RETRIEVAL OF EARTHQUAKE SOURCE MECHANISMS USING SOUTHERN CALIFORNIA ARRAYS

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Introduction

We made substantial progress toward our goal of retrieving the source mechanisms of local earthquakes during the single funded year of this contract. In particular, two papers sponsored by the contract have been published or are currently in press. A third paper, which deals with the Oaxaca (November, 1978) and Guerrero (March, 1979) earthquakes, is in an advanced state of preparation and will be submitted in the near future. We have four synthetic seismogram algorithms operating which produce the moment tensor Green's functions required for the source retrieval work; Wavenumber Integration, Discrete Wavenumber/Finite Element, WKBJ and Full Wave. The software for the inversion studies is operating in the time domain on our PRIME 750 computer and a flexible data archiving and interactive retrieval system is operating very smoothly. One of the Green's functions programs, the Discrete Wavenumber/Finite Element method, has been transferred to the Branch of Strong Motion Seismology at the USGS, Menlo Park, and is now being used by Drs. Archuleta and Spudich for modeling the recent Gilroy and Imperial Valley events.

I. Body Wave Calculations and Moment Tensor Recovery: Results

In the first of two manuscripts (Ward, 1980a, 1980b) culminated with the funds from this contract, a theoretical framework was developed by S. Ward for constructing body wave fields generated from moment tensor sources in a sphere. Although moment tensor characterization of seismic sources had been standard practice in normal mode and surface wave theory for some time, we were motivated by the fact that a similar parameterization was not yet common in body wave applications. To fill this need, and to bring the power of body wave observations to bear, an appropriate representation was assembled using asymptotic propagator matrices suitable for calculations in a slowly varying, inhomogeneous sphere. Specific attention was given toward making an expedient formulation for computing the absolute scale synthetic seismograms required in source recovery techniques. A significant result in Ward (1980a) was the complete specification of the three partial wave sums (I_0, I_1, I_2) which comprise the spectrum of any high frequency body phase. The spectrum $S(\omega)$ was found to be linearly related to the components of a point moment tensor $M_{ij}(\omega)$, located at radius r_s, through the equation

$$\begin{aligned} S(\omega) &= I_2(\omega,r_s)[M_{11}(\omega)\cos^2\phi + M_{22}(\omega)\sin^2\phi - M_{12}\sin 2\phi] \\ &\quad + I_1(\omega,r_s)[M_{23}(\omega)\sin\phi - M_{13}(\omega)\cos\phi] \\ &\quad + I_0(\omega,r_s)\, M_{33}(\omega) \end{aligned}$$

Here, ϕ is azimuth. Figure 1 shows an example of I_0,I_1 and I_2 in the time domain for a composite P phase.

In the second paper (Ward, 1980b), the above equation was used as the basis for a simplified moment tensor inversion. Our efforts there focused on designing an experiment which would minimize the effect of those "contaminants" that exist in all real seismograms, but not in idealized models (eg. noise, scattered

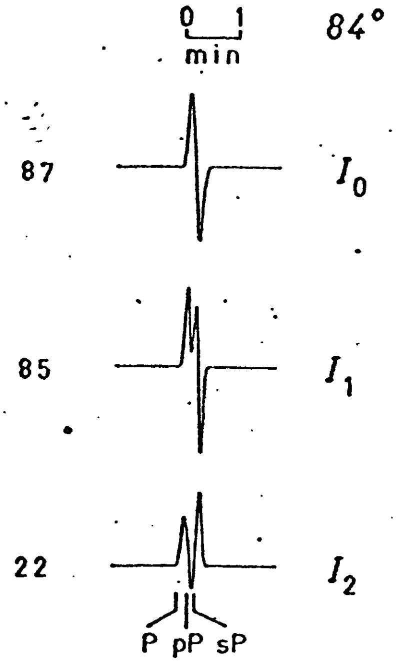


Figure 1. Three independent synthetic seismograms I_0, I_1 and I_2 showing vertical displacements due to the arrival of a composite P pulse at $\Delta = 84°$. Note the various polarities of the different rays P, pP and sP. Numbers to the left are maximum pulse height in microns from a 10^{27} dyne-cm base event buried 42 km.

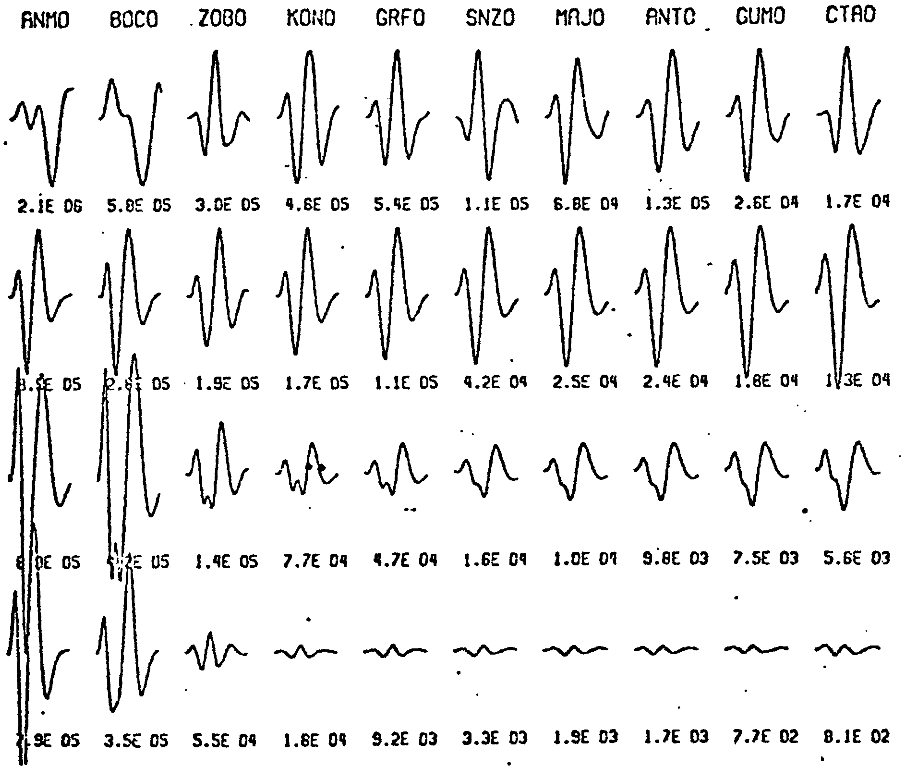
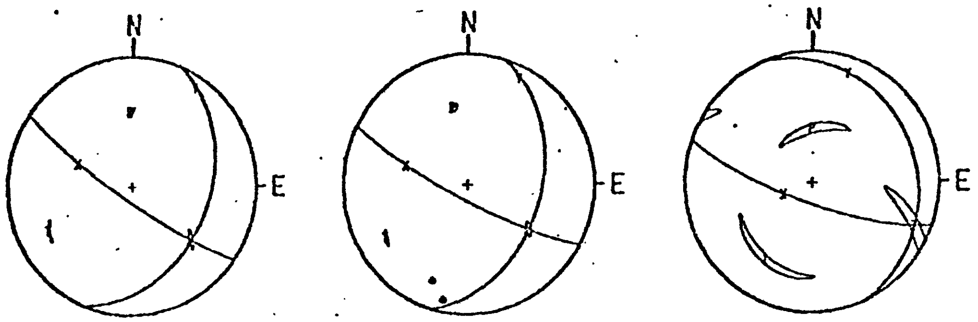


