Did SEP discover non-volcanic tremor?

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ABSTRACT

In 1989 using cast-off industrial gear we at SEP set up for just one night a square 2-D array of 4056 10 Hz geophones. To our utter surprise we found noise arriving from the east all night long with an emergent velocity greater than 8 km/sec. Stratified media seismology implies the source is continuous microearthquakes directly under Stanford Campus at 10-20 km depth.

EXECUTIVE SUMMARY

In September 1988 we at Stanford Exploration Project (SEP) laid out 4056 geophones uniformly in a half kilometer square grid several kilometers west of Stanford University campus on "cow hill" marked in the map in Figure 1.

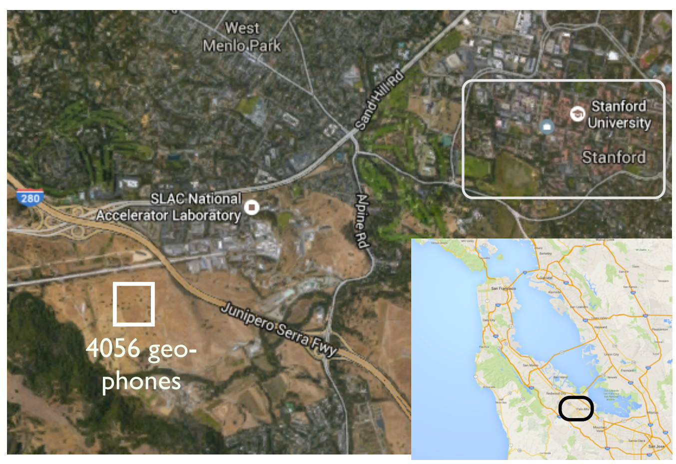

Figure 1: Experiment location. [**NR**]

We expected to see a random pattern of waves coming from the seashore west of us at an apparent surface velocity of about 3-5 km/sec typical of rocks several kilometers beneath the coastal mountain ranges. Big surprise! Instead we saw random signals arriving from the east at the astonishingly high velocity of 8-12 km/sec throughout the entire night of the experiment. Signal frequencies were in the range 8-10Hz.

Assuming horizontally stratified media, the sources should be located at continental distances because the observed emergent velocity significantly exceeds moho velocity. But this is unlikely because 8-10Hz signals dissipate before reaching such great distance. (Although I believed the earthquake seismologist who told me this, I claimed they never saw such waves because they never set out 4056 sensors.)

A revolutionary hypothesis that does explain the data is that the signals are generated deep beneath Stanford campus at depths consistent with California earthquake habits, roughly 10-15 km. The near and far potential source locations are black dots in Figure 2.

