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Demonstration of a Technique for Rapid Inversion of Geo-Acoustic Properties of Littoral Marine Locations

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13. ABSTRACT *(Maximum 200 words)*

This report describes how to invert seismic data collected with sonobuoys in littoral marine environments to obtain sea floor geo-acoustic properties. The inversion method is an adaptation of simulated annealing (SA) which can rapidly and automatically find the best Earth model for each data set. The established SA algorithm was enhanced with envelope fitting and layer stripping. The first example is a synthetic data set to demonstrate the method for a known Earth model. The second example is at a 750 m water depth site using a watergun source that has a very clean and sharp pulse. The offsets were accurately determined prior to the inversion calculation for this case and a clear subbottom reflector was modeled in only 5323 iterations. The third example was at a site with 250 m water depth using an airgun source. The direct airgun signal saturated the sonobuoys at small offsets causing distortions in the waveforms and amplitudes. Data offsets could not be accurately measured and had to be included in the inversion problem which tripled the number of variables. This more difficult third example was solved with 35,421 iterations.

This demonstration is with highly nonoptimal data. The receivers are sparsely and irregularly spaced and have too limited a dynamic range for the source strengths and sea floor reflections encountered. However, by adapting the inversion technique to the challenges presented by the field data, the geoacoustic parameters of the sea floor were measured using rapidly deployed inexpensive and expendable equipment. The geoacoustic properties that I modeled include the sea floor depth, the water sound velocity and the compressional wave velocity of the uppermost 150 m of sediment. In the last case I also inverted for the sonobuoy to airgun offsets.

The reliability of the sonobuoy – airgun and sonobuoy – watergun data collection and the SA inversion method is demonstrated with favorable comparisons with high quality multichannel seismic (MCS) data from nearby sites. All of the major Vp – depth features that can be expected to be modeled from the field data correspond well with measurements from the MCS data.

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Summary

This report describes how to invert seismic data collected with sonobuoys in littoral marine environments to obtain sea floor geo-acoustic properties. The inversion method is an adaptation of simulated annealing (SA) which can rapidly and automatically find the best earth model for each data set. The established SA algorithm was enhanced with envelope fitting and layer stripping. The first example is a synthetic data set to demonstrate the method for a known earth model. The second example is at a 750 m water depth site using a watergun source which has a very clean and sharp pulse. The offsets were accurately determined prior to the inversion calculation for this case and a clear subbottom reflector was modeled in only 5323 iterations. The third example was at a site with 250 m water depth using an airgun source. The direct airgun signal saturated the sonobuoys at small offsets causing distortions in the waveforms and amplitudes. Data offsets could not be accurately measured and had to be included in the inversion problem which tripled the number of variables. This more difficult third example was solved with 35421 iterations.

This demonstration is with highly nonoptimal data. The receivers are sparsely and irregularly spaced and have too limited a dynamic range for the source strengths and sea floor reflections encountered. However, by adapting the inversion technique to the challenges presented by the field data, the geoacoustic parameters of the sea floor were measured using rapidly deployed inexpensive and expendable equipment. The geoacoustic properties that I modeled include the sea floor depth, the water sound velocity and the compressional wave velocity of the uppermost 150 m of sediment. In the last case I also inverted for the sonobuoy to airgun offsets.

The reliability of the sonobuoy - airgun and sonobuoy - watergun data collection and the SA inversion method is demonstrated with favorable comparisons with high quality multichannel seismic (MCS) data from nearby sites. All of the major Vp - depth features that can be expected to be modeled from the field data correspond well with measurements from the MCS data.

Introduction

The purpose of the inversion technique presented in this report is to rapidly obtain sea floor geoacoustic parameters to support Navy ASW operations. This technique uses data that can be rapidly collected from ships and (potentially) aircraft using existing inexpensive and easily deployed equipment. This technique has been previously demonstrated using other types of marine seismic data. For example, in Wood and Lindwall (1996), this technique is applied to high frequency vertical acoustic profiles of the sea floor, Lindwall et al. (1995) applies this technique to deep tow multichannel seismic data and Lindwall (1995) demonstrates this same inversion method on the vertical acoustic profiles, the deep tow multichannel data as well as simulated seismic refraction data.