Figure 2. The full set of observations (top row) and synthetic seismograms (bottom three rows) after convolution with instrument. The number below each trace is the maximum pulse height in counts. For amplitude comparisons, each column of synthetics is displayed at uniform gain. Duration of each pulse is 60 sec.



	THETA	PHI
P AXIS	-0.5	48.3
T AXIS	242.9	63.2
X AXIS	-67.0	37.9
Y AXIS	34.3	81.3
Z AXIS	130.9	53.4

	THETA	PHI
P AXIS	-9.5	50.2
T AXIS	238.1	65.4
X AXIS	-72.9	41.7
Y AXIS	27.5	80.9
Z AXIS	125.3	49.8

	THETA	PHI
P AXIS	2.3	34.2
T AXIS	210.8	59.2
X AXIS	-112.9	18.7
Y AXIS	19.6	77.1
Z AXIS	112.7	76.7

Figure 3. Focal mechanisms resulting from the inversion of amplitude-weighted data for the cases A, B and C with double couple source model III.

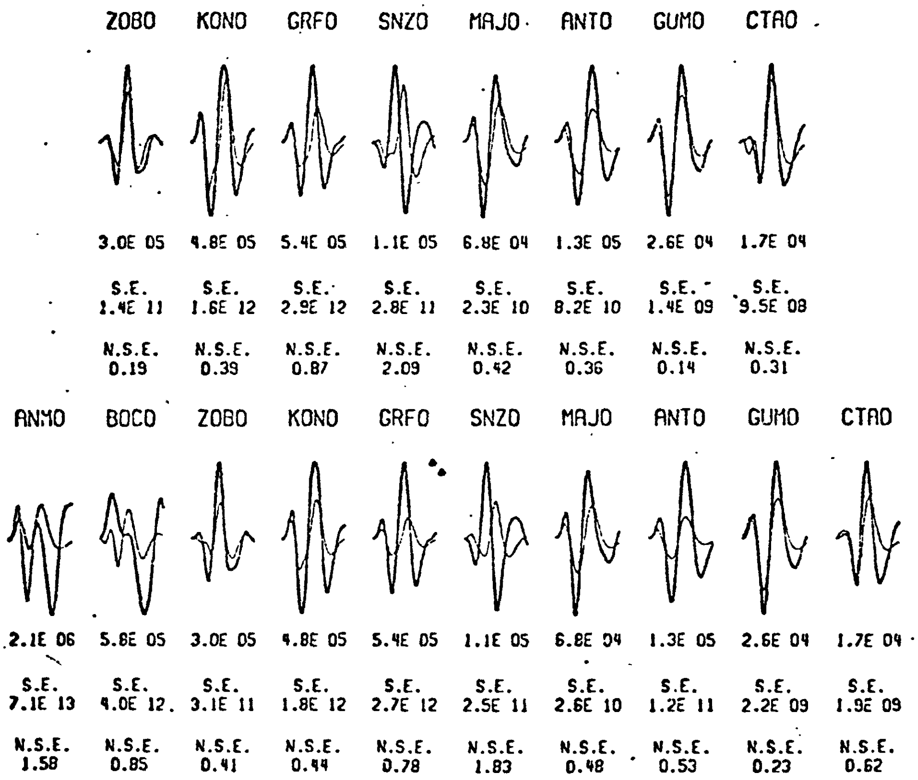


Figure 4. Predicted and observed seismograms for the inversions of Figure 3, A and C.

Table 1.

THREE POSSIBLE SOURCE MODELS

Source Model	Constraints	Eigenvalues	Major Double Couple	Minor Double Couple	Isotropic Component
I. Isotropic Four Couple	NON	$(a, b, c) =$	$(a - t, 0, -a + t)$ $\lvert a - t\rvert > \lvert b - t\rvert$	$+ \quad (0, b - t, -b + t)$ $t = (a + b + c)/3$	$+ (t, t, t)$
II. Four Couple	$Tr(\underline{\underline{M}}) = 0$	$(a, b, -a, -b) =$	$(a, 0, -a)$	$+ \quad (0, b, -b)$ $\lvert a\rvert > \lvert b\rvert$	$+ 0$
III. Double Couple	$Tr(\underline{\underline{M}}) = 0$ $Det(\underline{\underline{M}})O = 0$	$(a, 0, -a) =$	$(a, 0, -a)$	$+ \quad 0$	$+ 0$