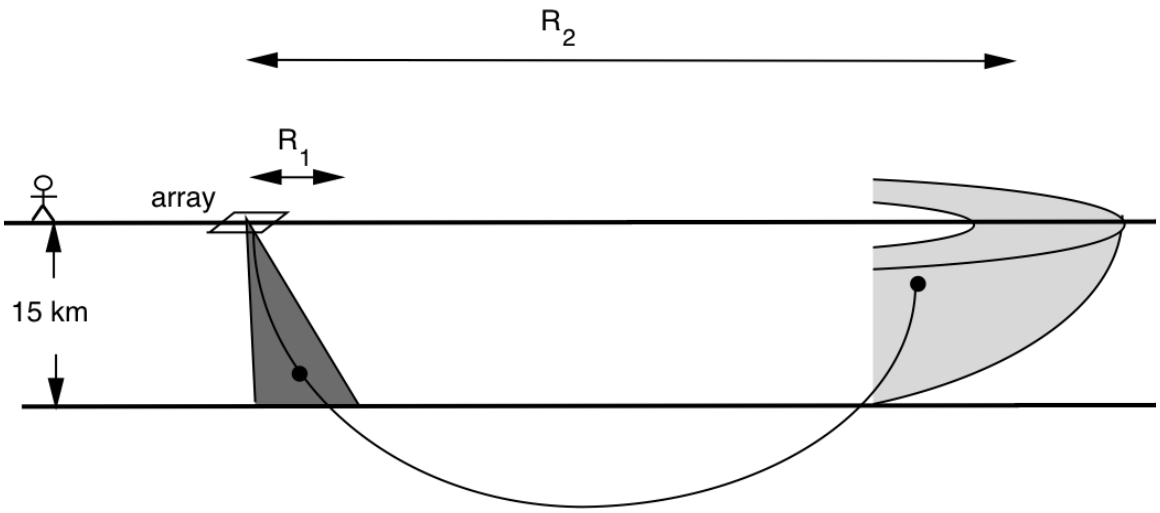

Figure 2: For rays emerging at the surface at angle θ, Snell's law says $dt/dx = \sin\theta/v$ is a constant function along a ray. Hence our observations could arise from the location of the near black dot or the far black dot. Both would arrive at an apparent surface velocity equal the rock velocity at the bottom of the ray, namely, below the 8 km/sec at the Mohorovicic depth. [**NR**]

We understood we might have observed a quasi-continuous distribution of micro earthquakes being generated by stresses in the general region of the San Andreas fault. At the time, this would have been big news.

Seeing it is all night long led us to wonder whether this phenomenon is omnipresent or whether it comes and goes like stormy weather.

Figure 3 shows crustal surface deformation in our neighborhood observed over the interval 1989-1994. Along an east-west traverse over a distance of 50-100 km, notice the earth shearing at a rate of about 3 cm/year (Bürgmann et al., 1997).

It would have been more exciting had we been able to measure the source depth. Triangulation from three arrays like ours separated 10-20 km should do the job. We calculated that we had enough geophones to split our array into three. We had not access to two additional array locations. We had not found academic partners to share the experimental burden. I advertised my offer of financial contribution ($50,000) to any academic partner interested and able to pursue studies of this nature. That

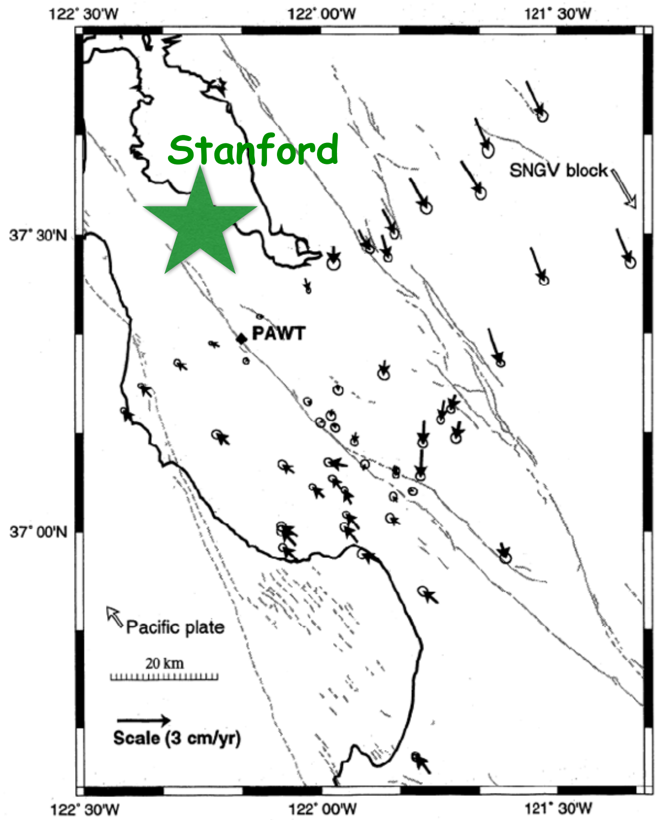

Figure 3: Motion of the earth surface in our neighborhood over a five year period. Notice an east-west traverse over a distance of 50-100 km shows a shear of about 3 cm/year. [from Burgmann et al., 1997, Loma Prieta postseismic strain] [**NR**]

advertisement remains at my website.

I presented these results to academics in a poster session at the American Geophysical Union in San Francisco. We reported this to our industrial sponsors. It was summarized in the PhD thesis of Steve Cole (Cole (1995)). Because we are not funded for academic research, we returned to our industrial research.

