Stanford Exploration Project, Report 111, June 9, 2002, pages 361–369

A return to passive seismic imaging

Brad Artman[1]

ABSTRACT

Rekindling the passive seismic imaging effort at Stanford, I have acquired grants with Simon Klemperer of the Stanford Crustal Research Group from both the Petroleum Research Fund and the National Science Foundation to pursue two- and three-dimensional imaging efforts of the subsurface in a passive listening methodology. Utilizing the outstanding SEP hardware and software infrastructure and expertise, I have begun to build the resources necessary to manipulate the massive datasets toward producing an image. Efforts to acquire several existing datasets that seem to fit the requirements of this method are presently underway, while 180 Gbytes of the Santa Clara Valley Seismic Experiment from 1998 arrived in house on the first of March.

INTRODUCTION

The autocorrelation conjecture of Claerbout (1979) is a long standing idea that motivating passive seismic imaging that has yet to either bear fruit or be put to bed. Claerbout et al. (1988) begins a suite of articles in these consortium reports by defining the scope of the 1989 SEP passive seismic data acquisition effort that is then subjected to increasing interrogation by many former students. The results of this effort and it's many conterminous developments are sprinkled within the SEP reports until the thesis of Cole (1995) summed up much of the effort. Articles by James Rickett and co-authors beginning with Rickett and Claerbout (1996) then resurface the topic upon receipt of a solar seismic data set[2], that not only met the requirements of the passive experiment, but returned excellent results.

Taking a lead from takes a lead from Claerbout (1968) where it is shown that the autocorrelation function of the transmission series of the earth is directly related to a reflection seismogram, Schuster et al. (1997) develops the mathematics behind prestack migration of autocorrelograms. Schuster and Rickett (2000) then go on the generalize that work outlining the imaging conditions for both reflectivity and source location of correlation datasets. Anstey (1964) gives a very thorough treatment of the fundamentals of correlation techniques in general.

Pre-dating all of the above is a patent application submitted by Weller (1969) describing this exact process of collection and correlation of passive seismic receiver stations. Weller

---

[1] **email:** brad@sep.stanford.edu

[2] The Michelson Doppler Imager, http://soi.stanford.edu/results/heliowhat.html

(1969) describes a 2-dimensional acquisition in the Gulf-coast region as returning convincing sequence boundary reflections from recordings on the order of eight hours long.

Recognizing that this imaging methodology will involve very long time records, the work of Kostov (1990) is applicable in handling spurious and coherent noise patterns endemic to recording stations with long residence periods. This thesis treats the closely related topic of seismic imaging utilizing a turning drill-bit as a source (also treated in Cole (1995)). Specific treatment of the handling and shaping of data in a pre-processing step as well as the multi-channel and areal nature of his experiments are beneficial to the development of this effort. This same topic has recently been advanced through the work of Yu and Schuster (2001) that explains migration of crosscorrelogram data collected during seismic profiling while drilling experiments as an application of the previously mentioned (Schuster and Rickett, 2000) derivations.

While the ultimate goal is to acquire another passive seismic data set, this paper will begin to describe investigation of this subject through the manipulation of existing data sets from the seismology community. Utilizing the capabilities of SEP3D to handle irregular datasets, I will attempt to apply the imaging methodology as described below on the 1998 Santa Clara Valley Seismic Experiment (additionally, a 1997 USGS experiment at the Kilauea volcano, Hawaii (Almendros et al., 2001) exists that features several areal arrays of seismometers).

THEORY REVIEW

With one schematic, the fundamentals of the correlation conjecture concept are easily digested. Figure 1 shows the incident plane wave acting as a virtual or 'ghost' source as it is reflected from the free surface. One final arm-wave will cover the rest of the plane waves needed for a successful passive seismic experiment and not pictured in the figure. Conventional seismology assumes an impulsive source and a randomly distributed subsurface that we attempt to deconvolve. The premise of this experiment lies in switching those two roles. If we have a structured earth and a random distribution of sources buried within it we can deconvolve, in much the same manner, our recorded signals to return the impulse response of the earth. Therefor, the perfect experiment would have sufficient noise activity to illuminate the free surface from every incidence angle, and around all azimuths.

Cross correlating each trace with every other trace manufactures a 5D data volume of pseudo-shots very analogous to conventional data, although here, the structure of the earth will be in the form of its autocorrelation. Visualization of the 3D volume constructed from one line is much easier on the brain and one notices that the main diagonal of the cube is the autocorrelations (analogous to zero offset and the CMP location) and successive lessor diagonals are correlations of traces with increasing offset. At the same time, the correlation process will illuminate our need to know our source timing and shape.