energy, etc.). The design was carefully drawn so that the information in the data was not significantly reduced. We selected a time domain, weighted least-squares procedure using teleseismic body phases recorded by the SRO network. This scheme included provisions for both double couple and non-double couple constraints on the moment tensor. Thus, three different source models (see Table 1) could be quantitatively evaluated. For an initial test, ten P phases obtained at stations 20° to 120° distant from a large, shallow focus Oaxaca Mexico earthquake comprised the data. These 60-second P phases are shown in the top row of Figure 2. In the lower three rows of the same figure are the synthetic seismograms I_0, I_1, and I_2 after being convolved with the instrument response. The inversion determined scalar moments of 2.7 ± .2, 2.8 ± .3 and 1.4 ± .4 x 10^{20} N-m from three groups of seismograms in the distance ranges of (A) 40° to 120°, (B) 25° to 120° and (C) 20° to 120°. Double couple mechanisms returned from the three groups are shown in Figure 3. A comparison of actual (dark traces) and predicted (light traces) waveforms is illustrated in Figure 4 for the groups A and C. On the basis of our statistical tests, the data could not discriminate the mechanisms of Figure 3, as each provided an equally good fit. In addition, no evidence was found to support the hypothesis that unconstrained source models, which include a minor couple with or without an isotropic component, described the Oaxaca earthquake significantly better than a moment tensor constrained to be a double couple. Our success in this experiment leads us to believe that an automated procedure such as described above is indeed a viable means for the routine recovery and cataloging of teleseismic earthquake sources.

II. Trial-and-Error Modeling of Teleseismic Data:

Mike Reichle and John Orcutt (Reichle et al., 1978, 1979) have also considered the Oaxaca and later (March, 1979) Guerrero events using P and PP phases from SRO and WWSSN data. The fundamental modes of R2 through R7 of the IDA (International Deployment of Accelerometers) array are used as additional constraints. The results will be the subject of a paper, in part supported by this contract, in the process of being completed.

In this case the fit of WKBJ Green's functions to the data has followed a more classical trial-and-error approach in order to investigate the effects of the source time function and the depth of burial of the source. In addition, the relative excitation of the long period surface waves and the body waves have been of interest.

Figure 4 shows the effect of varying the corner frequency of the source-time function. We have found the best fit has been obtained with a corner frequency of 0.25 Hz. Because of the rapid fall off of the SRO response near 6 sec. period we can say little more than the source time function has a very short duration. Recently, in order to provide further constraints on the source mechanism, we computed WKBJ synthetics to match the observed SRO trangential S, SS and SSS phases. Surprisingly, the effective source time function required was substantially longer in duration. The stretching could not be readily explained by reasonable propagation or attenuation models. The effects of finite fault dimensions are being investigated and the results will be presented at the upcoming John Muir Geophysical Society meeting at Asilomar, California.

Ward assumed in his inversion that the source depth was 42 km. The effect of source depth on the shorter period WWSSN station at La Paz, Bolivia is shown in Figure 5. As the source depth increases the phases P, pP and sP begin to interfere in a way which increases the seismogram complexity enormously. In general, when shorter period data were included we were forced to move the source depth to 20 km. The longer period SRO data are little affected by this change in source depth from 45 to 20 km. The source moment determined from the body and surface waves was $3.0 \pm 1.0 \times 10^{27}$ dyne-cm. Frequently, body wave moments are substantially smaller than surface wave moments, but for this simple, short duration event this obviously does not occur.

The Guerrero event is as simple as the Oaxaca earthquake although the moment is about half that of the former. In both cases the slip vector is consistent with the plate tectonic predictions of Minster and Jordan (1978).

III. Work completed on modeling/inversion of Imperial Valley Data

We anticipated, in our original proposal, one of the greatest difficulties we would encounter would be a lack of knowledge of the earth structure required to compute the requisite Green's functions. This has certainly been the case in the Imperial Valley. In our Semi-annual Technical Report we computed synthetics for an Imperial Valley structure of Biehler, et al. (1964) and a smooth model with only two discontinuities also consistent with the refraction seismology travel-time data. The two structures are shown in Figure 6 and Figures 7, 8 and 9 illustrate several examples of synthetic seismograms computed with the Discrete Wavenumber/Finite Element Method (Olson et al., 1978). The seismograms are 10 seconds long and contain frequencies from 0 to 4 Hz. All sources are strike-slip dislocations. The long period (T > 1 sec) nature of the seismograms for both models are very similar while the high frequency characteristics differ dramatically. For the two shallow sources at 0.93 and 1.2 km, the agreement is extremely poor. As the source depth approaches and enters the basement the agreement between models becomes much better.

The implications for source mechanisms studies is obvious: Unless the ambiguity in the velocity structure can be better resolved, the interpretation of strong motion waveforms at frequencies greater than one Hertz inherently contains a high degree of non-uniqueness.

We (Olson and Orcutt, 1979; Orcutt and Olson, 1980) have recently interpreted much of the data set from the 1978 U.S.G.S. Imperial Valley Refraction Survey (Fuis et al., 1978) using the travel time inversion methods of Garmany et al. (1979), Orcutt (1980) and Olson and Orcutt (1979). The results are illustrated in Figure 10 along with a preliminary model obtained from Mooney and McMechan (1980). No important discontinuities exist within the sedimentary section and the presence of a discontinuity at the sediment-basement interface is even very doubtful. We are using a smooth structure derived from this data to compute synthetic seismograms for treating the Imperial Valley event and accompanying aftershocks. Work, to date, is extremely encouraging and will continue in the future with support from the National Science Foundation.