Volcanic regions exhibit "seismic tremor", a steady rumble that may continue for hours, days, or longer. It is thought to originate from subsurface lava flow. Generally, the location of the source of such tremor cannot be located. In 2002, Kazushige Obara published a ground-breaking report in Science Magazine on non-volcanic tremor. He succeeded to identify its source location (Obara, 2002). A recent comprehensive review article on the topic of tremor is published by Beroza and Ide (2011). "Non-volcanic tremor" may be the best description of what we had observed. More recently it is being called "tectonic tremor."

Naturally today we would be delighted to see others make such measurements with modern equipment.

DATA FIRST VIEW

At 10-15 minute intervals over the course of the night, we triggered our recorders by radio. Recording would then begin and run for 30 seconds. The data is three-dimensional (x, y, t). To make it viewable on a 2-D screen, a student (Lin Zhang) made the four partial sums shown in Figure 4. Stretching our imaginations now we see arrivals at 2.2, 7.4, and maybe 1.2 seconds. We had 47 other similar panels.[1]

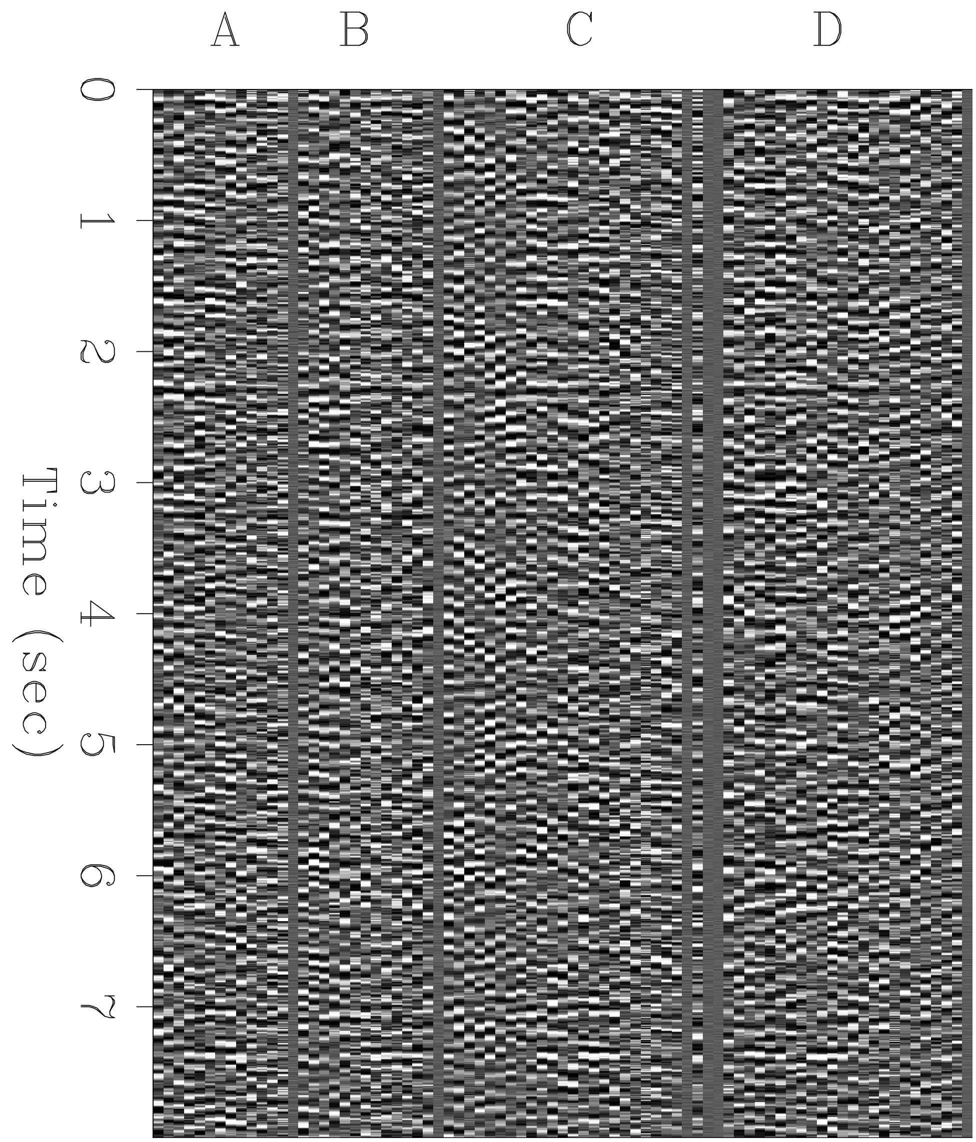

Figure 4: Region A is the east-west sum, B the north-south sum, C and D are sums along 45°. Do you see any horizontal alignments? Where? [HINT: View the page at a grazing angle from its side.] [**NR**]

[1] Although this is Steve Cole's original plot, Nori Nakata with Steve Cole performed the heroic task of recovering this 1989 dataset in 2016, thus making it available to interested parties. The dataset is now named "cowhill."

Greg Beroza asked me the penetrating question, "Is this noise continuous or episodic?" I replied it is episodic. I should justify my reply quantitatively, but until now, I am not able.

