

SIMULATED ANNEALING EXPERIMENTS IN STATICS COMPUTATION: SYNTHETIC AND REAL DATA EXAMPLES¹

KRIS VASUDEVAN², FRED COOK², ANGELA DU TOIT², WILLIAM G. WILSON³ AND WILLIAM G. LAIDLAW³

ABSTRACT

Removal of residual statics, commonly referred to as surface-consistent statics, is crucial in seismic data processing for refining subtle and complex structures in seismic sections. Methods using simulated annealing search techniques to compute statics are becoming common. Application of simulated annealing statics corrections to both synthetic and field data shows that the coherency of seismic events is enhanced. Preliminary study of the dependency of the simulated annealing search method on cooling schedules in this work suggests the use of slow cooling.

INTRODUCTION

Direct search methods are routinely used to solve residual statics problem (Taner et al., 1974; Wiggins et al., 1976; Russell, 1989; Bancroft, 1990; Kirchheimer, 1990). However, in some extreme cases, they can be expected to have little hope of resolving the optimization problems presented by the residual statics estimation. This is largely because the optimization function defined in the statics parameter space generates an extremely complex surface with many local minima and even a "degenerate" global minimum where the degeneracy refers to the multiple minima having the same value for the optimization function (Ronen and Claerbout, 1985). The complexity of the surface in most cases is so extreme that trapping in a local minimum seems inevitable!

There are two steps which can be undertaken to increase the efficiency of the search. The first step is to "clean up" the surface by removing as many of the irrelevant minima as possible. The second step would be to employ a search technique which reduces the likelihood of terminating in any of the remaining local minima. These goals can be addressed by the use of a "stack power" to define the surface and by the use of the simulated annealing technique which avoids trapping in local minima through the use of a tunable "tempera-

ture" parameter (Kirkpatrick et al., 1983; Rothman, 1985, 1986; Paulson, 1986). Variations of this method were applied to improve the field data from the Wyoming Overthrust belt by Rothman (1986). However, stack power optimization still presents difficulties in that the ground state statics solution remains highly degenerate. Partial removal of this degeneracy has been accomplished by introducing a constraint on the difference between neighbouring shot and receiver statics (Dahl-Jensen, 1989) and this has led to some success.

The approach proposed recently by Vasudevan et al. (1991) abandoned the stack power as the "coherence function" and instead introduced a cross-correlation between two stacks. Although some degeneracies in the ground state remain, the degenerate solutions that most severely corrupt the overall coherence are seriously reduced. A search for the optimum set of statics parameters can then be carried out using the steepest descent, the iterative improvement, or the simulated annealing technique, depending on the remaining complexity of this cleaned-up surface. However, even after the use of the cross-correlation between two stacks, there are many situations where the complexity of the surface still requires the use of the simulated annealing technique to ensure that the global minimum or near-global minimum solution is reached.

This paper is divided into two sections. In the first section, the simulated annealing approach is discussed in terms of a physical annealing process as well as the specific application to processing seismic data where residual statics must be removed. A detailed general description of the simulated annealing technique can be found in literature (Rothman, 1985, 1986; Aarts and van Laarhoven, 1987). Only a brief overview is presented here. Three characteristically-different "cooling" schedules and their effects on the data are outlined.

In the second section, results obtained with synthetic and field data are presented. The field data are typified by a

¹Presented at the C.S.E.G. National Convention, Calgary, Alberta, May 16, 1991. Manuscript received by the Editor November 8, 1991; revised manuscript received February 15, 1992.

²LITHOPROBE Seismic Processing Facility, Department of Geology and Geophysics, The University of Calgary, Calgary, Alberta T2N 1N4

³Department of Chemistry, The University of Calgary, Calgary, Alberta T2N 1N4

This work carried out at the LITHOPROBE Seismic Processing Facility is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canadian Department of Energy, Mines and Resources. William Wilson would like to acknowledge The University of Calgary post-doctoral fellowship. Thanks are also due to Dr. Don Lawton of the Department of Geology and Geophysics for making a synthetic shot record available to us and to Academic Computing Services for providing valuable computer time on the IBM RISC/6000 systems. This is LITHOPROBE contribution number 281.

generally low signal-to-noise ratio. The size of the field data used for the example is large and, as a result, solving the simulated annealing problem is very computer intensive; hence, only one time window was used for simulated annealing runs. This window corresponds to a zone of reflectivity interpreted to be near the top of North American basement (4.0–7.0 s) and is taken from LITHOPROBE reflection data obtained in the southeastern Canadian Cordillera (Cook et al., 1987, 1988). The results obtained from three different cooling schedules on a segment of the field data are also discussed.

SIMULATED ANNEALING METHOD

The physical annealing process

Because our eventual goal is the enhancement of the coherence of seismic reflector interfaces in a seismic data set, it is worthwhile to explore the appearance of order in a very physical situation, the solidification of a fluid into an ordered crystal. The physical annealing process in the most general terms is a phase transition from a chaotic state to an ordered state (i.e., crystallization of a melt) brought about by a gradual cooling. Slow cooling allows local “energy” fluctuations to occur that enable imperfections to remelt and recrystallize to yield a more ordered crystal. If the liquid is cooled too quickly, the crystal is trapped in a local minimum with many imperfections. These features are analogous to the recovery of coherence (order) out of noisy (disordered) seismic data.

In the simulated annealing optimization technique, the optimization function and the temperature need to be explicitly defined. In our work, we have chosen to use an optimization function based on the coherence between neighbouring common-depth-point (CDP) gathers, as opposed to only coherence within CDPs (Rothman, 1985). This optimization function favours stacks with good internal coherence, but it trades off some degree of incoherence within stacks for increased coherence between stacks. We call this optimization function a cross-correlation coherence function and define it by:

$$C = \sum_y \sum_t \left\{ \sum_h d_h^y [t + s(y, h) + r(y, h)] \right\} \\ \times \left\{ \sum_h d_h^{y+1} [t + s(y+1, h) + r(y+1, h)] \right\}. \quad (1)$$

The summations are over all CDPs, all time samples, t , of the trace, and all offsets, h , within a CDP gather. The trace data are represented by $d_h^y [t + s(y, h) + r(y, h)]$, where $s(y, h)$ and $r(y, h)$ are the shot and receiver statics for the CDP y and offset h . It is the negative of C that is considered and so C is to be minimized. Computation of C requires more computer cycles than the stack power used by Rothman (1985). However, an advantage is that some of the degeneracies found in the phase space of the stack power expression (Rothman, 1985) are removed by using (1). For example, the ground state degeneracy due to linear shot/receiver trends in the stack power problem are removed by the optimization function (1), making the energy surface somewhat cleaner.

Applying the Monte Carlo technique to data fitting also requires the introduction of a quantity analogous to the temperature of the physical case (crystallization temperature). The purpose of this quantity is twofold: 1) it scales the size of the fluctuations that appear in the acceptance criteria; 2) it allows the rate at which the quality of the fit increases to be tuned. These are not, as explained above, independent roles. We propose to call this quantity the “control parameter.” Lowering the control parameter favours fits of higher quality and simultaneously decreases the relative size of the fluctuations. In our discussion, we shall use control parameter and temperature interchangeably.