The method described in this report is available as a set of FORTRAN programs that can analyze field data in the proper (relatively simple) format. The field data must first be corrected for shot time and shot to receiver offsets as well as possible. A standard seismic processing software package such as Seismic Unix (available from the Colorado School of Mines at http://www.cwp.mines.edu/cwpcodes) is ideal for this task. Accurate measurements of the water sound velocity, water depth and source and receiver depths need to be made in the field for a fast and accurate inversion solution. Unknown or inaccurate environmental variables can be inverted for but slow down the process. This is shown in my third demonstration where the shot offset variables are included in the inversion and turn a 30 minute calculation into a 10 hour calculation.

The inversion is first applied to synthetic data as a test and then to two sets of field data. The field data was collected in the STRATAFORM area near the mouth of the Eel River in California. The STRATA FORmation on Margins program is a coordinated multi-investigator study of continental-margin stratigraphy initiated by the Office of Naval Research.

Methods

The rapid inversion method described here is adapted from Simulated Annealing (SA). SA inversion uses synthetic data from a forward modeling algorithm and an evolutionary test criterion to determine the best fitting physical model (environmental parameters) for a given data set. SA inversion is used in cases where the physical model cannot be directly determined from the data and the model space is too complex for the best solution to be found by iteratively moving from a random starting solution to a better one. The forward algorithm used in this demonstration is a ray trace code that uses a one dimensional environmental model, includes shear wave conversion losses, but does not include compressional wave multiples or the sea surface reflections (Chapman, 1976; Cerveny et al., 1977). It was chosen for this demonstration because it is extremely fast relative to full wavefield methods such as reflectivity (Fuchs and Müller, 1971).

The original SA algorithm was set forth by Metropolis et al. (1953) and reintroduced by Kirkpatrick et al. (1983). The first application of SA inversion to velocity estimations from seismic waveform data is by Basu and Frazer (1990) and was much further developed by Sen and Stoffa (1991). The Very Fast Simulated Annealing (VFSA) modification of Ingber (1989) accelerates the conversion by progressively focusing the model search space onto the better fitting solutions. The SA algorithm used here is an extension of all of these previous methods.

The SA algorithm used here has the option of using a different temperature (or convergence criteria) for each layer in the earth model. By using lower temperatures for the upper layers, the model parameters for these layers can be fit prior to fitting the lower layers. This is similar to the technique of layer stripping. The upper layers, especially the sea floor, usually give stronger reflections than lower layers. Fitting the stronger features from the upper layers is usually easy and can be done quickly. Then with the solution for the upper structure, the lower model parameters are easier to fit. The second significant new option is for fitting the waveform envelope rather than the waveforms. Fitting the waveform envelopes greatly smoothes the residual function particularly for high frequency and limited bandwidth signals making the inversion much faster (Wood and Lindwall, 1996).

Demonstrations

The first inversion demonstration is on synthetic data (Figure 1a). Testing an inversion algorithm on synthetic data where the exact solution is known tests the inversion method rather than data collection or processing. The environmental model used for the synthetic data in Figure 1 has 15 layers with six variables for each layer; these variables are: thickness, density, compressional velocity (Vp), shear velocity (Vs), compressional attenuation, and shear attenuation. The search was done only over Vp and layer thickness for the upper 3 sediment layers in order to reduce computation time. All other model variables were set to the true values. Within a limited time (877 iterations) the inversion found a very good solution shown in Figure 1d. The residual amplitude (Figure 1c) was less than ten percent of the data amplitude. This first inversion fit the waveform rather than the envelope as was done for the two field data cases.

The second inversion demonstration is with field data (Figure 2a) from a 750 m water depth site in the Eel River - STRATAFORM region offshore Eureka, California using ship deployed sonobuoys and a watergun sound source. The watergun produced a very sharp impulse so source deconvolution was not used. The data resolution was lowered with a 50 Hz low frequency bandpass filter (from a 2 kHz sample rate) to allow for simpler models and an easier inversion. Source to receiver offsets were carefully determined from the direct wave arrival times. I fit the envelope rather than the waveform since the forward modeling algorithm does not include important parts of the waveform in the calculation, specifically the sea surface multiples and interbed multiples from the detailed structures near each of the major interfaces. Fitting the waveform envelope allows for a much faster inversion with nearly the same precision as a full waveform fit (Wood and Lindwall, 1996). The residual from the inversion solution shown used 5323 iterations and has 55 percent of the amplitude of a random solution which is a good result for field data.