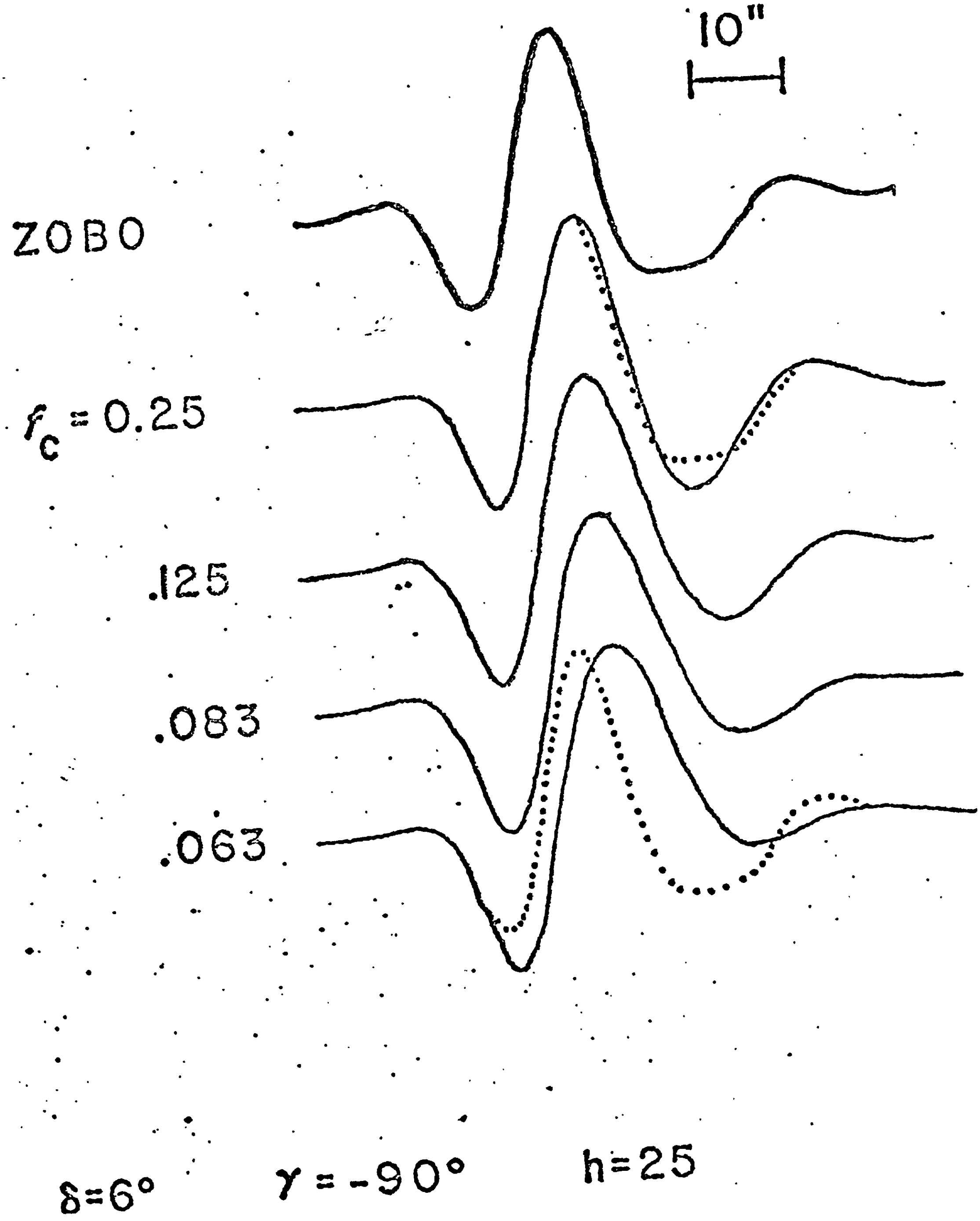


Figure 5. The effect of the corner frequency of the source-time function on the synthetic seismograms for ZOBO (La Paz, Bolivia). The data are shown in the top frame and the synthetics fall below. The data is repeated with dots to illustrate the fit.