Just as the physical annealing process follows a cooling protocol, so must the simulated annealing method. Cooling too quickly is equivalent to a steepest descent search, but cooling slowly prevents being trapped in local minima.

Application of simulated annealing to seismic data

We now discuss the application of the simulated annealing technique with the optimization function given by (1) into a seismic data analysis. Assume a data set is given, with shots numbered 1 through n_s and receivers numbered 1 through n_r . The system is first initialized at a random point in the statics parameter so as not to bias the final ground state in any way. This initial disordering of the system corresponds to a very high “temperature” (or control parameter) starting condition. At this point we also calculate initial quantities such as the coherence function between neighbouring CDPs and store these values for future use. We now enter the annealing process. This process is divided into simulation steps, loosely referred to as time steps, in which a change in each of the $n_s + n_r$ parameters of the system is considered. A cooling schedule, discussed later, is given as a function of these simulation steps. Simulation steps are subdivided by the consideration of each parameter in turn. We choose a random ordering of the shots and receivers as Dahl-Jensen (1989) has observed favourable results with a disordered progression of stations in the statics computation problem. Because each station, whether a shot or a receiver, is treated identically in our method, we shall discuss the operations performed for a single station.

Let us label the station R , with the understanding that it may refer to either a shot or receiver station. The static shift of the station is r , and the value of the optimization function C for the present configuration of parameters is E_0 . In the simplest form of the annealing procedure, a new value for the shift, r' , is proposed. As the value of this parameter changes, the value for the new configuration, E' , is calculated. The difference is $\Delta E = E' - E_0$, and we then evaluate the acceptance criterion (Metropolis et al., 1953). To accommodate this procedure, we introduce a term for describing the transition probability (Rothman, 1986) which is equal to $\exp(-\Delta E / T)$.

If $\Delta E < 0$, the shift is accepted automatically since the new state is more ordered than the old state. If $\Delta E > 0$, the optimization function is increasing, meaning that the new state is

less coherent (and lower probability). The decision whether to accept the new shift is made by comparing the transition probability with a randomly chosen number σ , uniformly distributed between 0 and 1. If σ is less than the transition probability, the new state is accepted; otherwise, the new state is rejected and we return to the old state.

Cooling schedules

As mentioned above, the cooling schedule is of paramount importance. If the cooling is done too quickly, the system may be trapped; if the cooling is done too slowly, time is wasted. We have tried several cooling schedules of the simplest nature — instant quenching, repeated annealing and slow cooling. All of these use a control parameter versus simulation time curve of the form:

$$T(q) = \alpha^q T_0, \quad (2)$$

where q refers to the simulation time step, T_0 is the starting temperature, chosen semiarbitrarily, and $1-\alpha$ is the relative decrease in the temperature each time step. In the case of instant quenching, T_0 and $T(q)$ are set at 0. This corresponds to an iterative improvement solution (Kirkpatrick, 1984; Ronen and Claerbout, 1985). The problem with this solution is that it represents one of the local minima. In the repeated annealing experiments, after each instant quenching, the system is “heated” to a temperature near the phase transition temperature, only to let the system go through another instant quenching. The hope is to find a global or near-global solution. Slow cooling experiments followed the prescription given in equation (2). By keeping the cooling rate low enough, it is hoped that entrapment in local minima can be avoided.

Rothman’s procedure (1986) was to cut this cooling schedule off at some temperature, then leave the temperature constant for the remainder of the simulation. We have had the best results by continuing the cooldown until the system freezes into a minimum so that no more shifts are observed in any of the shots or receivers during any one simulation step.

Finally, a word is in order on the qualitative determination of the starting temperature. When the system is at a very high temperature and is far from its ground state, we examine the rms value of the fluctuations resulting from the shifts applied to the parameters. The “crystallization temperature” is expected to be the same order of magnitude as the rms value. Thus, we use a starting temperature T_0 an order of magnitude larger than the observed rms fluctuation and cool the system rather quickly such that the temperature decreases by an order of magnitude in a few hundred time steps. A jump should be observed signalling the crystallization temperature. At this point, one can begin a more careful search with a starting temperature anywhere from 2 to 10 times the crystallization temperature and follow a much more gradual cooling process. How gradual depends in principle on the complexity of the surface, but in practice depends on the available computer resources.

RESULTS

Synthetic data

A subset of 16-fold, NMO-corrected CDP gathers was extracted from a synthetic data set (Vasudevan et al., 1991). The synthetic data set contained seven reflectors and carried with it a typical admixture of background noise. The data had a temporal length of 2.0 s with a sample interval of 4.0 ms. For cross-correlation purposes, 225 samples corresponding to a window from 0.60 s to 1.50 s were selected. For the experiments described below, 61 CDP gathers spanned by 23 shot and 93 receiver station statics were utilized.

(a) *Random statics* — To test the ability of the simulated annealing method to find well-defined structures in the presence of surface and subsurface anomalies, several data sets were created from the basic data. These sets were generated by applying random source and receiver shifts to each of the shot and receiver stations, and passing those shifts onto the traces in each CDP gather. The perturbations, ranging from slight to significant, were up to 2 and 10 samples per shot/receiver static, leading to a maximum shift per trace of 4 and 20 sample shifts, respectively. The stack sections for 61 CDPs resulting from the 2 and 10 sample shift perturbations are shown in Figures 1(a) and 2(a). These sections represent the data sets A1 and A2 for a physical situation where surface and subsurface anomalies cause minor and severe aberrations in the traveltimes delays, respectively.

Figures 1 and 2 show the results of the annealing process for the statics case at five different stages for data sets A1 and A2, respectively. Panel (a) in both figures represents the respective data sets after perturbation and panel (b) corresponds to the first step of the simulated annealing process. As the “temperature” is gradually lowered, a degree of order begins to appear. The panels shown in sections (c), (d) and (e) display the gathers at iterations 1000, 2000 and 3000, respectively. Annealing is continued until a Monte Carlo step occurs in which none of the attempted changes to the n_s+n_r statics are accepted. The last panel (f) is the CDP gathers with the set of statics giving the greatest coherence. Panel (f) is nearly identical to the desired solution in both cases, providing testimony that the simulated annealing method will return to a well-ordered (coherent) data set even if the initial perturbations are very large.