DATA PROCESSING AND PRESENTATION

Over 12 hours we acquired 48 groups of data ($d_i(t, x, z)$ for $i = 1, 48$). All seismograms had a 30 second time duration. Each group was stacked at a range of slopes (p_x, p_y) (more precisely, a range of emergent angle stepouts) to make a "Record".

$$\text{Record}_i(p_x, p_y) = \sum_{t=0}^{30 \text{ sec}} \sum_x \sum_y d_i(t - p_x x, t - p_y y)^2. \tag{1}$$

Atop each Record in Figure 5 is drawn the ring of $p_x^2 + p_y^2 = 1/(8 \text{ km/sec})$. A small red (or dark) cluster near the ring center identifies the 1% of values of maximum amplitude.

ALTERNATE INTERPRETATIONS

Cars, trucks, and airplanes

It is surely true that local noises are large in strength, even in the middle of the night. But, surface noises move slowly in horizontal directions. Our 4056 geophones do a good job of suppressing them. We see no evidence in Figure 5 of low velocity arrivals from the freeway east of our array in Figure 1.

Electronic pickup

When we first recognized these all-night-long events we saw them as nearly simultaneous on all seismograms. We feared they might be electronic pickup from the Stanford Linear Accelerator, only several hundred yards distant. But, they were not quite simultaneous as Figures 5 and 6 show. For further confirmation we randomly scrambled the order of our signals and found the "arrivals from the east" model immediately disappeared. This is exhibited in Figure 7.

Lateral heterogeneity

One can always doubt the validity of the horizontally layered media assumption. Challenging this assumption, while certainly reasonable, is surely nihilistic. Give up the stratified media assumption (deform the trajectory in Figure 2) and it becomes difficult to deduce much of anything in earthquake seismology without a massive