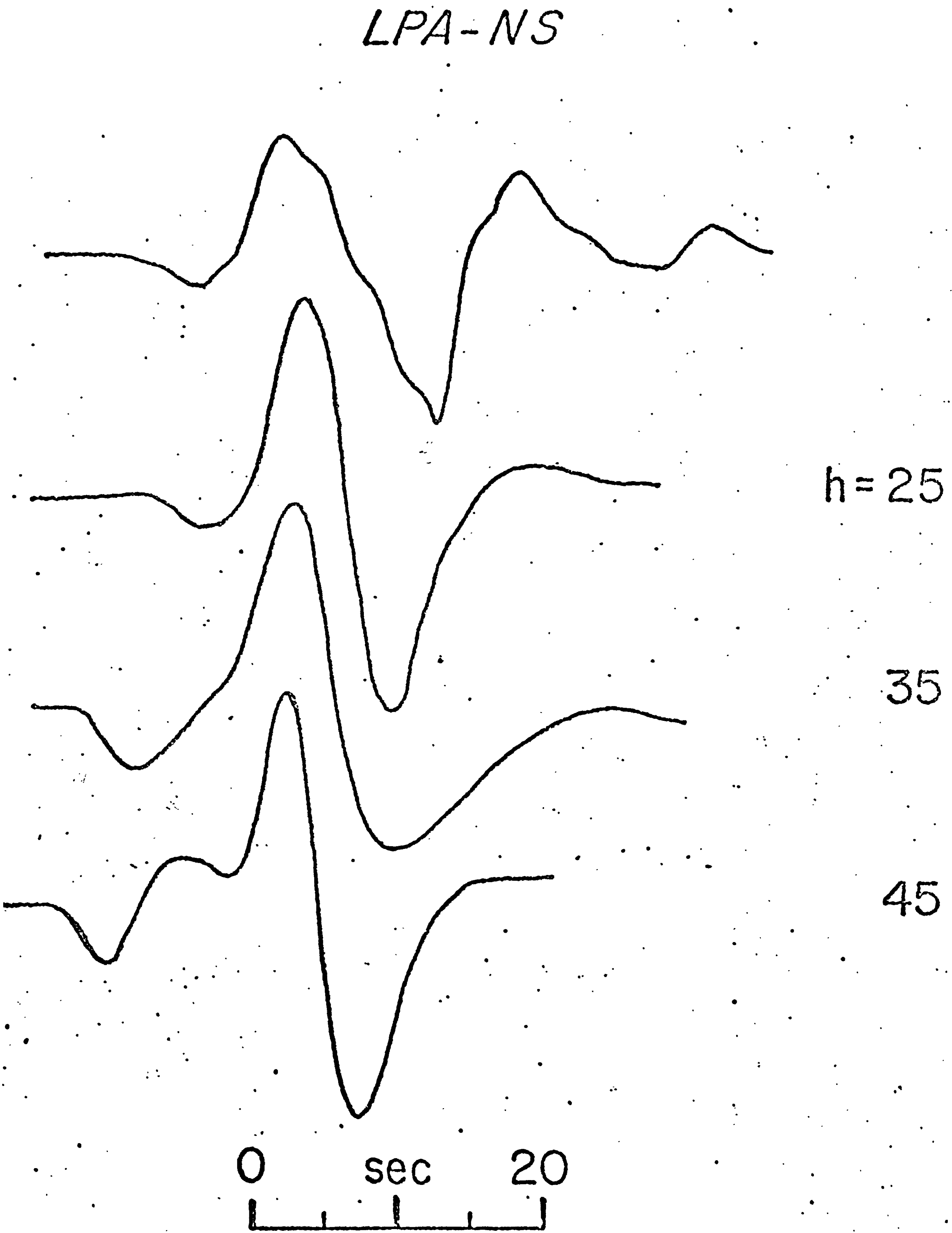


Figure 6. The effect of source depth on the synthetics for LPA-NS, the North-South component of the La Paz, Bolivia, WWSSN station. Many of the WWSSN stations were driven off scale by the event. The data is shown in the top frame.

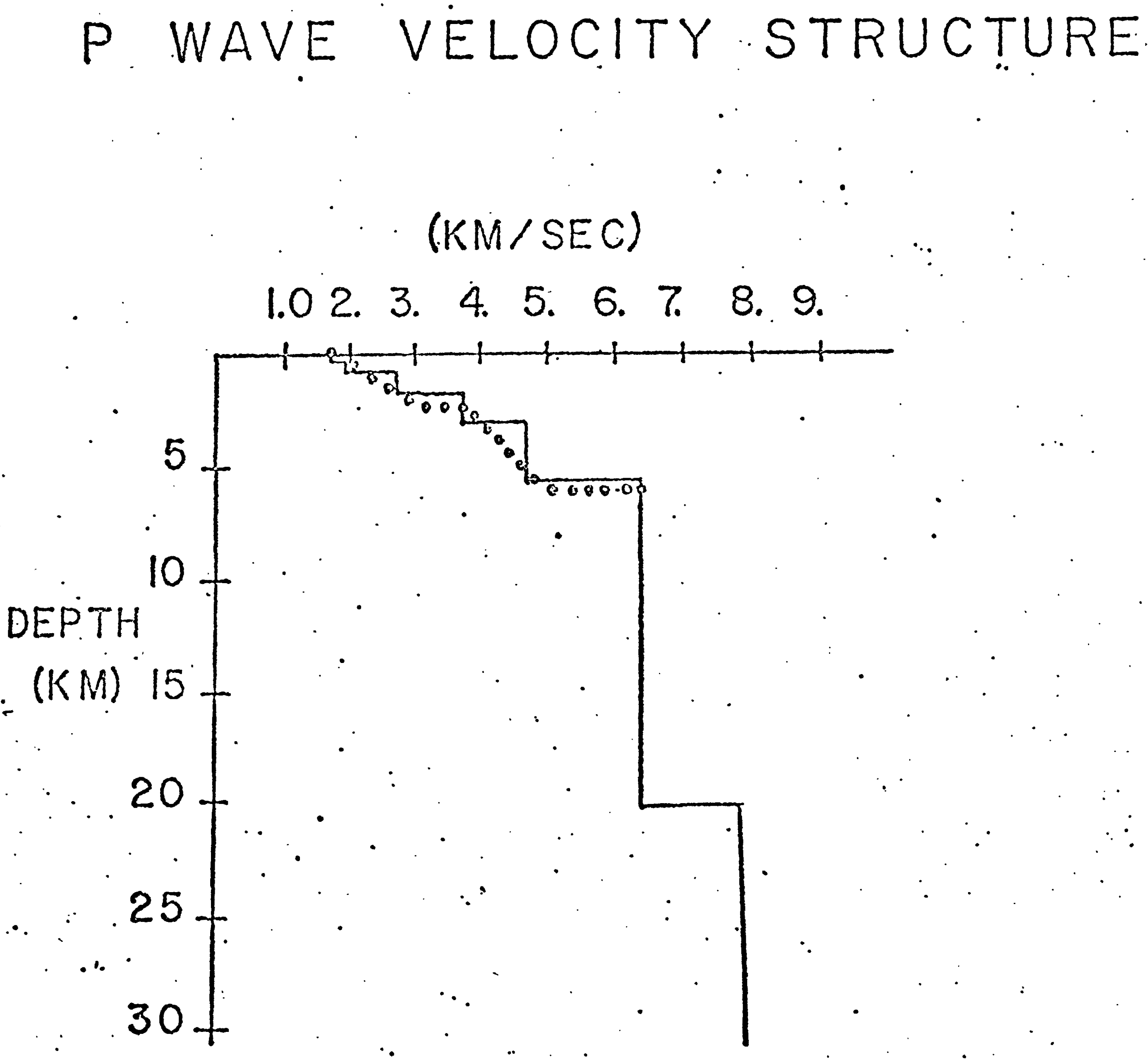


Figure 7. Two equivalent structures which fit the first arrival travel time data available in the Imperial Valley. One model consists of thick, homogeneous layers; the other of gradient zones.