(b) *Vertical fault with random statics* — To test the ability of the simulated annealing method to find structures offset by a vertical fault line and overlain by surface and subsurface anomalies, we utilized the 61 CDP gathers of the above basic data set, but included an arbitrary 15-sample bulk shift on one-half of the CDPs. A simple stack of the gathers is shown in Figure 5(a). A similar fault model was utilized by Rothman (1985) and Dahl-Jensen (1989) to test their algorithms. The effect of weathering layers was introduced by applying random shifts to each of the shot and receiver stations. The perturbations, as in data set (a), ranged from slight to significant to stressful, and were up to 5, 10 and 15 samples per shot/receiver static, leading to a maximum shift

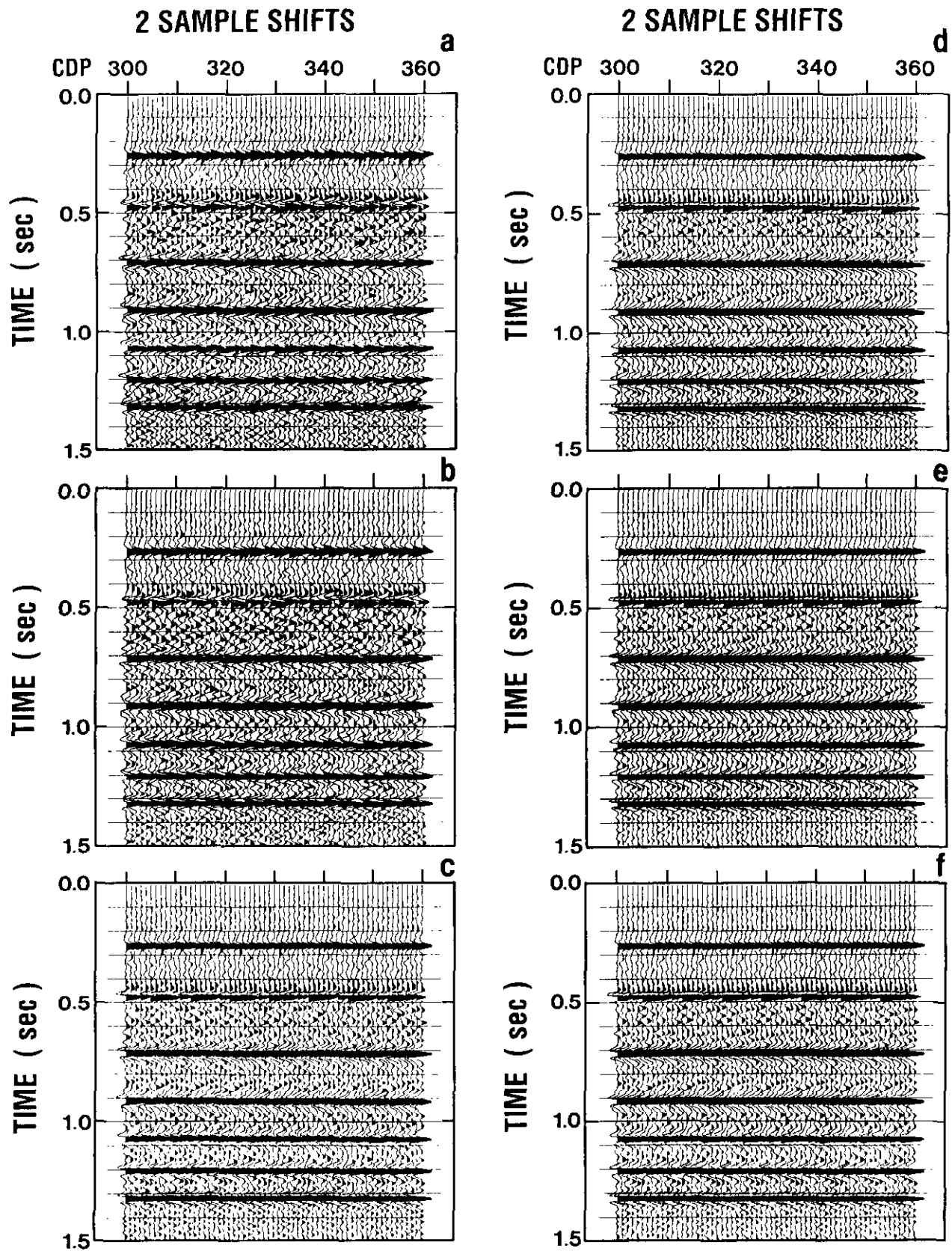


Fig. 1. Simulated annealing experimental results: the starting temperature and the cooling rate parameter α were set at $1.20e7$ and 0.9992 , respectively.