There are only two features in the data (Figure 2a) that were modeled, the sea floor and a subsurface reflection about 0.2 seconds after the sea floor reflection. The sea floor here is 755 m deep, the sea floor reflection hyperbola fit a water velocity of 1.498 km/s, the Vp of the upper sediments is 1.538 km/s. The subsurface reflection is 0.147 km below the sea floor and the sediments below have a Vp of 1.558 km/s. The Vp of the lower sediment is poorly constrained since only the relative amplitude of the reflection is known which is also dependent on the density contrast, another unknown value. Velocity models from nearby multichannel seismic lines (C. Fulthorpe, personal communication; J Yun, personal communication) have similar subbottom velocities (Figure 2d). The MCS data are adjusted so that the sea floor depth is the same as my SA inversion solution. The sediment Vp is equal to the lowest value obtained from the MCS data and all but one of the MCS shows a significant reflector within 50 m depth of the reflection fit by the SA inversion. Most of the MCS data used a 168 channel, 2.5 km long streamer giving much higher quality data than the sonobuoy data used for the SA inversion. The reliability of the SA inversion is indicated by the overall agreement with the MCS data.

The third set of data for this demonstration was collected at a 250 m water depth site in the Eel River-STRATAFORM region near Eureka California using ship deployed sonobuoys and an airgun source. The airgun has a lower frequency and narrower bandwidth than the watergun used at the 750 m water depth site. Source to receiver offsets were initially determined from the direct wave arrival times but were not accurate enough for a good inversion. I had to include the offsets as inversion variables adding twenty variables to the existing ten model variables. Solving for thirty variables instead of ten means not only that each sweep (once through all variables) takes three times as many calculations but the cooling process must also be done much more slowly. There have been no studies of how many more iterations are needed for each new variable added to an inversion but my experience suggests that it is a power law function rather than linear. This third inversion case used 35421 iterations for thirty variables while the second case used 5323 iterations for seven variables. I again fit the envelope rather than the waveform. The lower frequency of the airgun signal reduced some of the complications of having a limited bandwidth and the lack of surface reflections in the synthetic calculations. The shallower depth here however complicated the analysis since the sea floor and subbottom reflections were perilously close to the direct arrivals which saturated the sonobuoy receivers. Sonobuoy records do not have the correct amplitudes or waveforms when they are saturated and the sonobuoy electronics take several tenths of a second to recover. The distorted amplitudes of the sea floor reflections and the overlapping, decaying direct signal make reliable inversions difficult.

Features in the data (Figure 3a) modeled include a complex sea floor reflection and a subsurface reflection about 0.04 seconds after the sea floor reflection. The sea floor here is 245 m deep, the sea floor reflection hyperbola fit a water velocity of 1.482 km/s, the Vp of the first 9 meters of sediment is 1.573 km/s and then increases to 1.612 km/s in a 43 m thick layer. The Vp below this was modeled at 1.618 km/s but is poorly constrained for the same reasons as in the 750 water depth site. Velocity models from nearby multichannel seismic lines (C. Fulthorpe, personal communication; J Yun, personal communication) have similar subbottom velocities (Figure 3d). The MCS data are adjusted so that the sea floor depth is the same as my SA inversion solution. My sediment Vp values are in the middle of the MCS values. All of the MCS data shows a significant interface at the 400-440 m depth range but the reflection arrival times are the same as the sea floor reflection multiple in my data so it is not visible in this sonobuoy data. Most of the MCS data used a 168 channel, 2.5 km long streamer giving much higher quality data than the sonobuoy data used for the SA inversion. The reliability of the SA inversion is indicated by the overall agreement with the MCS data. A curve from Table IV of Hamilton (1980) is plotted on the inversion and MCS models (Figures 2d and 3d) to contrast Hamilton's gradient with the discontinuous seismic models. Hamilton fit a smooth polynomial curve through Vp values from 20 sites. These two individual sites may be approximately consistent with Hamilton's Vp values but the discrete reflectors and the discontinuous velocity - depth functions are likely to dominate the geoacoustic responses of these two sites.