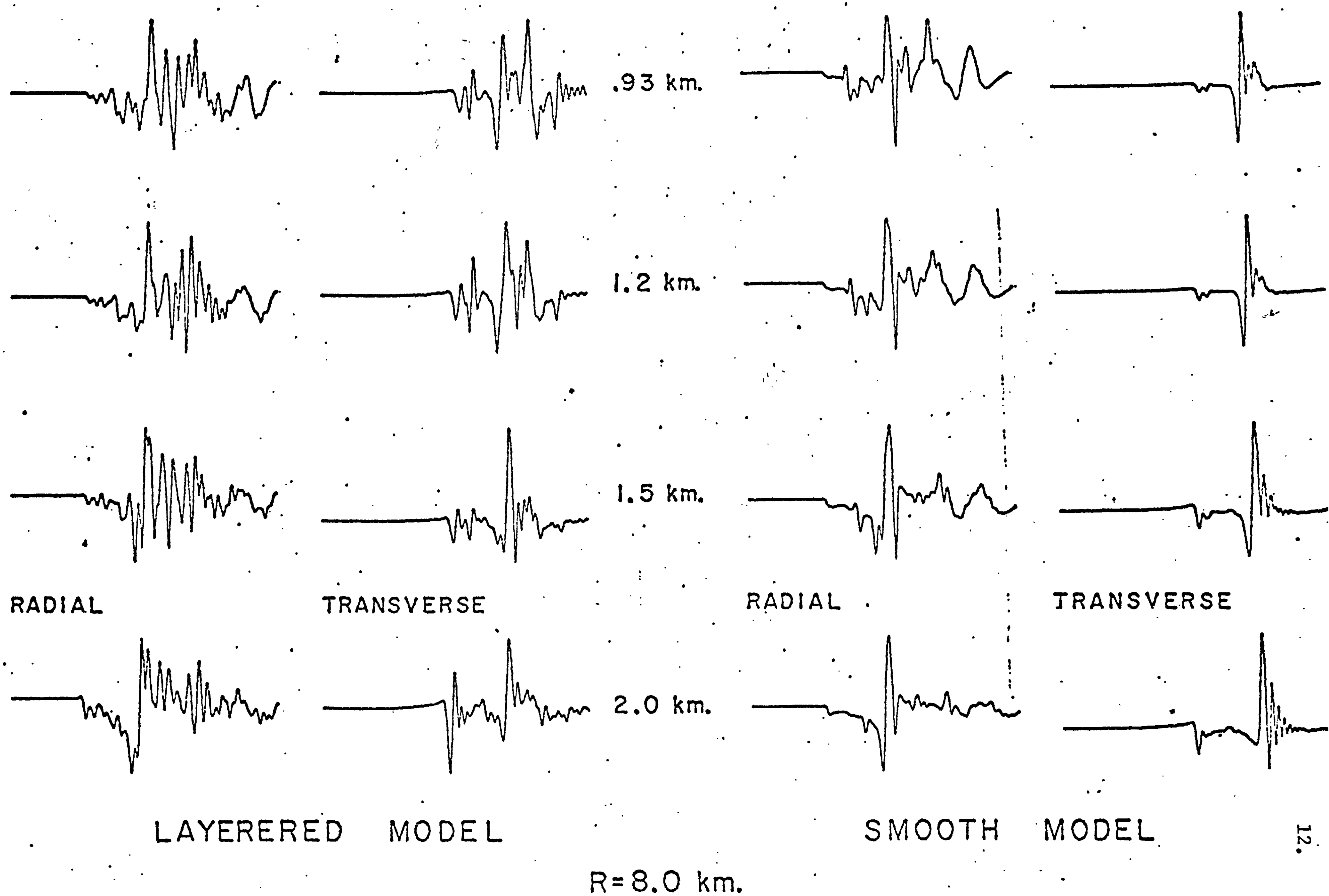


Figure 8. Synthetic seismograms at an epicentral distance of 8 km for the two models in Figure 7. Illustrated are source depths at 0.93, 1.2, 1.5 and 2.0 km.