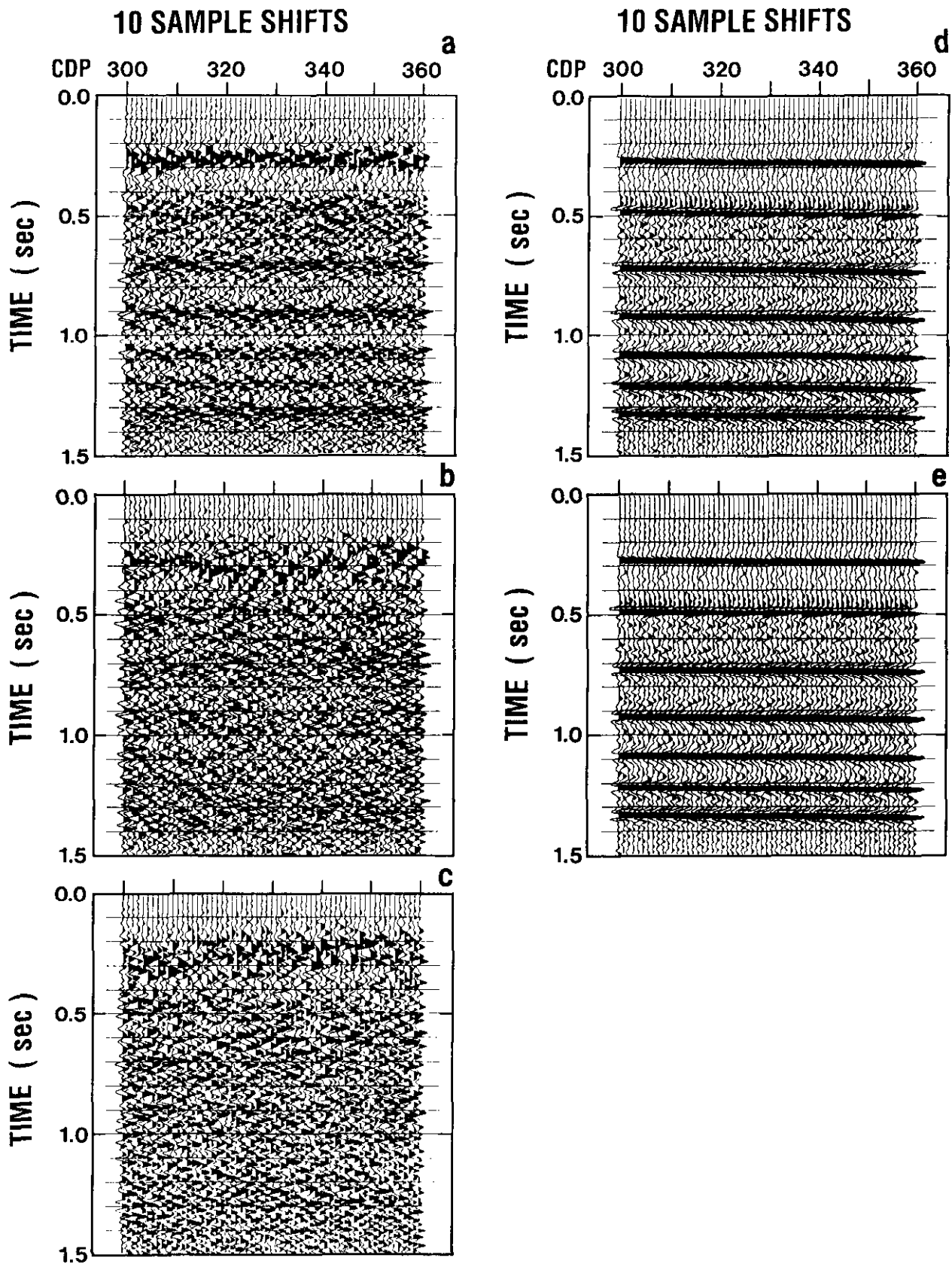


Fig. 2. Simulated annealing experimental results: the starting temperature and the cooling rate parameter α were set at $1.60e7$ and 0.9992 , respectively.

per trace of 10, 20 and 30 sample shifts, respectively. The 15-sample shift was introduced to severely stress any remaining coherence in the data as it resulted in trace shifts greater than the fundamental reflector phase shift of the original data. Figures 3(a), 4(a) and 5(a) indicate the resulting data sets B1, B2 and B3 for a vertical fault situation overlain by surface and subsurface anomalies causing three different degrees of aberrations in the traveltimes delays.

Figures 3, 4 and 5 display the results of the annealing process for the statics case at five different stages using the data sets B1, B2 and B3. In these figures, panel (a) shows the desired final result, (b) corresponds to panel (a) with random statics applied and panels (c-e) show the simulated annealing results after 1000, 2000 and 3000 annealing steps, respectively. Panel (f) presents the final solution. In Figure 5, the severity of the static shift is the least (5 sample shifts). After applying the computed statics at the final stage, we very clearly see the underlying seven reflector vertically-faulted data. The second and third examples, as shown in Figures 4 and 5, differ in that the former had a 10-sample shift and the latter had a 15-sample shift. There is a slight difference in the cooling schedule in terms of the starting temperature and the actual cooling rate. The final results suggest that processing time can be saved by carefully planning the cooling schedule. For example, lowering the starting temperature slightly reduced the number of computer cycles (Figures 4 and 5).

Real data

The field data example is from one of the five lines acquired by LITHOPROBE in the southeastern Canadian Cordillera. The data are from line 2 in the eastern part of the Purcell anticlinorium in southeastern British Columbia (Cook et al., 1987, 1988; Vasudevan et al., 1991). The recording parameters for line 2 can be found elsewhere (Cook et al., 1988). Prestack processing considered the crooked-line geometry. The processing included spectral balancing of all of the shot gathers (15 – 55 Hz). No statics corrections beyond elevation corrections were applied to the data. The coherence-filtered section of this stack with only signals exceeding a certain threshold value for coherence is shown in Figure 6a. Although the data were recorded to 18.8 s with a sample interval of 4.0 ms, we focus on only the first 9.0 s in this paper. Coherent reflections are barely noticeable between 4.0 s and 7.0 s. These reflections are considered to be from near the top of North American basement beneath the Cordilleran thrust sheets (Cook et al., 1987, 1988). Their geological importance suggests that statics computed using the simulated annealing algorithm could be valuable in enhancing the coherence of reflection events.

NMO-corrected CDP gathers of the data corresponding to 1592 CDPs for a total of 41 917 traces were considered for the simulated annealing experiments. The parameter space was spanned by 503 shot station and 1019 receiver station statics. Based on a few simulated annealing experiments, 15 sample shifts were considered to be the optimal shifts. Final simulated annealing experiments were carried out with a

slow cooling schedule as envisaged in equation (2). The cooling rate parameter, α , was set at 0.9992. Statics-applied stacked section was subsequently coherence-filtered for display purposes. The final result is shown in Figure 6b. A comparison of Figures 6a and 6b shows that the application of the simulated annealing statics does, indeed, show improvement in the coherence of events in both the near-basement reflection zone as well as in other areas.

Results from cooling schedules

Cooling schedules play a role in the quality of the statics solution. A portion of line 2 was put to test with three different cooling schedules — instant quenching, repeated annealing and slow cooling. The subset of data was made up of 554 CDP gathers for a total of 10 635 traces. The parameter space was defined in terms of 123 shot station statics and 367 receiver station statics. The window for simulated annealing experiments was confined to 250 samples — 5.0 s to 6.0 s. Several instant quenching, repeated annealing and slow cooling runs were carried out. Only a window of 4.0 s to 7.0 s was shown for this comparative study.

Results of the stacked sections without statics and with statics derived from instant quenching, repeated annealing and slow cooling experiments are shown in Figures 7a, 7b, 7c and 7d. A comparison of these figures shows that there is a gradual improvement in the coherence of the section as one goes from instant quenching to slow cooling. In the instant quenching case, the statics solution apparently corresponds to one of the local minima. The repeated annealing shows slightly better results since there is some opportunity to escape from local minima. Clearly, the possibility exists that the newly found solution could be another minimum. Even with slow cooling, the final solution could be trapped in one of the local minima except that this minimum is near the global minimum.

CONCLUSION

The Metropolis simulated annealing method implemented with cross-correlation power can be considered a viable solution of residual statics in seismic data processing problems. If the residual statics of a particular data set are expected to be small, direct search techniques should give sufficiently good results. This is due to the definition of small statics; one is already close to the desired minimum. However, when the residual statics are expected to be large or the signal-to-noise ratio of seismic data is low, alternate methods such as simulated annealing search techniques should be considered. The usefulness of the simulated annealing method is demonstrated here with line 2 in the southeastern Canadian Cordillera.