Restrictions and Future Improvements

Knowing the source function is crucial for a good waveform or envelope inversion. Most real sources (such as airguns and explosives) have waveforms complicated enough to obscure or mimic real interface reflections. The negative effects of a complex source function can be eliminated by either deconvolving the source function or by including the source in the forward calculation. The SA inversion code described here has only a few rudimentary sources built into it, and its utility would be greatly enhanced by improving the source functions or by building a deconvolution module. Deconvolution is an inversion problem itself and could either remove the source and receiver responses from the data or to accurately determine the source wavelet for inclusion in the forward calculation.

The sea surface is a nearly perfect reflector so for shallow receivers or sources, the surface multiples will be as strong as the primary. Inversion with a forward code that does not include surface reflections will try to solve for these multiples as part of the sea floor reflection response and will put strong interfaces where none exist. The currently used forward code (ray1D) does not include surface multiples. We plan to include computation of sea surface reflections in the next version of this code.

Accurate inversions require offsets to within half a wavelength (1 m for some of the data shown here) and this must be determined from the data itself using the direct wave. The direct wave is not a simple pulse but a complex waveform that changes due to the nonlinear response of the sonobuoys from being saturated due to the overly strong signal.

The sonobuoys response to the direct arrival is due to the overdriving of the electronics from a strong signal. The recovery of the electronics depends on the signal strength. For these reasons the direct wave response changes enormously with offset and can not be done by picking the peak amplitude or the first swing in amplitude. A program to determine offsets by cross correlating the direct waves for a window of similar offsets and moving the offset window over the whole data set would be much faster and more reliable than the manual offset picking and iteration that is used now. This enhancement also should be included in further development of the rapid inversion technique.

The inversion technique presented here should be enhanced with the addition of dip as a model variable. This would accommodate smooth 2-D earth models, models that are much more realistic for littoral regions. Inclusion of dip is straightforward in ray trace forward codes and the ability to run a line at any azimuth would reduce the logistics of the field activities. The data used in this demonstration was acquired along strike (parallel to bathymetry lines), a restriction that need not remain in future version of this inversion code.

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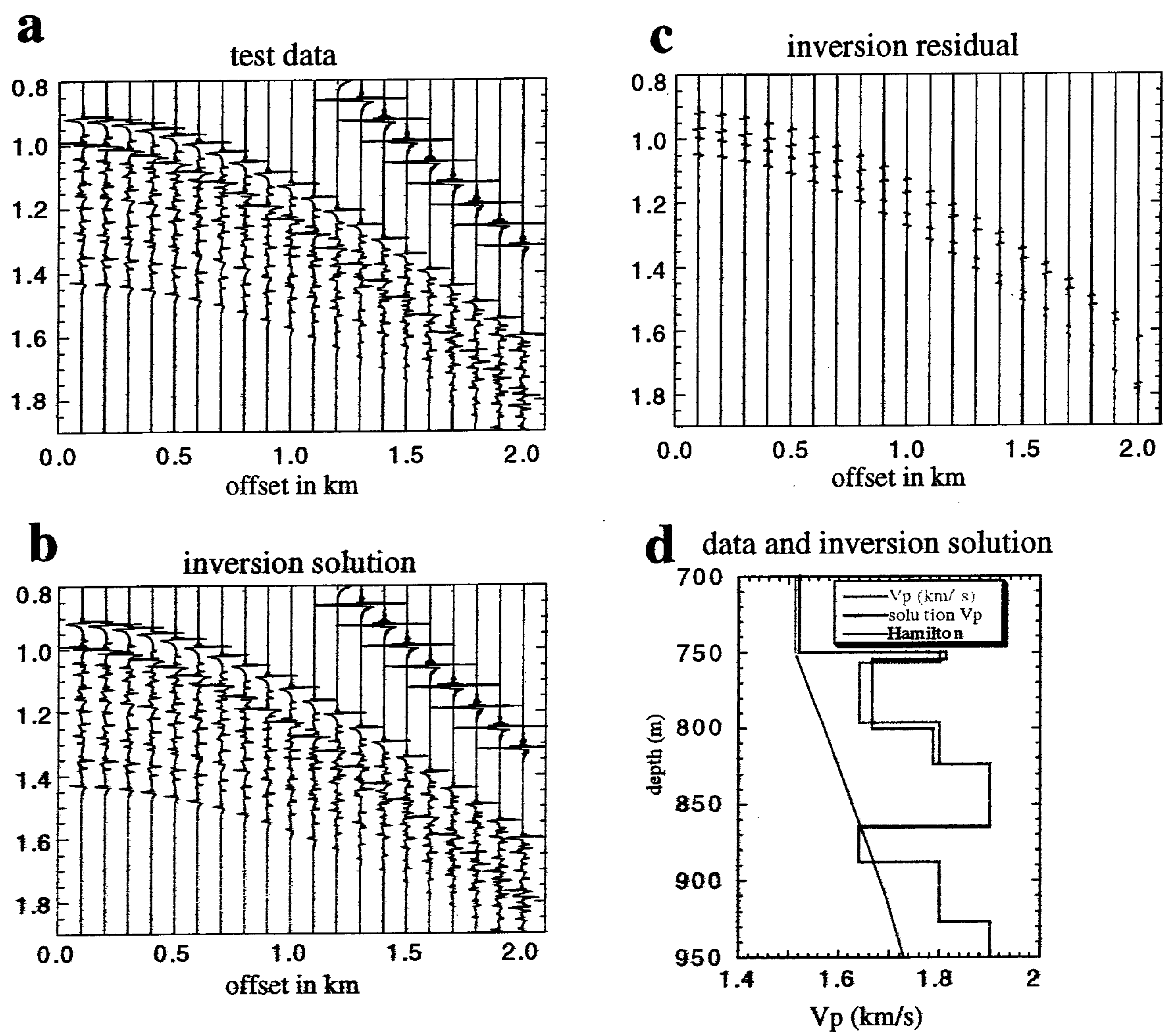
Figure Captions

