Chapter 1

Introduction and Overview

The determination of interval velocities is a primary goal of seismic data processing. These interval velocities are conventionally derived from picked stacking velocities. The velocity-analysis algorithm proposed in this thesis is also based on stacking velocities; however, this new method does not require that stacking velocities be picked. To eliminate the conventional picking stage, the method always considers stacking velocities from the point of view of an interval-velocity model. This view leads to a model-driven, automatic velocity-analysis algorithm.

The connection between the interval-velocity model and the stacking velocities plays an important role in the algorithm proposed in this thesis. This connection can take different forms, depending on the model assumptions that one is willing to make. The first part of this thesis makes some restrictive assumptions about the model: that it consists of flat layers, with laterally invariant velocities. When these assumptions are made, a simple, one-dimensional form of the velocity-analysis algorithm can be used. The latter part of the thesis extends the algorithm to two dimensions; in the process, the assumption of laterally-invariant velocities is removed. Thus, the resulting algorithm is both automatic and valid for laterally variable velocities.

1.1 STRUCTURE OF CONVENTIONAL METHOD

The velocity-analysis method proposed in this thesis is based on the use of stacking velocities; the way they are used is quite different from the way they are used in the conventional method. These differences can best be understood through a careful examination of the basic structure of the conventional velocity-analysis method.

The conventional method is a three step process. The first of these steps takes the data in each common midpoint (CMP) gather and tests for alignments along curves that are hyperbolic in offset (x) and time (t). Each hyperbola is parameterized by a stacking velocity v_s and a zero-offset time τ, according to the well-known normal-moveout (NMO) equation:

$$t^2 = \tau^2 + \frac{x^2}{v_s^2} . \tag{1.1}$$

Each hyperbola, corresponding to a particular choice of v_s and τ, defines a summation trajectory over offset. The greater the power in the sum, the better the alignment along that hyperbola.

In practice, a normalized version of the power, the semblance S is used (Taner and Koehler, 1969). For the midpoint gather at midpoint y, the semblance S, corresponding to the hyperbola described by v_s and τ, is

$$S(v_s, \tau, y) = \frac{\left[\sum_x D\left(x, t = \left(\tau^2 + \frac{x^2}{v_s^2}\right)^{\frac{1}{2}}, y\right)\right]^2}{\sum_x \left[D\left(x, t = \left(\tau^2 + \frac{x^2}{v_s^2}\right)^{\frac{1}{2}}, y\right)\right]^2} . \tag{1.2}$$

Thus, by sweeping through a range of zero-offset times and stacking velocities, the first step of the conventional method transforms the data in each CMP gather, $D(x, t, y)$ to semblance, $S(v_s, \tau, y)$. Figure 1.1a shows the data in a midpoint gather; Figure 1.1b shows the corresponding semblance values.

The second step of the conventional velocity-analysis method takes the semblance panel of Figure 1.1b, and locates or "picks" the peaks. One peak must be picked for each zero-offset time of interest; the location of that peak is considered to be the stacking velocity for that particular time. This second step involves some interpretation: if more than one peak exists at a zero-offset time of interest, which peak should be picked? The answer provided by the conventional method is that the peaks must be picked manually.

The third and final step of the conventional velocity-analysis method takes the stacking velocities picked in step two, and calculates a corresponding interval-velocity model. This calculation depends on a key assumption: stacking velocities (v_s) are equal to root-mean-square velocities (v_{rms}). When this assumption is made, the interval velocities v_{in} can be easily calculated with the Dix formula (Dix, 1955). The Dix formula