Given any one receiver line, only ray-paths contained in the plane defined by the receiver line and the 90^o azimuth to it will have zero move-out across the line. These events will contribute a direct event of infinite velocity and no reflected energy as azimuth will be maintained

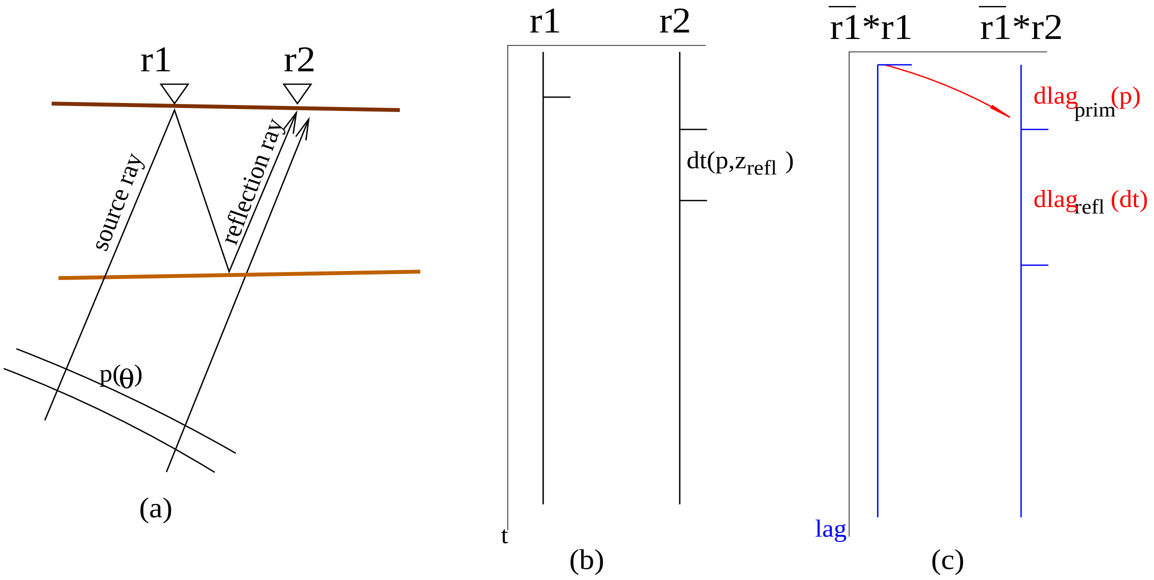

Figure 1: (a)Given a simple earth model, an upcoming plane wave will be recorded with measurable move-out unless incidence angle is zero or its azimuth is perpendicular to the receiver line. (b) Each plane wave reflecting from the free surface provides only one reflection path to each receiver. (c) Correlating all traces with each other yields a second data space with components indicative of subsurface structure and the incident energy. brad1-noise [NR]

along its travel path. This thought experiment highlights the problem that only direct ray paths traveling in the same azimuth as the receiver line will catch a ghost reflection. This topic is addressed more fully in the next paper in this volume (Artman, 2002b).

To investigate the efficacy of these assertions, I will use the existing data from a Santa Clara, California seismology campaign that benefits from the recent shooting of a 2D profile across the same area.

SANTA CLARA VALLEY SEISMIC EXPERIMENT

In June 1998, 40 seismometers were deployed in the Santa Clara Valley on a roughly $3x5$ km grid (see Figure 2 for locations) by the USGS and the University of California, Berkeley using PASSCAL[3] equipment. The goal of the experiment was to: (1) constrain the basin structure of the valley from P and S travel times, (2) investigate site responses for earthquake hazards, and (3) better locate small quakes that occur on the basin margin. The results of this study should include tomographic velocity models to provide a beginning earth model. The results are as yet unpublished however. Also advantageous with this data, is the co-existence of an active seismic profile within the former array. From conversations with researchers at the USGS, the line will trend north-east from the south-west corner of the array and be completely contained

---

[3] Program for the Array Seismic Studies of the Continental Lithosphere, http://www.passcal.nmt.edu/iris/passcal/passcal.htm

by perimeter of the passive array. The USGS acquired the data late last year, and results and accurate positioning should be available soon.

Continuous logging of data every 0.02 seconds for six months yields an outrageous 180 Gbytes of passive seismic data. Each of the stations log vertical and northerly and easterly oriented shear motions. All time signals are synchronized with GPS clocks.