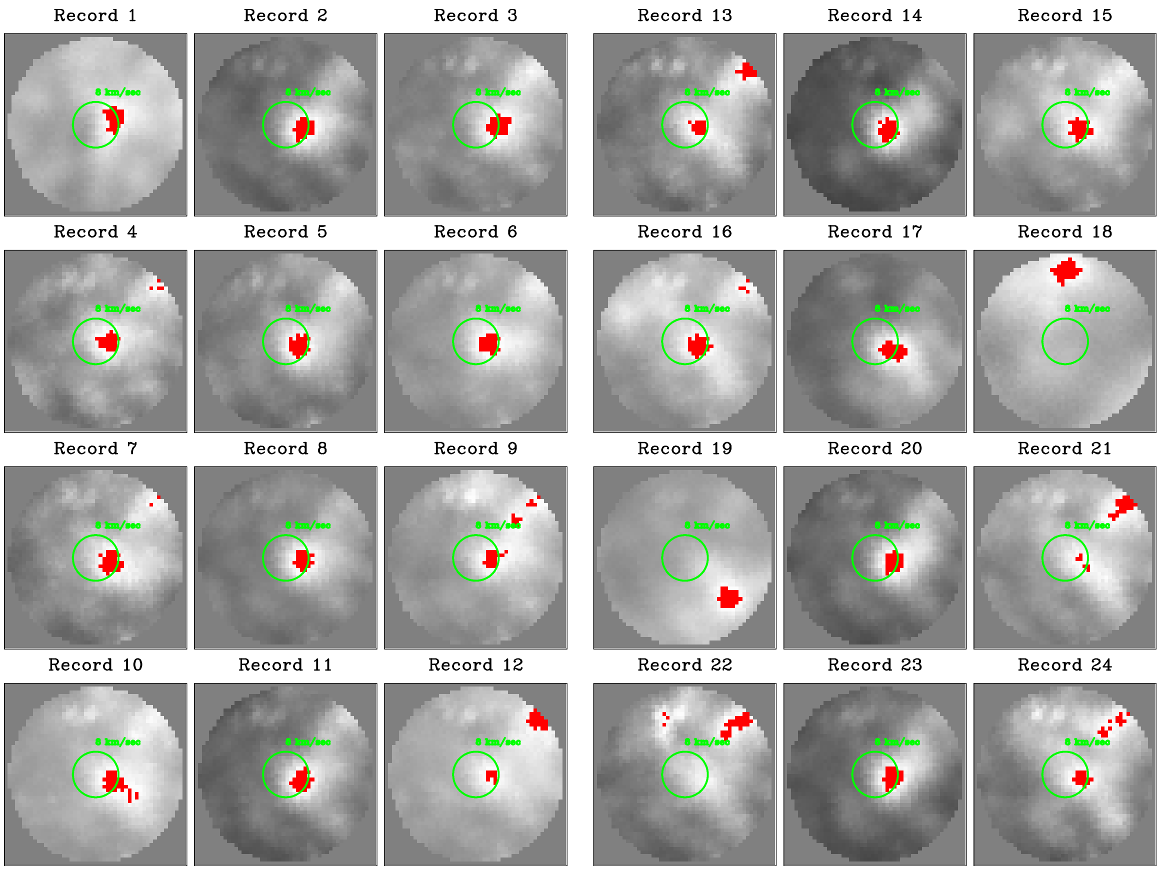

Figure 5: The earliest 24 stacks. That the red clusters are not centered in the rings shows the energy is not emerging straight up. It is coming from the east (right side of page). That the clusters are inside the rings says the velocity exceeds 8 km/sec, and that the angle of emergence is steep (unlike atmospheric noises which would arrive nearly along the earth surface at slow speeds, hence along or beyond the radius of the display circles). [**NR**]