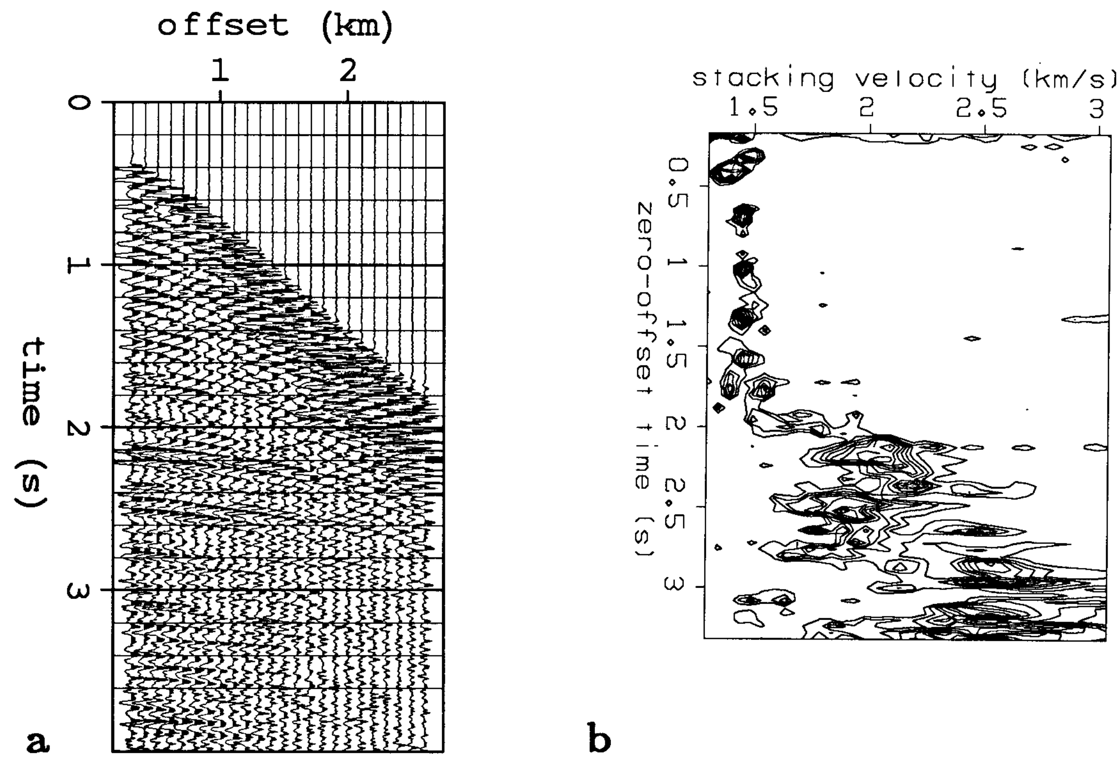

FIG. 1.1. The first step of velocity analysis takes the data in a midpoint gather (Figure 1.1a) and transforms them to semblance (Figure 1.1b). For one midpoint, the coordinates of the input data are (offset x, time t). The coordinates of the output data are (stacking velocity v_s, zero-offset time τ). These data are from the Grand Banks of offshore Newfoundland.

calculates the interval velocity in the j^{th} layer from the stacking velocities at zero-offset times τ_{j+1} and τ_j as

$$\left(v_{in}{}^2 \right)_j = \frac{\tau_{j+1} \left(v_s{}^2 \right)_{j+1} - \tau_j \left(v_s{}^2 \right)_j}{\tau_{j+1} - \tau_j} . \tag{1.3}$$

The conventional velocity-analysis method is thus a three-step process. Because the velocity-analysis method proposed in this thesis is based on stacking velocities, this method uses the same first step as the conventional method. The second and third steps are, however, combined into one step and the manual picking of peaks is thereby eliminated. Furthermore, instead of using the Dix formula to connect interval velocities and stacking velocities, this thesis uses an alternative formula, which is valid for laterally varying velocities.

1.2 PROBLEMS WITH THE CONVENTIONAL METHOD AND SOLUTIONS

Problems with picking

Suppose for the moment that the assumption underlying the use of the Dix formula is valid, that $v_s = v_{rms}$. A basic problem with the conventional method remains: the method requires that an interpretive step (the peak picking of step 2) be performed with no reference to an earth model. The earth model enters later, in the third step, when the interval velocities are calculated. At that point, it might turn out that the picked stacking velocities lead to a physically unfeasible set of interval velocities; for example, negative interval velocities might be required.

An experienced data processor knows that certain peaks should be avoided because they would lead to ridiculous interval velocities. Indeed, other automatic-velocity analysis methods use some form of pick validation, to first decide if the picks are reasonable (Hubral and Krey, 1980). Thus, a good job of peak-picking implicitly incorporates an interval-velocity model. This thesis goes one step further: it explicitly incorporates an interval-velocity model in the evaluation of stacking velocities.

Thus, throughout this thesis, stacking velocities are always interpreted from the point of view of the interval-velocity model, that is as $v_s(v_{in})$. As in the conventional method the goal of the velocity analysis is to find the peaks in the semblance panel. The difference is that the method of this thesis finds these peaks by changing the interval velocity model; that is, the velocity analysis is model driven.

This model-driven velocity analysis has the advantage over the conventional method that the physical constraints can now be applied directly where they belong: to the interval velocity model. Thus, only feasible models are examined. The result is an automatic velocity-analysis method that is directly subject to physical constraints.

Chapter 2 of this thesis develops this automatic velocity-analysis method for the simplest possible case: for one CMP gather, under the assumption that the Dix formula is valid. The simplicity of this case allows a clear exposition of the velocity-analysis algorithm. The algorithm is applied to several sets of field data. Because velocity analysis is often performed on single CMP gathers, under the assumption that the Dix formula is valid, the algorithm developed for this simple case should be useful in its own right. Furthermore, the principles of the algorithm are also valid for the more general case, that is, one in which velocities vary laterally.

Problems due to $v_s \neq v_{rms}$

By eliminating the need for stacking velocities to be picked, the algorithm proposed in Chapter 2 of this thesis solves one problem of the conventional method. But a second problem is faced by any method based on stacking velocities. The assumption that stacking velocity, v_s , equals rms velocity, v_{rms} , is simply not valid for laterally varying velocities, nor is it valid for depth-varying velocities when the depth variation is strong and wide offsets are used (Hubral and Krey, 1980). Thus, two alternatives are possible: either interpret stacking velocity as something other than rms velocity, or use some measurement other than stacking velocity.