Finally, a few comments on the cooling schedule are in order. It should be pointed out that slight differences in the slow cooling schedule (for example, changes in the starting temperature and the cooling rate) do not appear to have a significant effect on the converged solution. However, careful selection of the cooling parameters can reduce the number of

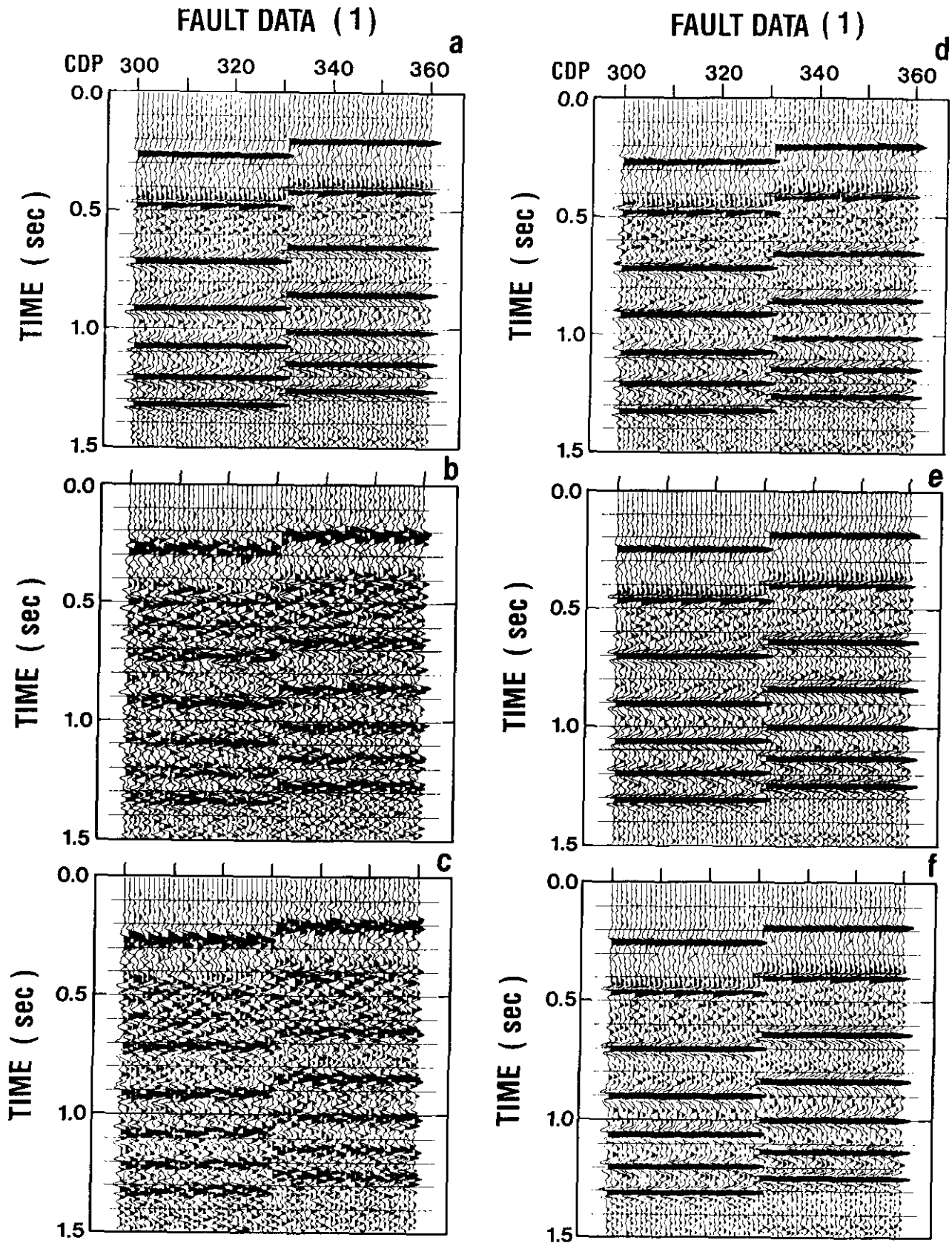


Fig. 3. Simulated annealing experimental results: the starting temperature and the initial critical parameter α were set at $3.60e7$ and 0.9992 , respectively.

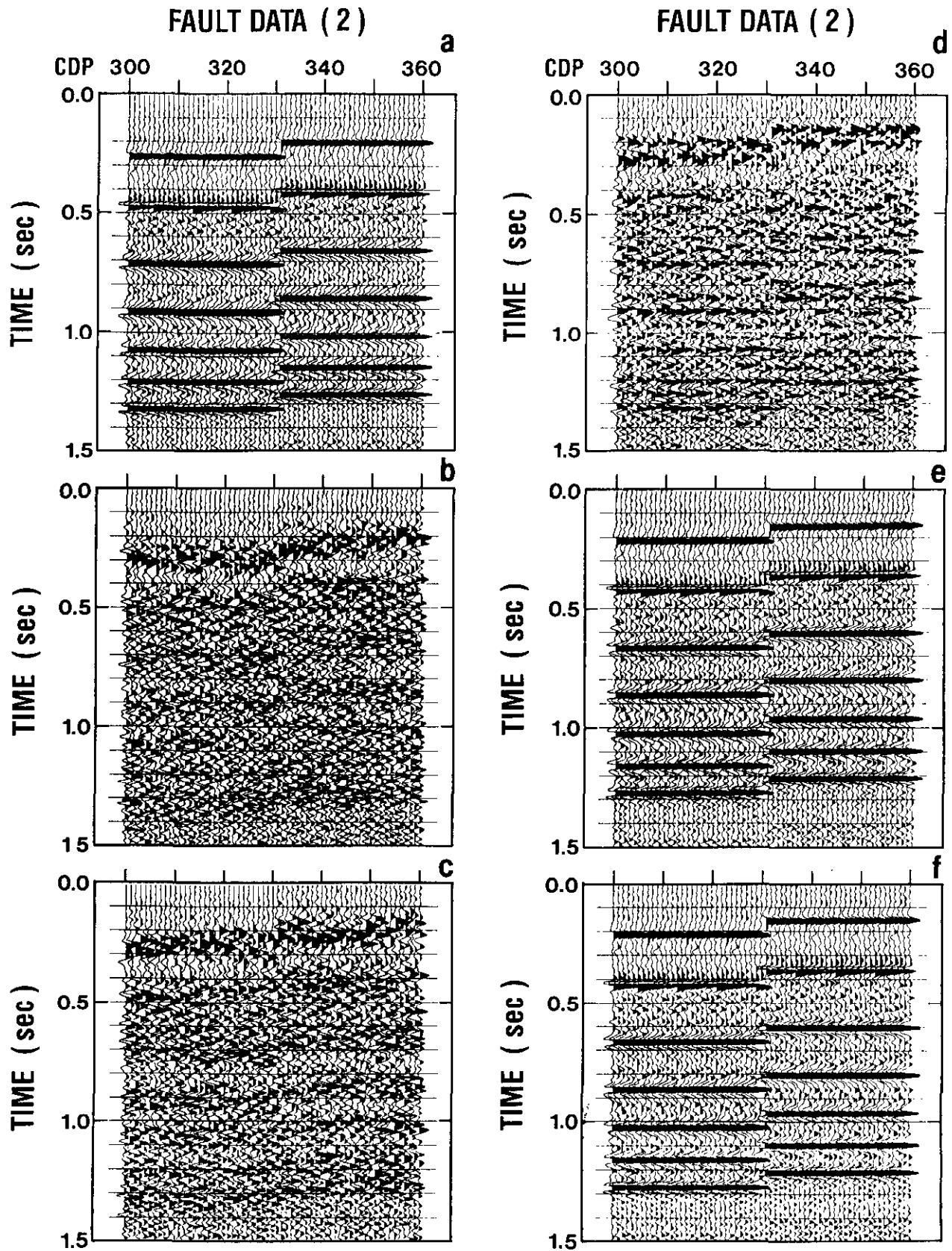


Fig. 4. Simulated annealing experimental results: the starting temperature and the cooling rate parameter α were set at $3.60e7$ and 0.9992 , respectively.