1. Synthetic data calculated from a realistic marine sediment model (**a**) is inverted using simulated annealing (SA) to find a good fit with limited computational resources (877 iterations and 110 minutes on a Sun SPARC10). The solution synthetic is in panel **b** for comparison. The residual (**a** - **b**) is shown in panel **c** and has only 9.6% of the amplitude of the data (summed over the time window) demonstrating that the fit is very good. Panel **d** compares the known physical model (red line) to the inversion solution (blue line). The velocity search window was from 1.5 to 2.5 km/s and the layer thickness window was ± 33% of the true value.

2. Field data collected in the Eel River STRATAFORM area at a water depth of 756 m (**a**) is inverted using simulated annealing (SA) to find a good fit with limited computational resources (5323 iterations and 27 minutes on a Sun SPARC10). The solution synthetic is in panel **b** for comparison. The residual (**a** - **b**) is shown in panel **c** and has 55% of the amplitude of a random solution. Panel **d** compares the inversion solution (thick line) to velocities determined from several high resolution multichannel seismic (MCS) data (thin lines) collected at nearby sites and adjusted so that the sea floor depths correspond. The SA inversion solution is identical to the lowest MCS solution (the two lines are superimposed down to 905 m) and 3 MCS sites have a reflector between 900 and 920 m depth. This approximate agreement with the MCS data indicates that the SA inversion gives reliable results.