The most common alternative is the latter: stacking velocities are abandoned entirely, in favor of traveltimes. Thus, the three steps of the conventional method are replaced by an analogous set based on traveltimes: first, alignment is measured by the cross-correlation of traces; second, peaks of the cross-correlation functions are picked, and then identified as traveltime differences; third, an interval-velocity model that fits the picked traveltimes is built.

Although this type of traveltime method can be quite successful, it can also encounter serious problems when the data are noisy (Donaho, 1979). For those data, the picking required in the second step is even more difficult for traveltimes than it would be for stacking velocities. Thus, because the traveltime method is also based on picked peaks, it faces many of the same problems as those of the conventional stacking-velocity method: which peak is the right one to pick, and how can the influence of incorrectly picked peaks be diminished? Ronen and Claerbout (1985) and Rothman (1985) have successfully dealt with these problems in their work with the simplified traveltime method of residual statics. Although the velocity-analysis algorithm of this thesis is based on stacking velocity and not traveltime, it has the same underlying philosophy as do these two traveltime (residual statics) methods: rather than building a model from data consisting of picked peaks, velocity analysis should build the model from the original data.

A velocity-analysis method based on stacking velocities does have several advantages over one based on traveltimes. Stacking velocities, unlike traveltimes, are routinely determined in conventional seismic-data processing. When the data are noisy, stacking velocities are also determined more reliably than are traveltimes. Finally, because the computation of stacking velocity removes the offset dimension from the data, the number of stacking-velocity measurements is smaller than the number of traveltime measurements by a factor equal to the number of offsets. Thus, a velocity analysis method based on stacking velocities is computationally more efficient than one based on traveltimes.

As long as the velocity-analysis algorithm is based on the interpretation of stacking velocity as rms velocity, the interval-velocity model constructed from strongly varying stacking velocities will be incorrect. An advantage of speed or relative insensitivity to noise will not compensate for this basic incorrectness of the model. On the other hand, this thesis shows that an algorithm based on the correct interpretation of stacking velocity can build a very reasonable interval-velocity model from strongly varying stacking velocities.

The key to this correct interpretation of stacking velocities is the observation that for a particular reflector and midpoint, the stacking velocity at which a peak of semblance occurs depends on the traveltimes to the reflector. This dependency arises from the fact that, as previously stated, the stacking velocity is a parameter describing a hyperbolic summation trajectory. The traveltimes determine what value of this parameter corresponds to the largest semblance. Thus, the relationship between stacking velocity and interval velocity, $v_s(v_{in})$, is more properly written as $v_s[t(v_{in})]$.

A linearized version of the relationship $v_s[t(v_{in})]$ was first proposed by Lynn (1980), then more fully developed by Loinger (1983). In Rocca and Toldi (1983), we continued the development of this linear theory and showed how it could be used in an inversion procedure. Chapter 4 of this thesis discusses this linear theory in detail. It presents a detailed derivation that explicitly uses the fact that stacking velocities and interval velocities are related through the intermediary of traveltimes. The earlier work did not allow for the general geometries (a dipping reflector, and a depth-variable background) that this derivation takes into account.

1.3 TWO-DIMENSIONAL VELOCITY ANALYSIS WITHOUT PICKING

With the help of this linear theory, Chapter 3 extends the application of the automatic velocity-analysis algorithm of Chapter 2, to media with laterally varying velocities. The extended algorithm is structurally identical to the simple, one-dimensional algorithm that is proposed in Chapter 2. However, one important detail of the two algorithms is different. Whereas the one-dimensional algorithm independently considers each common-midpoint gather, the extension of Chapter 3 requires that all midpoints be simultaneously considered. This difference arises because of the laterally variable velocities: if the interval velocity model is changed at one midpoint, the linear theory requires that the stacking velocities from all surrounding midpoints be changed.

The second half of Chapter 3 applies the two-dimensional algorithm to a field-data example that has flat reflectors and strong lateral variation of the stacking velocities. The algorithm constructs an interval velocity model, which explains this lateral variation with a shallow, low-velocity anomaly. Not only does this anomaly explain the laterally varying stacking velocities: it also explains the laterally varying traveltimes. Thus, the automatic velocity-analysis algorithm proposed in Chapter 3 is valid for laterally variable velocities.

The strength of this velocity-analysis algorithm is that it is based on stacking velocity—a measurement that is routinely and reliably made. This algorithm overcomes the main weakness with stacking velocities—that moveouts might not be hyperbolic—by treating laterally varying stacking velocities as parameters that depend on the traveltimes. Because the algorithm requires no picking, it is able to avoid the problems with efforts to fit spurious peaks.