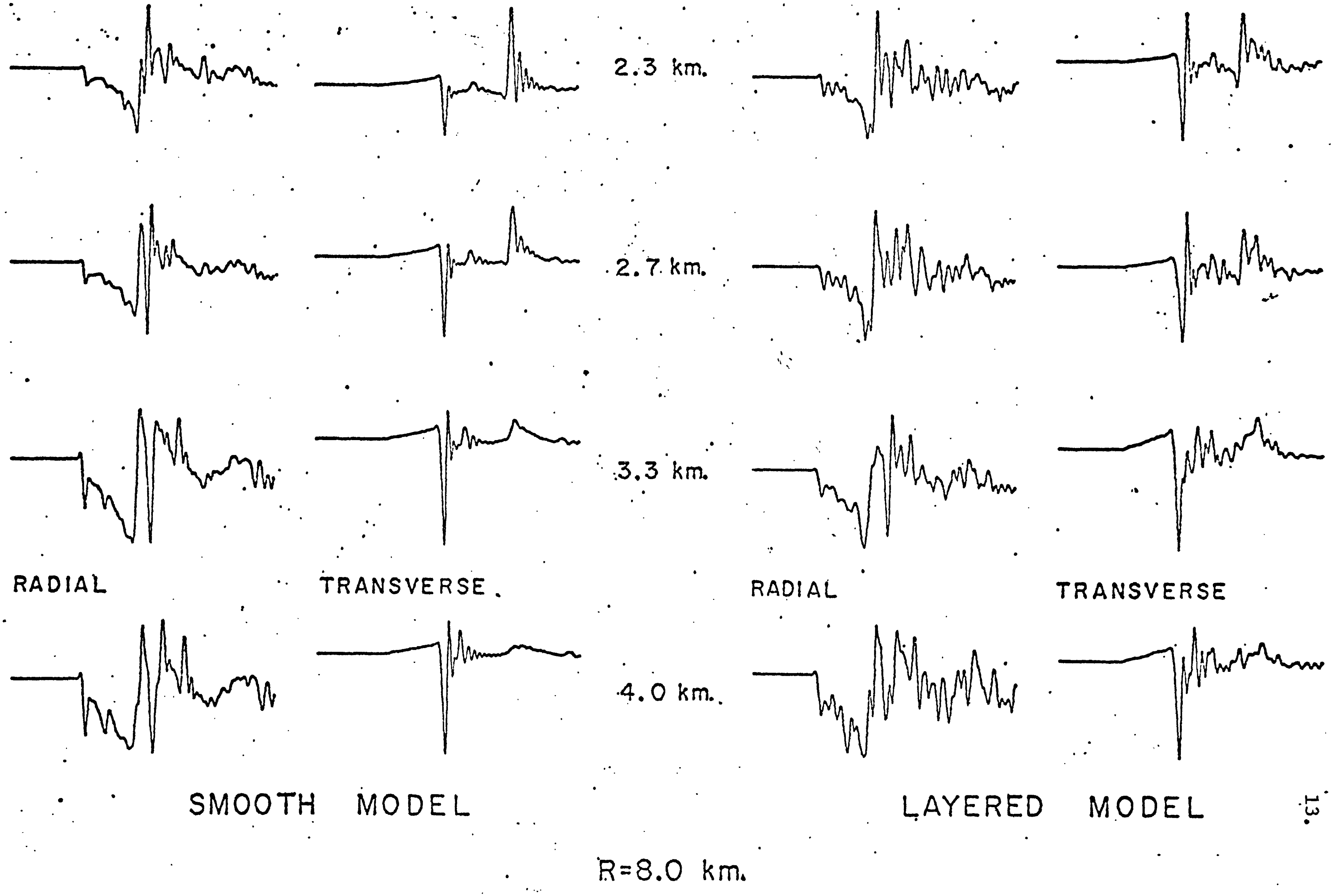


Figure 9. Same as Figure 8 except the source depths are greater: 2.3, 2.7, 3.3 and 4.0 km.

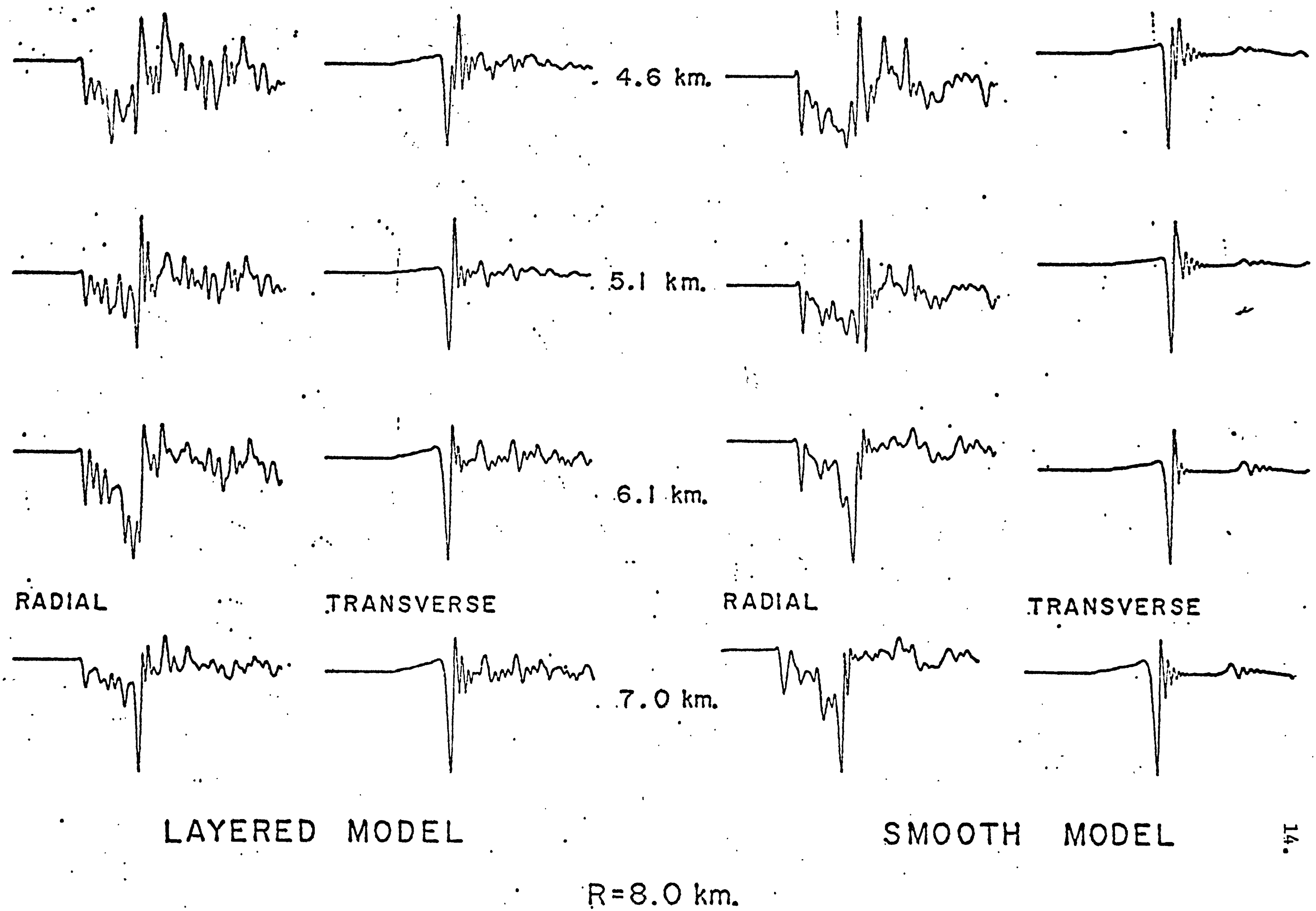


Figure 10. Same as Figure 8 except source depths begin to penetrate basement: 4.6, 5.1, 6.1 and 7.0 km. Note the layered and smooth models produce synthetics which are reasonably alike for these greater depths.