3. Field data collected in the Eel River STRATAFORM area at a water depth of 245 m (**a**) is inverted using simulated annealing (SA) to find a good fit with limited computational resources (35421 iterations and 9.6 hours on a Sun SPARC10). The solution synthetic is in panel **b** for comparison. The residual (**a** - **b**) is shown in panel **c** and has 80% of the amplitude of a random solution. Panel **d** compares the inversion solution (thick line) to velocities determined from several high resolution multichannel seismic (MCS) data (thin lines) collected nearby and adjusted so that the sea floor depths correspond. The Vp values for the upper 150 m of sediment from the SA inversion are in the middle of the MCS derived values indicating a reliable result from the inversion. The prominent reflector in the MCS data at a depth range of 380-440 m is obscured in the sonobuoy data by the sea surface multiple so is not modeled in the SA inversion.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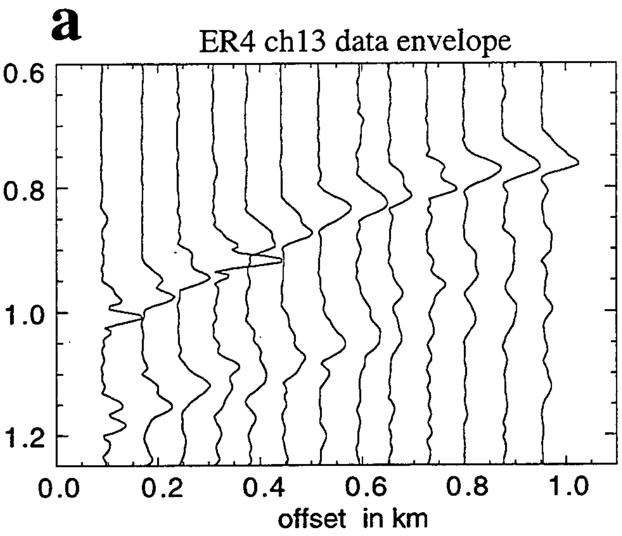