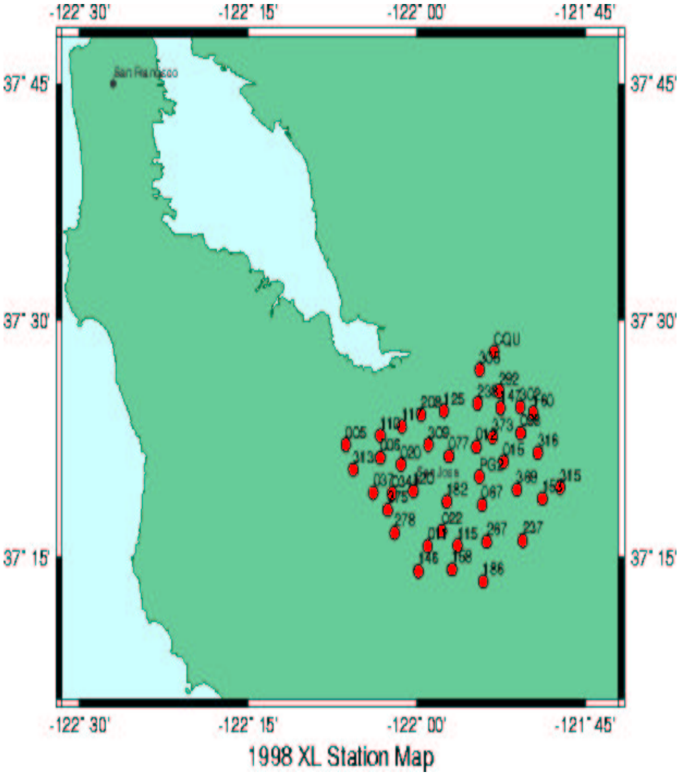

Figure 2: Station location of the 40 short-period seismometers deployed in the Santa Clara Valley of California. Six months of continuous recording every 0.02 seconds results in 180Gbytes of data currently in house. brad1-map [NR]

The Mark Products (now owned by Sercel) L22 short period seismometer is ubiquitous in the seismological community. Therefor, it is reasonable to understand its characteristics. W. Menke (1991) performs a comprehensive analysis of the performance of the L22. It has a resonance frequency of 2 Hz, which is significantly lower than that of an exploration geophone. However, as seismologists are normally not interested in higher frequencies, the response functions shown never extend above about 30 Hz. The authors claim to have seen significant cross-axis coupling of the shear and compressional channels over frequency bands near the natural frequency, but this seems to be of little concern to this use of the data. Of more concern, the authors identify "one of the main instrument defects" of the L22 being strong amplitude resonance peaks centered at 28 Hz in over 20% the instruments.

Preliminary manipulation of the SCVSE data show that traces are indeed white show no coherence in their raw form. Cross correlating the records at this time provides no useful information as I have not been able to implement the code with the irregular geometries required with the data shown in Figure 2.

At this stage, it is unclear whether strong earthquake energies will help or hinder the experiment. While we desire strong incident wave fields, over representation of energy from particular azimuths and incidence angles may be detrimental. The underlying question here is whether or not teleseismic events (earthquake signature from long distances) will be the predominant energy source to illuminate the subsurface by reflecting from the free surface. If so, focusing our efforts in time around the arrival times of known events (from published earthquake catalogs) may significantly reduce the length of the time series that need be processed. Rather than long, continuous time records, we can isolate discrete time windows that can be treated analogously to single shot experiments. The price to pay for this however will be in resolution. Due to the geometry of the radial structure of the earth, we can only expect incident waves in a limited window of incidence angles from below. In addition, the usable period of these events is centered around one or two seconds which will greatly reduce the resolution of the image.

Figure 3 shows the earthquake and blasting events within 500 km of the survey location during the time the recording units were deployed. As these events and their times are readily available, it will be easy to window data series within and between major quake events to address this question.

Alternatively, it may be possible to use the earthquake energy in both contexts within the framework of an illumination study. Because the timing, azimuth and ray parameter of the earth-quake energy is available, it may be possible to normalize or otherwise manage what could be over-abundant energy.

Of benefit to this type of survey is that those who design and utilize these surveys are principally interested manufacturing tomographically derived velocity models from earthquake events utilizing both vertical and shear components of ground motion. This fact results in the availability of initial velocity models for migration studies and rudimentary practices in separating incident and scattered wave fields. However, it is my sincere hope that ambient noise will provide sufficient images as to not need to focus on teleseismic events. Due to the large offset between stations (three to five kilometers in this instance) the transmission losses of some of the ambient noise will undoubtedly prevent correlated signal from spanning the entire breadth of the survey layout.