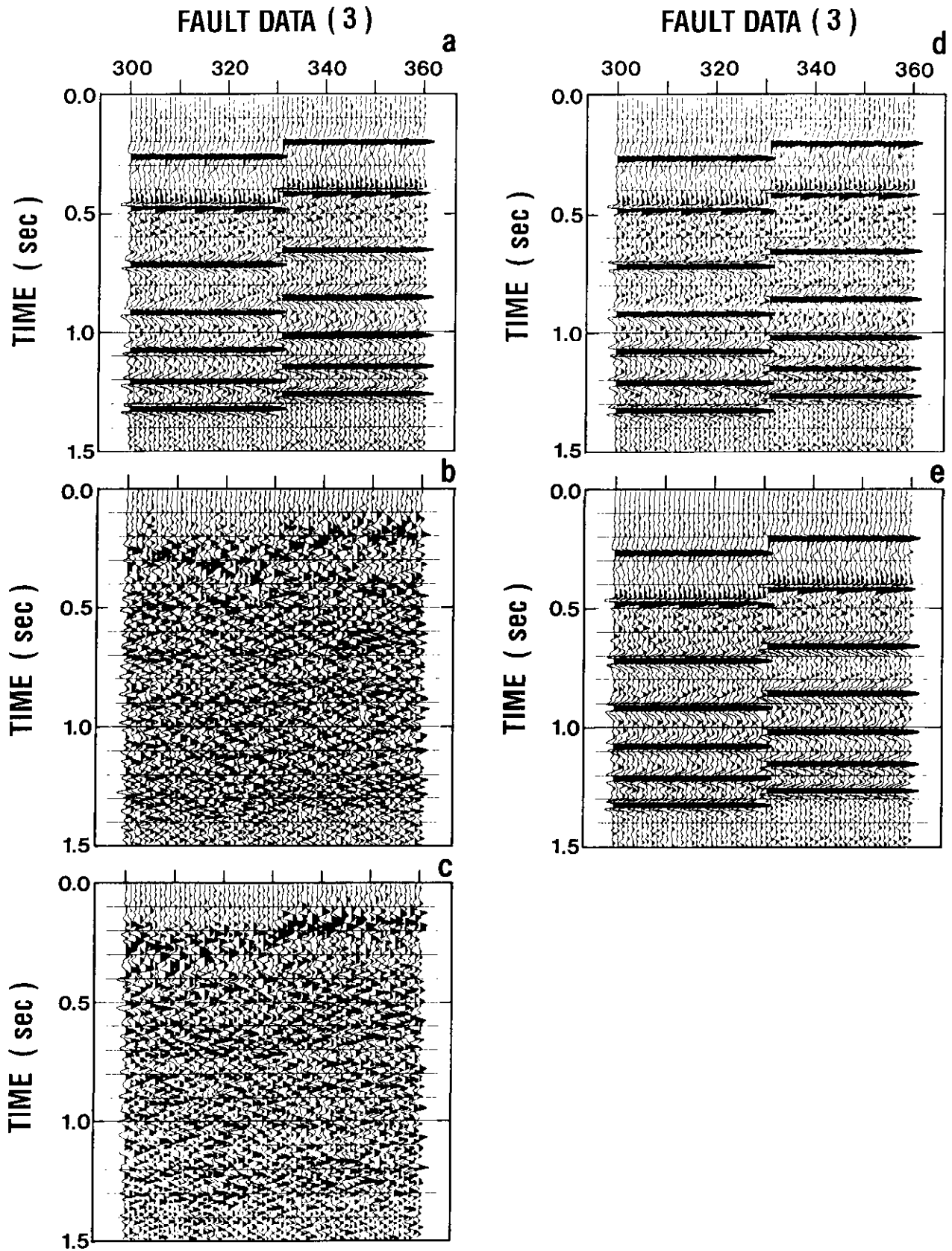
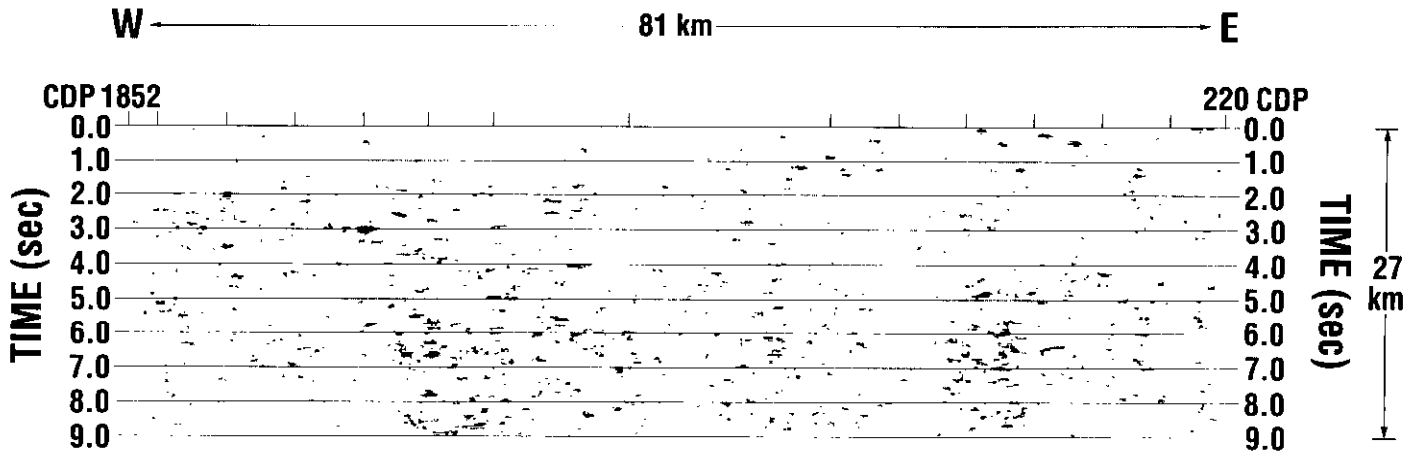


Fig. 5. Simulated annealing experimental results: the starting temperature and the cooling rate parameter α were set at $1.20e7$ and 0.9992 . Lowering the starting temperature from $3.60e7$ to $1.20e7$ reduced the number of computer cycles.