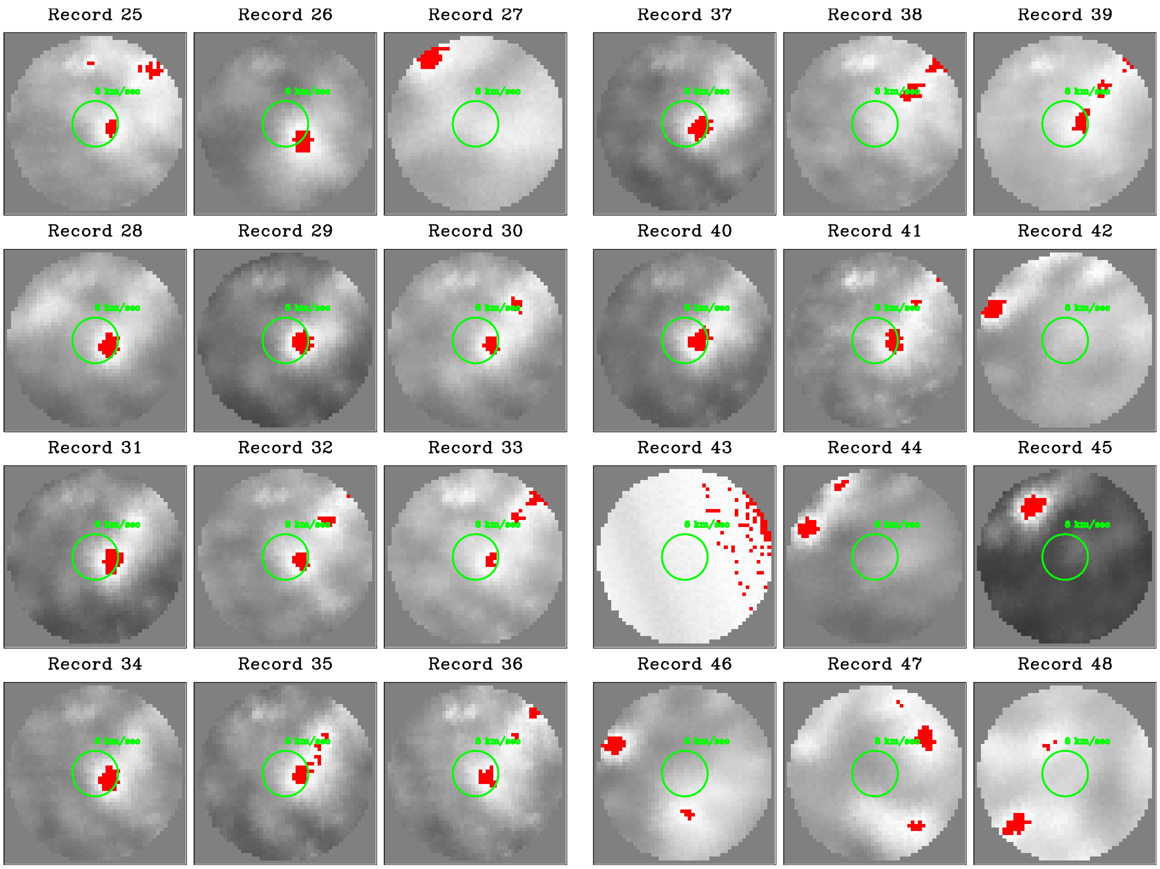

Figure 6: The later stacks. Signal degrades towards morning as vehicular traffic and air traffic picks up, wind picks up, and 169 recorder batteries start going dead. [**NR**]

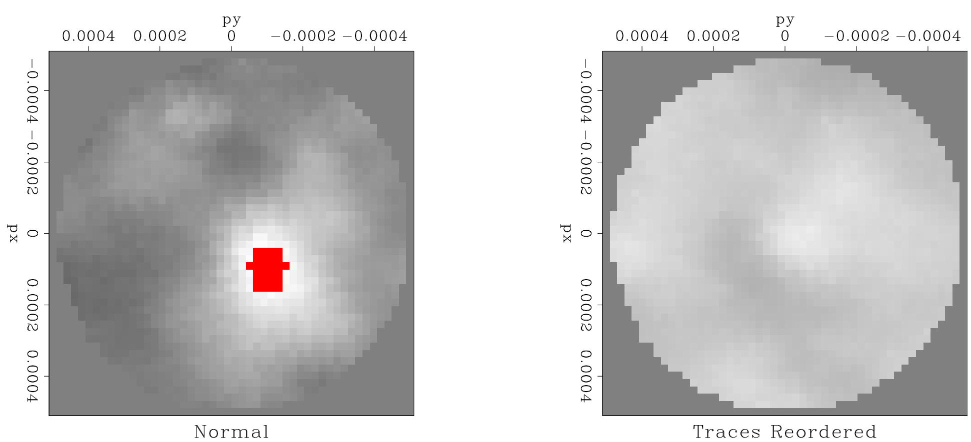

Figure 7: A test of whether our beam measurements are valid was done by randomly scrambling the locations of the raw data. A good quality Record from Figure 5 was selected (shown left) and its raw data randomly repositioned and restacked (shown right). Don't look for the peak on the right. Simply notice that the signal on the right, while fluctuating with position, is generally strong in all directions by comparison with the Record on the left. [**NR**]

amount of additional spatial data coverage, an amount virtually unknown in this field.

Late in our recording, towards morning, a local quarry set off a blast shown in Figure 8. From the map and knowledge of the quarry location we see the great circle path to our array is from the southeast while these arrivals come from the southwest. That adds credence to the nihilistic assumption (lateral heterogeneity). But, it is important to remember that these near surface waves sense an entirely different portion of the earth than seen by waves emerging nearly vertically.