Vp (km/s)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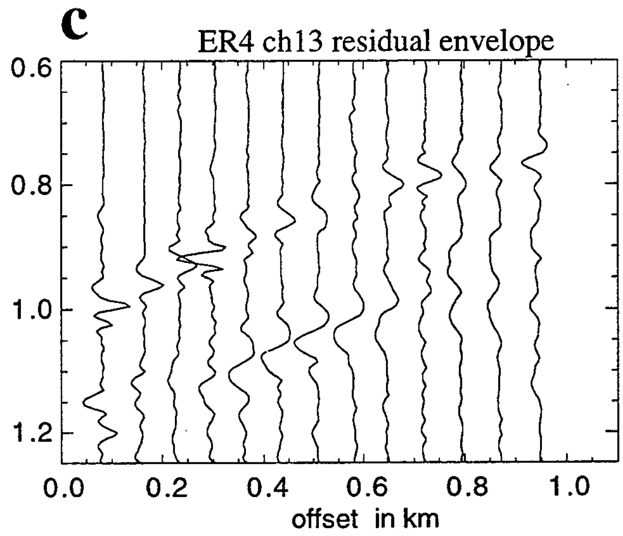
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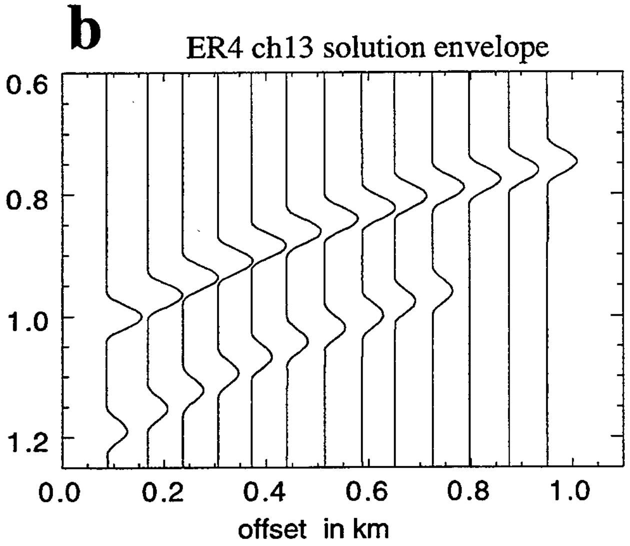
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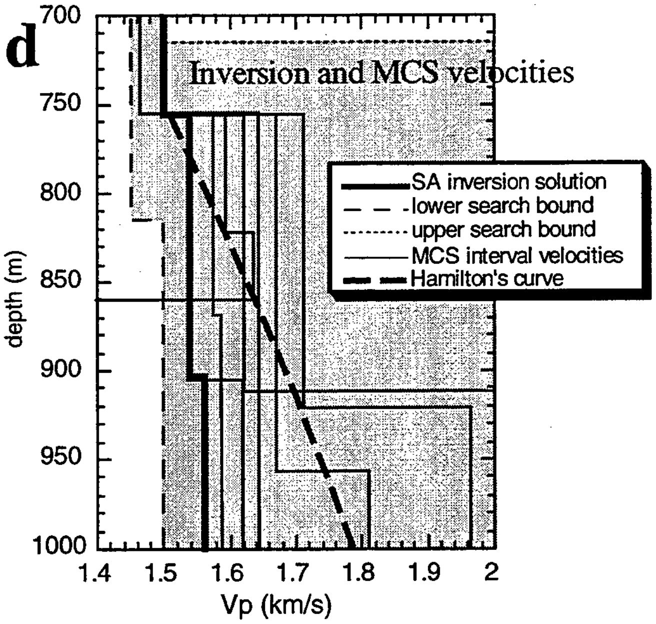
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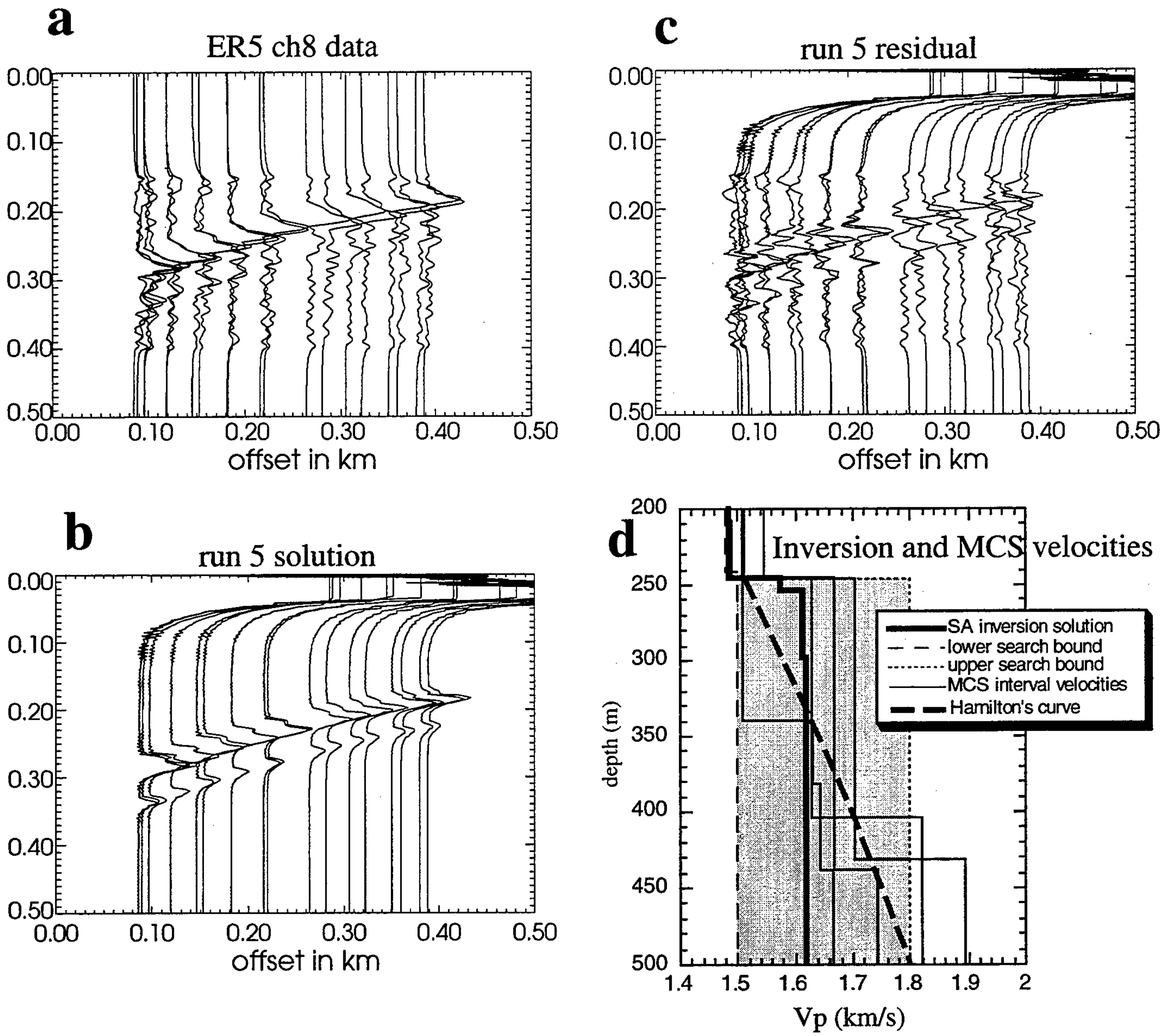
Vp (km/s)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Inversion and MCS velocities
SA inversion solution
lower search bound
upper search bound
MCS interval velocities
Hamilton's curve
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300
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400
450
500
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1.5
1.6
1.7
1.8
1.9
2
Vp (km/s)