LITHOPROBE DATA

STARTING DATA SET

(a)



LITHOPROBE DATA

SIMULATED ANNEALING STATICS APPLIED

(b)

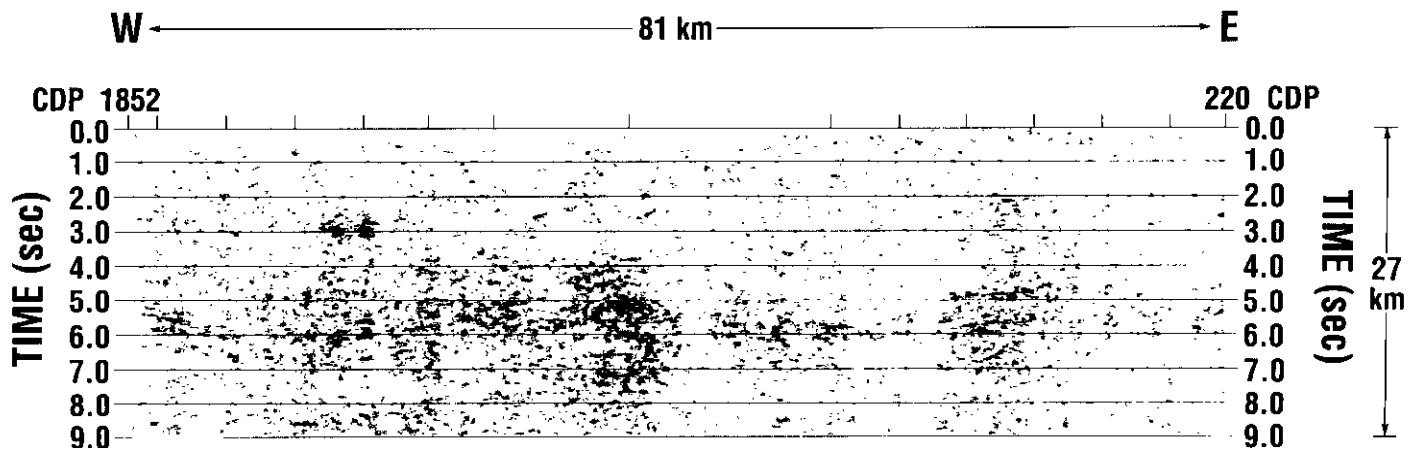


Fig. 6. Coherency filtered section of stack of line 2: (a) before applying the simulated annealing statics; (b) after applying the simulated annealing statics.

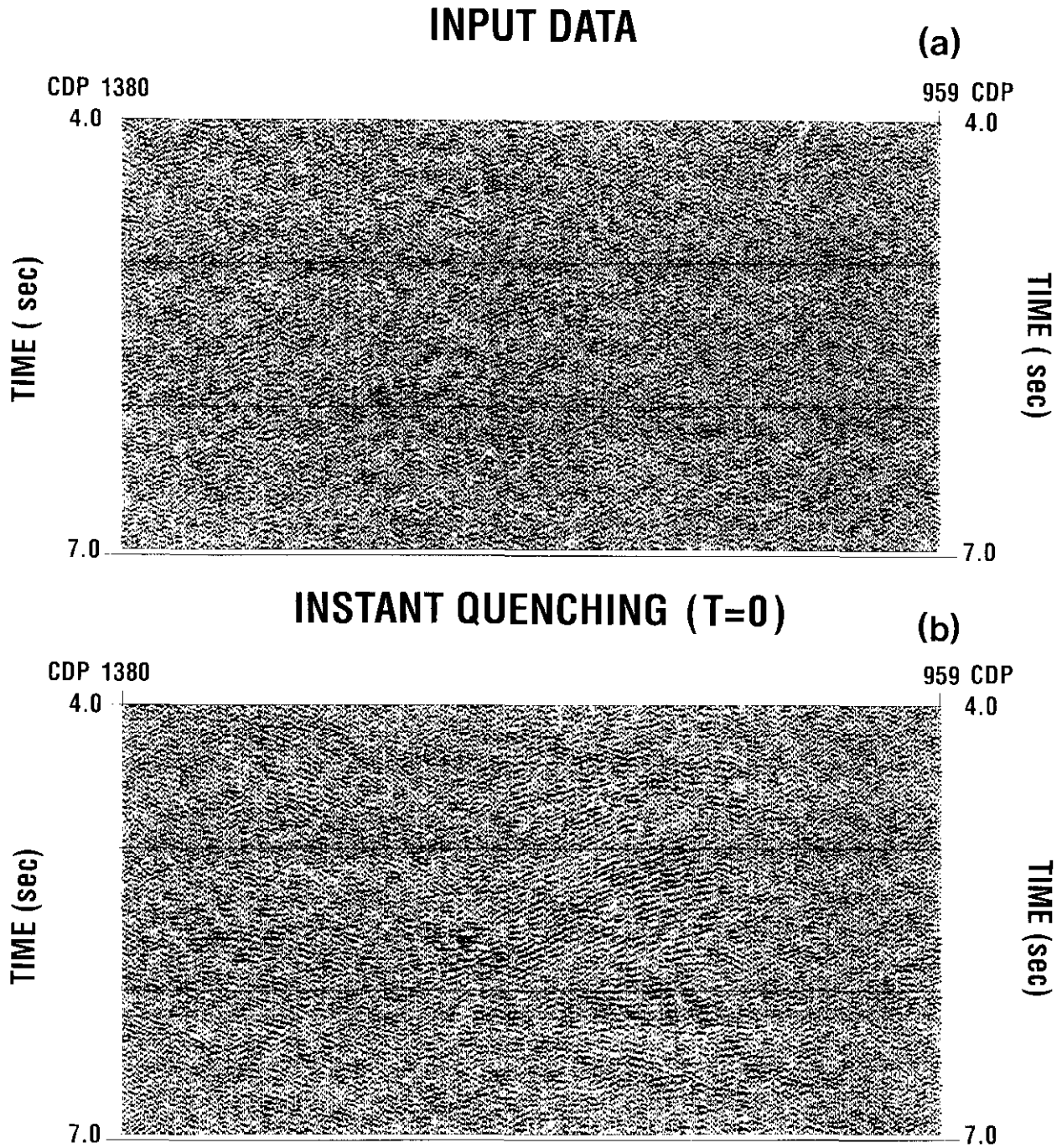


Fig. 7. Stack of a segment of line 2 (CDPs 959 to CDPs 1380). **(a)** without any residual statics. Events seen in the middle of the section around 6.0 s are weak. There is also an indication of slightly dipping events between 5.0 s to 6.0 s; **(b)** with statics derived from an instant quenching run. Slight improvement is seen in the coherency of events noted in Figure 7a.