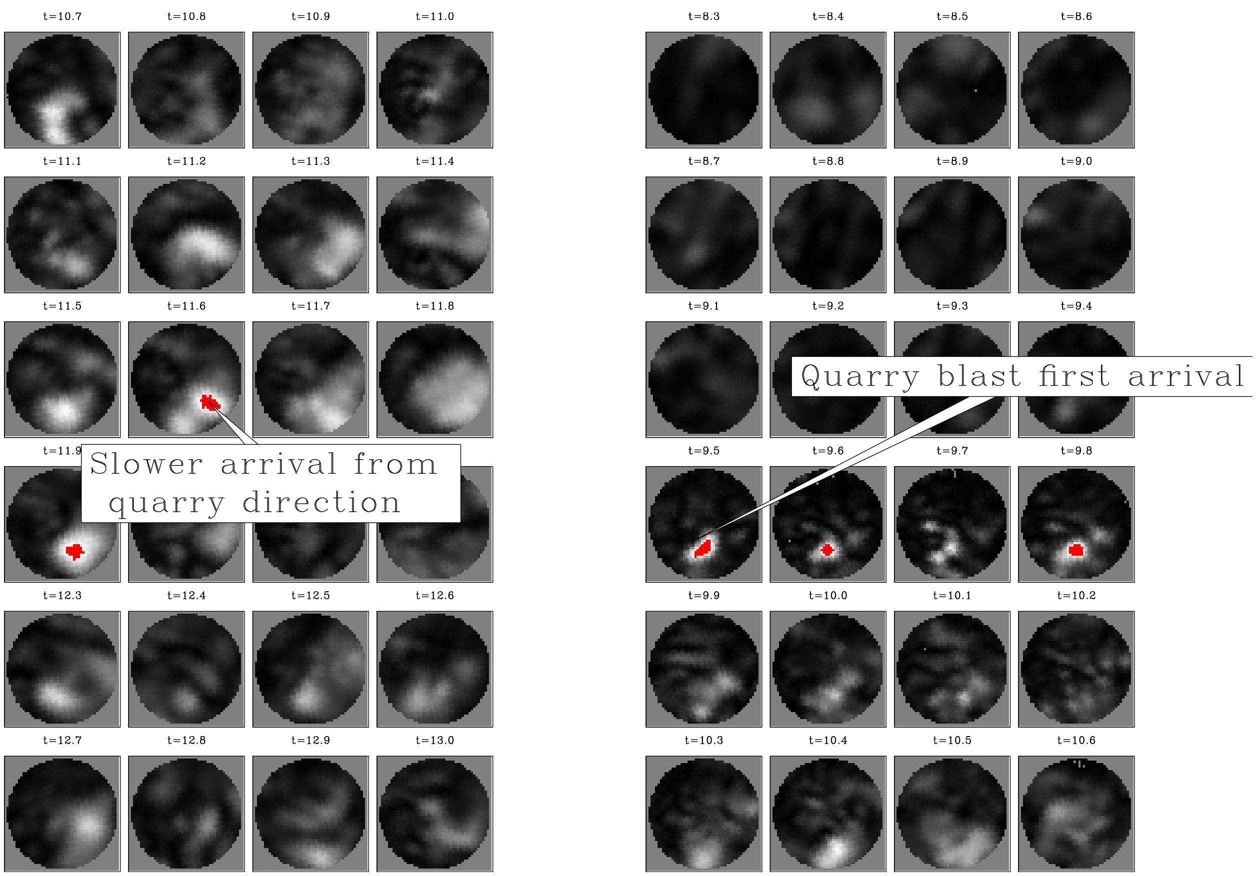

Figure 8: Two arrivals from the quarry blast coming from different directions! [**NR**]

ACQUISITION DETAILS

Data acquisition generally involves a human element recounted evenings afterward over beer. I'll see what I can recall (and pull from my friends).

I needed access to land with cows on it, land owned by the university. My purpose for the experiment was to see something I visualized, kind of dreamed, a kind of turbulent pattern sweeping across our array. Mainly, I hoped to see that crosscorrelation between stations would show hyperbolic moveout trajectories. Not being able to explain such matters to farmers and administrators, I simply said we wanted to listen to the ocean. I had no clue we might discover something amazing!