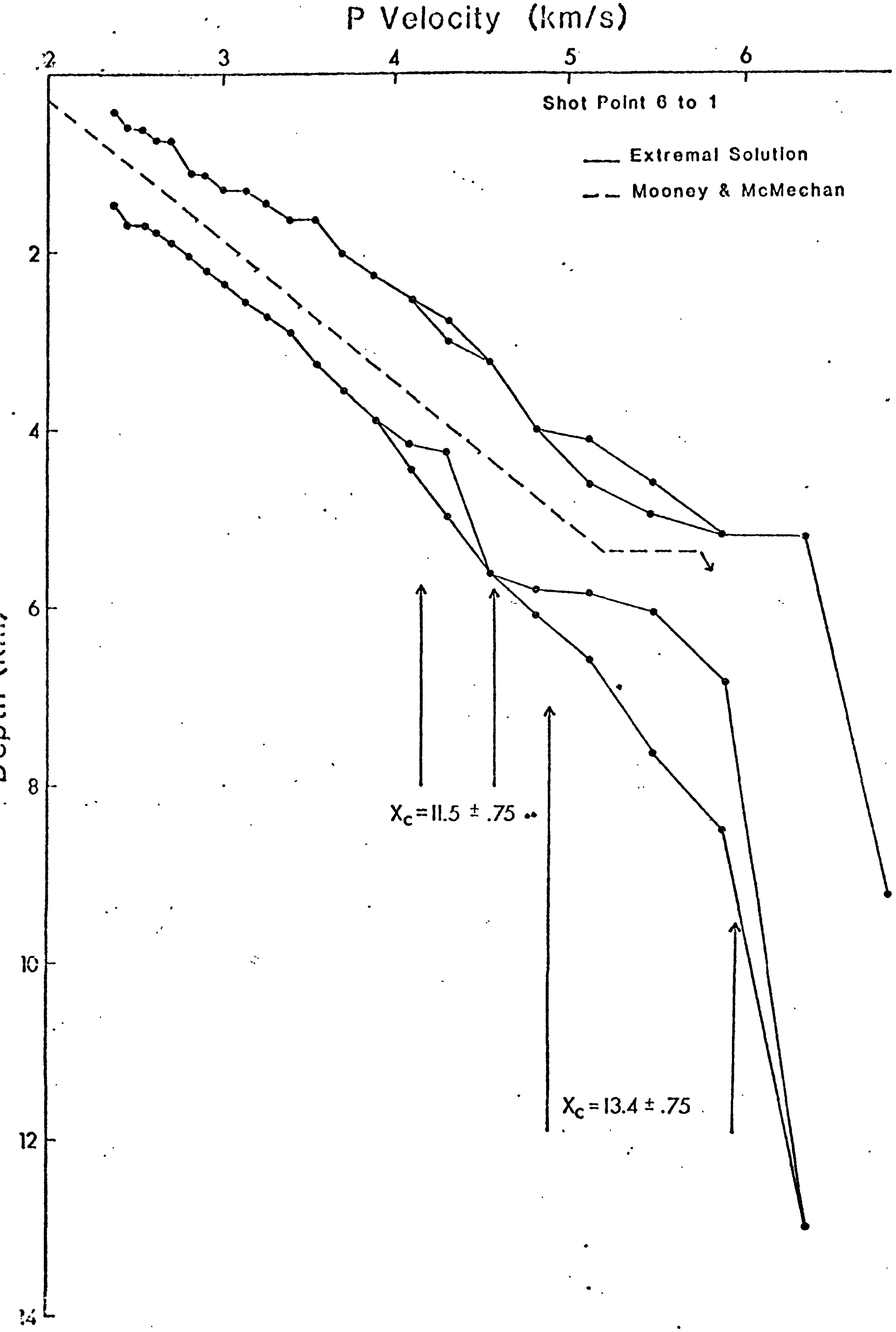


Figure 11. Results of extremal inversion of USGS Imperial Valley explosion data for a line paralleling the international border. The inner bounds employed the additional constraints of crossover points in the indicated ranges. The dashed line is a trial and error fit obtained by Mooney and McMechan (1980) using synthetic seismograms.

IV. Conclusions

We are convinced, based upon the year's supported research, that computing the source mechanisms for local events using the moment tensor formalism is practical. This, of course, presupposes an accurate knowledge of the earth structure in the area from detailed explosion studies and requires well-calibrated instrumentation. The difficulties with non-linearities arising from a lack of knowledge of source depth, although serious, can be solved through an iterative or generalized inverse approach.

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Retrieval of Earthquake Source Mechanisms Using Southern California Seismic Networks

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Investigations

1. Produce software designed to retrieve the seismic moment tensor from local digital recordings of earthquakes.

2. Analyses of the November, 1978, Oaxaca earthquake and the October, 1979 Imperial Valley earthquake.

3. Trial-and-error modeling of near field data using complete synthetic seismograms computed using the Wavenumber Integration and Discrete Wavenumber/Finite Element methods.

4. Investigate the role of source depth and local structure in the inverse problem of inferring the source mechanism directly from seismic recordings.

Results

1. Software has been developed to compute the inverse problem in the time domain using L^1 and L^2 norms. Future investigations will involve testing of the technique in the frequency domain where the lower frequency and more stable portions of the seismograms can be readily treated.

2. The methods have been applied to the Oaxaca, Mexico earthquake of November, 1978. We conclude: 1) The moment lies between 2.4 and 3.5×10^{27} dyne-cm; 2) The event is shallow, less than 25 km deep; 3) The slip vector corresponds to the well-known relative motion vector between the Cocos and North American plates; 4) The dip is small, less than 20°; 5) The effective time constant for the shear waves is larger than for the compressional waves.

3. In order to stabilize the inverse problem it has been necessary to normalize all data to the same peak-to-peak displacement and to heavily weight the initial part of the seismogram.

4. Experiments with different velocity-depth models in the Imperial Valley clearly show substantial differences in the synthetic seismograms in all parts of the wavetrain for a very shallow source in the sediments. The differences become less apparent as the source depth increases.

5. The effect of varying source depth, a non-linear constraint on the Inverse Problem, can be adequately accounted for through cataloging synthetic seismograms for several possible depths and allowing human intervention in the problem to decide which is most adequate.

6. Trial-and-error fitting of complete synthetic seismograms which include all near field terms, body and surface waves and leaky modes has been encouraging. In particular, a synthetic fit to a station from the 1977 Brawley swarm yielded a source moment corresponding to an M_L of 2.1 while the southern California network reported 2.2.

7. Two papers have been written, to date, sponsored by this contract and a third is in the final states of preparation.

8. Analysis of the extensive USGS explosion seismology experiment in the Imperial Valley during the summer and spring of 1979 has produced a reliable velocity structure for use in synthetics computations. The results of this work and the implications for strong motion modeling were presented at the Fall and Spring AGU's and the annual SSA meeting.

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