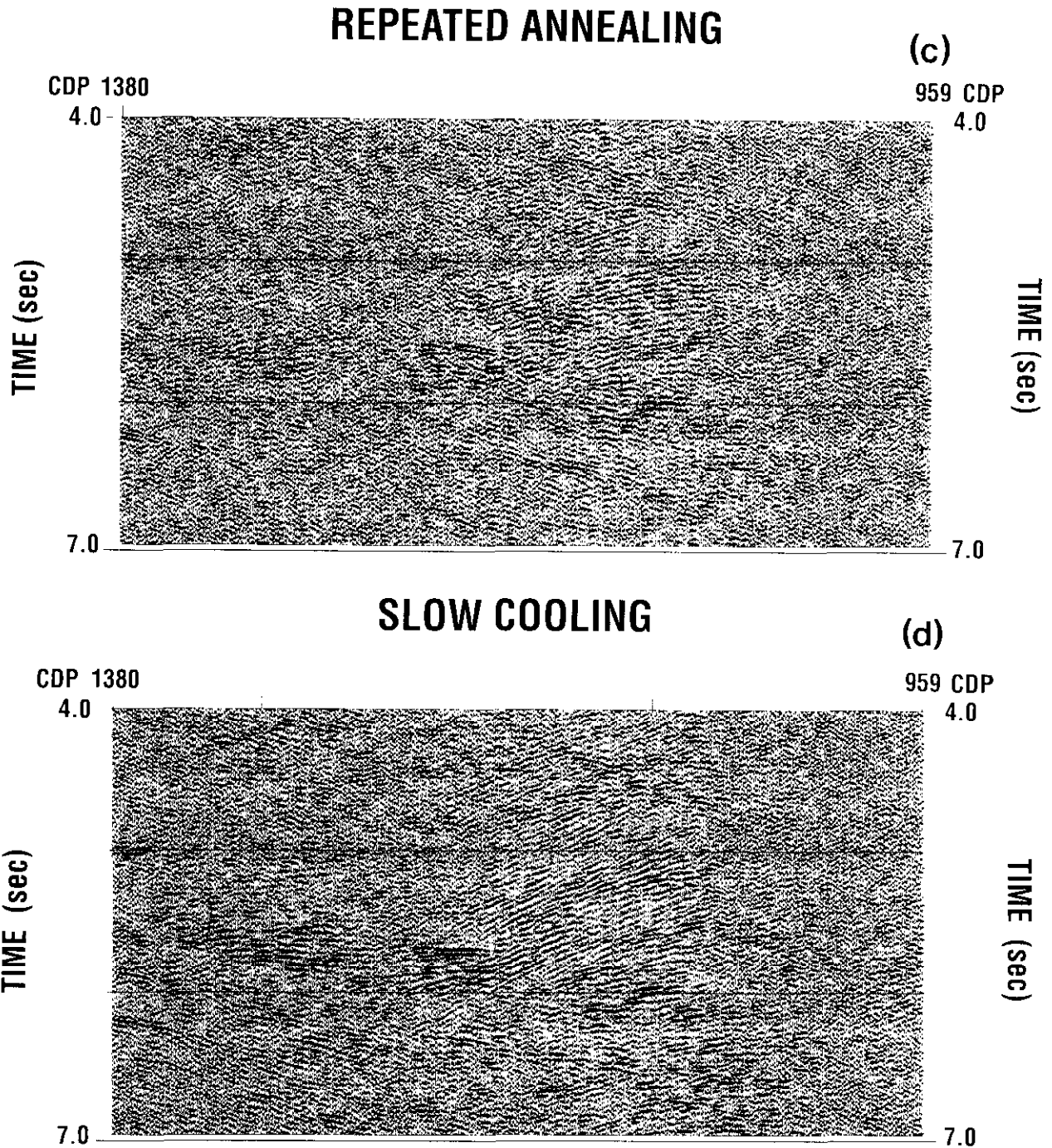


Fig. 7. (cont'd) Stack of a segment of line 2 (CDPs 959 to CDPs 1380): (c) with statics derived from a repeated annealing run, there is a significant improvement in the coherency of events over the entire time window. (d) with statics derived from a slow cooling run. Additional improvement of coherency of events as well as new structural features are seen within a time window, 4.0 s to 7.0 s.

computer cycles and hasten the convergence. Among the cooling schedules, instant quenching and repeated annealing, as is reported in this work, do not afford a "quick fix" to the speed of the simulated annealing algorithm.

REFERENCES

- Aarts, E.H.L. and van Laarhoven, P.J.M., 1987, *Simulated annealing: theory and applications*: Reidel, Dordrecht.
- Bancroft, J.C., 1990, Tutorial on statics estimation using surface-consistent methods: Presented at the 1990 Nat. Conv., Can. Soc. Expl. Geophys., Calgary.
- Cook, F., Green, A.G., Simony, P.S., Price, R.A., Parrish, R., Milkereit, B., Gordy, P.L., Brown, R.L., Coffin, K.C. and Patenaude, C., 1987, Lithoprobe southern Canadian Cordilleran transect: Rocky Mountain thrust belt to Valhella gneiss complex: *Geophys. J. Roy. Astr. Soc.* **89**, 91-98.
- _____ and _____, 1988, Lithoprobe seismic reflection structure of the southeastern Canadian Cordillera: initial results: *Tectonics* **7**, 157-180.
- Dahl-Jensen, T., 1989, Static corrections on crystalline rocks: *Geophys. Prosp.* **37**, 467-478.
- Kirchheimer, F., 1990, Residual statics by CDP-localized stack optimization: *Geophys. Prosp.* **38**, 577-606.
- Kirkpatrick, S., 1984, Optimization by simulated annealing: quantitative studies: *J. Stat. Phys.* **34**, 975-986.
- _____, Gelatt, C.D., Jr. and Vecchi, M.P., 1983, Optimization by simulated annealing: *Science* **220**, 671-678.
- Metropolis, N., Rosenbluth, A., Rosenbluth, M., Teller, A. and Teller, E., 1953, Equation of state calculations by fast computing machines: *J. Chem. Phys.* **21**, 1087-1092.
- Paulson, K., 1986, An efficient implementation of Monte Carlo statics: 56th *Ann. Internat. Mtg., Soc. Expl. Geophys., Houston, Expanded Abstracts*, 589-591.
- Ronen, S. and Claerbout, J., 1985, Surface-consistent residual statics estimation by stack-power maximization: *Geophysics* **50**, 2755-2767.
- Rothman, D.H., 1985, Nonlinear inversion, statistical mechanics, and residual statics estimation: *Geophysics* **50**, 2784-2796.
- _____, 1986, Automatic estimation of large residual statics corrections: *Geophysics* **51**, 332-346.
- Russell, H.B., 1989, "Statics corrections — a tutorial": *Recorder* **14**, 16-30.
- Taner, M.T., Koehler, F. and Alhilali, K.A., 1974, Estimation and correction of near-surface time anomalies: *Geophysics* **39**, 441-463.
- Vasudevan, K. and Wilson, W., 1990, Does the Monte Carlo method afford a solution to residual statics problem?: Presented at the 1990 Nat. Conv., Can. Soc. Expl. Geophys., Calgary.
- _____, Cook, F.A. and Wilson, W., 1991, Simulated annealing experiments in seismic data processing — crustal data example: Presented at the 1991 Nat. Conv., Can. Soc. Expl. Geophys., Calgary.
- _____, Wilson, W. and Laidlaw, W.G., 1991, Simulated annealing statics computation using an order-based energy function: *Geophysics* **56**, 1831-1839.
- Wiggins, R.A., Lamer, K.L. and Wisecup, R.D., 1976, Residual statics analysis as a linear inverse problem: *Geophysics* **41**, 922-938.