CHAPTER 1

Introduction

1.1 OVERVIEW

The near-surface of the Earth is often highly irregular. Typical irregularities include changes in surface elevation, uneven consolidation of soil, and extreme lateral variations in seismic velocity. These anomalies can twice degrade the quality of a seismic signal: first as the signal travels downward from the source, and again when the signal returns upward to the receivers. Among the many effects caused by near-surface anomalies, the most obvious and most important are often delays in recorded traveltimes. Because these timing delays distort apparent structure and cause misalignment of signals, the analysis of reflection seismic data acquired on land routinely includes the use of timing adjustments called statics corrections, or "statics." In their most elementary form, statics corrections can be derived deterministically from measurements of elevations and uphole times—these corrections are called "field statics." Statics corrections that cannot be derived from these field measurements are called "residual statics." Residual statics are usually estimated statistically from the seismic data.

When near-surface velocity anomalies are severe, residual statics can be as large as several multiples of the dominant period of the recorded data. Because noise significantly contaminates most seismic data, the automatic identification of large static shifts is difficult. When the true peaks of crosscorrelation functions are obscured, the so-called "cycle-skipping" problem results, and the difficulties posed for accurate statics estimation increase considerably.

This thesis introduces a new algorithm for the estimation of large residual statics corrections. Statics estimation is formulated as a nonlinear inverse problem in which the solution of the cycle-skipping problem depends on locating the global minimum of a multidimensional objective function. Nonlinear inverse problems of this nature are generally solved by linearization about a first guess of the solution, and subsequent iterative descent to the nearest minimum of the objective function. The success of linearization, however, is limited by the accuracy of the first guess. In the conventional linearized approach to residual statics estimation (Wiggins et al., 1976; Taner et al., 1974), the role of a first guess is played by a set of observed time delays. These observations are often contaminated by errors; as the quality of seismic data decreases and the severity of near-surface anomalies increases, reliable observations of time delays are increasingly difficult to obtain. In this thesis, therefore, I attempt to answer the following question: How can the residual statics problem be solved *without* making a first guess?

Conventional techniques of optimization are inappropriate for this task. Because the number of sub-optimal local minima is immense, gradient-descent methods will generally locate only a local minimum. Likewise, algorithms based on iteratively improving the estimates of each parameter will also generally fail to find the global minimum. Although an exhaustive search would succeed, the very large number of possible solutions makes an exhaustive search computationally impossible. Thus the estimation of large statics requires a new approach to optimization.

A statics estimation algorithm that is independent of the first guess must successfully deal with the enormity of the parameter space. To render the problem computationally tractable, I employ the method of *simulated annealing* (Kirkpatrick et al., 1983). Simulated annealing is a Monte Carlo optimization technique that mimics the physical process by which a crystal is grown from a melt. I make an analogy between crystallization and residual statics estimation, and show that the mathematical structure of the residual statics problem is similar to the structure of a stochastic model used in statistical mechanics. In the application of simulated annealing to residual statics estimation, geophysical parameters are treated as if they were atoms or molecules in a physical system. The algorithm randomly generates new values for these parameters in a way that simulates thermal equilibrium; an external control parameter analogous to absolute temperature determines the freedom with which the parameters' values are changed. A non-zero temperature allows changes that can either decrease or increase the objective function; as the temperature decreases, however, the tendency to move downhill increases. If temperature decreases slowly enough so that equilibrium is maintained, the algorithm locates the optimal statics solution (the "ground state") as temperature approaches zero.

The most efficient form of the Monte Carlo statics algorithm derives estimates of time delays from crosscorrelation functions. Instead of deriving these estimates from the lags associated with the maximum of each crosscorrelation function, however, the algorithm transforms the crosscorrelation functions to probability distributions. Estimates of time delays are then randomly drawn from these probability distributions. The algorithm repeats this procedure iteratively until it reaches a stable solution.

The computational techniques introduced in this thesis might be widely applicable. The most fruitful extensions of the present work are probably in velocity estimation and deconvolution: statics estimation is easily generalized to either problem. In general, two characteristics of a nonlinear inverse problem make it amenable to a statistical-mechanical model. First, the problem must be structured such that it may be subdivided naturally into small, interconnected subproblems. Second, changes in the objective function due to perturbations of a parameter must be easy to compute, regardless of the magnitude of the perturbations. Residual statics estimation satisfies these requirements well; other problems, including velocity estimation and deconvolution, might also meet these criteria.

1.2 STRUCTURE

This thesis begins with a statement of the problem to be solved. I first show how large near-surface anomalies degrade reflection seismic data, and then briefly highlight the principal results of the work described in the ensuing chapters. Thus Chapter 2 gives a broad perspective of both the problem and its solution. In particular, several key concepts and some terms that are used throughout the thesis are introduced. Readers familiar with residual statics estimation may skip Chapter 2 without losing continuity. Chapter 2 contains many illustrations, however, which should be of interest to all readers.

Chapter 3 contains a detailed description of how simulated annealing is used to estimate large statics corrections. The application of simulated annealing is justified using heuristic arguments. I then show how a parameter analogous to absolute temperature can be used in two ways. In one approach, the parameter explicitly determines an algorithm's ability to move uphill on an objective function. In the second approach, the parameter explicitly determines the relative heights of the peaks and troughs of multimodal probability distributions. In both cases, the key result is the algorithm's ability to escape local minima using a controlled random search.

Experimental results are illustrated and analyzed in Chapter 4. Results are demonstrated for both synthetic and field data. In each example the Monte Carlo statics algorithm is able to estimate the optimal (or nearly optimal) statics corrections in situations where alternative automated approaches would have fallen prey to a cycle-skipping problem. Thus global optimization in the presence of many local minima can be performed in a practical context.

Having examined the application of simulated annealing to residual statics estimation in Chapters 2 through 4, I then describe a general theory for the analysis of non-linear inverse problems in Chapter 5. I delineate where simulated annealing is applicable, and show how the problem of residual statics estimation conforms to this model. Then, after developing this general theory, I propose further applications of the technique.