I told the farmer about our equipment and said I saw no need for him to move the cows off the field. He contradicted me saying cows will eat anything. He said he wouldn't leave cows alone with a tractor for fear they would eat it!

Since it never rains here in summer, the road through the farm was incredibly dusty. The farmer gave me strict instructions that no vehicle was to pass his farm house at a speed exceeding 5 mph. So most of us never did, but the farmer did complain about one car which we figured belonged to M.P.

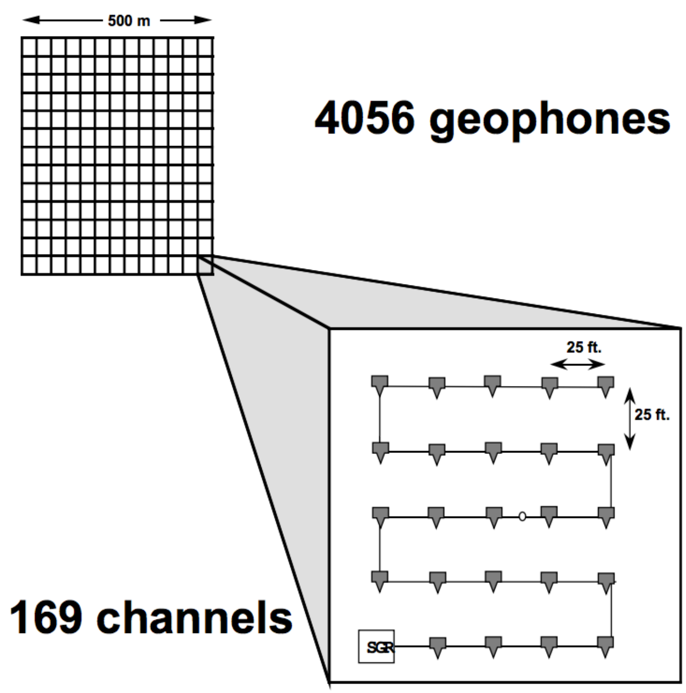

Figure 9: We laid 169 seismic group recorders (SGRs) in a 13×13 grid covering a one half kilometer square. Each SGR recorded the sum of 24 geophones. The geophones were on strings of 12. Each SGR had two geophone strings connected in series. [Cole thesis] [**NR**]

Figure 9 shows details of the field recording geometry. Because it never rains in summer around here; the soil gets really hard—and friable. I feared we might not be able to stamp the geophones into it, and then when we did, it might fracture and the phones simply fall out. This sometimes happened. When we went to tear down the whole business and put the phones back on their hangers we found in some cases rodents had dragged the cables down their little holes. I lugged one string (organized bundle) back to the truck and tossed it in only to see a snake crawl out of it.

Everyone was there the first day but Francis Muir who was the only one of us with any significant amount of field experience. I had hoped someone would take a photo from an airplane, but that never happened. Too bad nobody took a picture the first day when we had a genuinely large group. Plenty room here for more stories.

Figure 10: The first day of setup nearly all of SEP researchers were present and working hard, and too busy to take pictures. This photo is from the second day. From the left, Rick Ottolini, Biondo Biondi, Josef Jedlicha, Dave Nichols, Martin Karrenbach, Steve Cole, Jon Claerbout, Marta Woodward. [**NR**]

ACKNOWLEDGEMENT

We thank Amoco Oil Company (now a part of British Petroleum) for donating the equipment we used.

All the data analysis was done by Dave Nichols, Lin Zhang, and Steve Cole. Because the work was finally presented as a part of the PhD thesis of Steve Cole (who shared with me most of the illustrations in this paper) we may assume Steve did the majority of the calculations. Thanks to Steve we have recovered the original data but not yet repeated the original calculations.

Figure 11: From the left, Josef Jedlicha, Carlos Cunha, Martin Karrenbach, Steve Cole, Rick Ottolini, Dave Nichols, and Jon Claerbout. The pile of cables at our feet is one hand-carried hanger with its cable and 12 geophones. We laid out $338 = 2 \times 13 \times 13$ hangers in all. [**NR**]

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