Despite the outcome of this question however for this particular training set, the issue needs addressed specifically with an experimental mobilization tailored for our interests. This means that it should have receiver arrays designed to attenuate surface waves, station spacing on the order of a few meters (rather than the kilometers associated with seismologic data sets), and a roughly square map view (as suggested by Artman (2002b)) with a regular station spacing. The harder the near surface that the receivers are coupled to, the less high frequency surface noise will conflict with our desired signal.

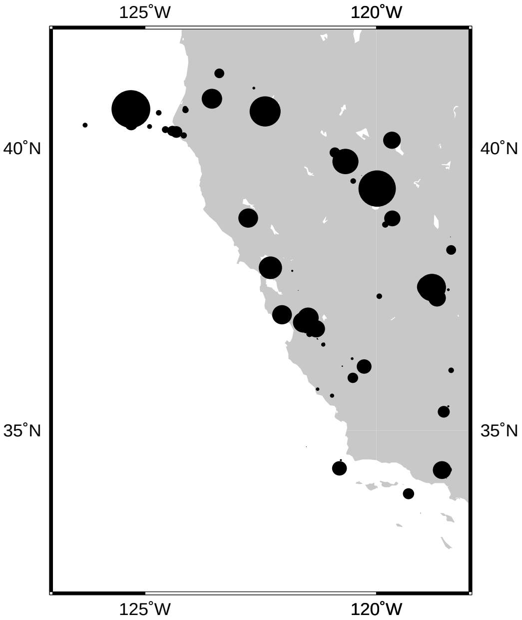

Figure 3: 210 Earthquakes and blasting events most likely to be recorded by the deployed instrumentation. Plotted are events between magnitude 3 and 5 within 500 km from the survey. These events will likely correspond to incidence angles of approximately 35^o. Further afield teleseismic events will contribute more vertical events, but suffer from decreased frequency range. brad1-quakes [NR]

PLAN FORWARD

The correlation of the geophone time series outputs a volume that is roughly equivalent to the raw data of conventional seismic acquisition. The parallel code to manufacture this output volume is almost running. The road ahead is a long one that will involve velocity estimation, converted wave problems, noise suppression and separation, simultaneous inversion of multiple experiments, and migration- in short: the rest of the field of modern seismic data processing.

Before all of these issues are addressed however, one of the principal problems to be addressed is that of the separation of the direct incident Wave field from that reflected from the free surface. This will be my principal goal in the short term. Some preliminary ideas for this are outlined in Artman (2002a).

Assuming positive results, the next step will be to identify a location and acquisition strategy for SEP to collect its second passive seismic dataset as suggested in Claerbout et al. (1988).

REFERENCES

Almendros, J., Chouet, B., and Dawson, P., 2001, Spatial extent of ta hydothermal system at kilauea volcano, hawaii, determined from array analyses of shallow long-period seismicity: Journal of Geophysical Research, **106**, no. B7, 13,581–13,597.

Anstey, N. A., 1964, Correlation techniques a review: Geophys. Prosp., **12**, no. 04, 355–382.

Artman, B., 2002a, Coherent noise in the passive imaging experiment: SEP–**111**, 379–383.

Artman, B., 2002b, Is 2d possible?: SEP–**111**, 371–379.

Claerbout, J. F., Cole, S., Nichols, D., and Zhang, L., 1988, Why a big 2-D array to record microseisms?: SEP–**59**, 1–10.

Claerbout, J. F., 1968, Synthesis of a layered medium from its acoustic transmission response: Geophysics, **33**, no. 02, 264–269.

Claerbout, J. F., 1979, Errata: Fundamentals of geophysical data processing: SEP–**20**, 257–258.

Cole, S. P., 1995, Passive seismic and drill-bit experiments using 2-D arrays: SEP–**86**.

Kostov, C., 1990, Seismic signals from a drillbit source: SEP–**63**.

Rickett, J., and Claerbout, J., 1996, Passive seismic imaging applied to synthetic data: SEP–**92**, 83–90.

Schuster, G., and Rickett, J., 2000, Daylight imaging in V(x,y,z) media: SEP–**105**, 209–226.

Schuster, G. T., Liu, Z., and Followill, F., 1997, Migration of autocorrelograms: 67th Ann. Internat. Mtg, Soc. Expl. Geophys., Expanded Abstracts, 1893–1896.

W. MenkeL. Shengold, G. H. H. G. A. L., 1991, Performance of the short-period geophones of the iris/passcal array: Bulletin of the Seismological Society of America.

Weller, C. E., 1969, U.s. patent application: Appl.No. 877,350.

Yu, J., and Schuster, G., 2001, Crosscorrelogram migration of IVSPWD data: 71st Ann. Internat. Mtg, Soc. Expl. Geophys., Expanded Abstracts, 456–459.