost of performing the migration on the raw data rather than first computing the cross-correlation of all the traces with each other is less.

6. The Minimally Passive Teleseismic Experiment

The case presented here explains the use of a modified shot-profile migration algorithm to image the subsurface with ambient subsurface seismic energy. However, as demonstrated next door (S11E-0335, Wave-equation Imaging of Teleseismic Body-wave Coda), the use of wave-equation migration algorithms can and should be used to migrate specific, localized (in time) events to provide excellent focusing of lithospheric structure.

ACKNOWLEDGEMENTS: Deyan Dragonov of Delft Univ., Biondo Biondi, NSF-EAR Geophysics & ACS-PRF to Simon Klemperer and the sponsors of the Stanford Exploration Project