Traveltime Tomography with Multioffset Common-Reflection Points

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SUMMARY

Reflection traveltime tomography has evolved away from layered models toward independent parameters for velocities and reflectors. We introduce a simple method of optimizing interval velocities and common-reflection points simultaneously. Interval velocities are parametrized as a smooth function of spatial coordinates, independently of common-reflection points.

Dynamic ray methods and explicit traveltime extrapolations identify common-reflection points that best model prestack traveltimes. The error between a modeled and measured traveltime is scaled by the cosine of a raypath's angle of reflection. This scaled traveltime error is equivalent to the error of a reflection at normal-incidence, or zero-offset. Velocities are revised to minimize the *variance* of these equivalent errors for all offsets of a common-reflection point.

A North Sea seismic line was particularly unsuitable for a layered velocity model. Salt interrupted reflections, and chalk velocities increased rapidly with depth. The tomographically estimated velocities showed strong lateral changes. Prestack depth migration confirmed that the velocity model accurately explained traveltimes.

INTRODUCTION

Few independently developed methods of reflection traveltime tomography share identical physical parameters, input data, or numerical methods. This paper attempts to isolate features that adapt to a variety of data with the fewest physical constraints. Sattlegger et al (1981) introduced the tomographic optimization of layered models: continuous reflectors that vertically delimit sharp changes in interval velocities, usually with smooth lateral changes. With few parameters, layer boundaries and velocities can be optimized simultaneously. Sherwood's survey (1989) shows the continuing popularity of this model. The first three-dimensional applications (Chiu et al, 1986) extended the layered model.

Bishop et al (1985), Bording et al (1987), Dyer and Worthington (1988), and Toldi (1989) preferred models that decouple velocities and reflector geometries. Velocities can vary continuously, with resolution dependent on discretization and binning. Sword (1987), Harlan (1989), Biondi (1990), van Trier (1990), and others avoided continuous reflectors and estimated common-reflection points. The additional degrees of freedom raise concerns about convergence. Fowler (1988), Etgen (1990), and Stork and Clayton (1991) carefully analyzed the effect of perturbed velocities on migrated reflection points and concluded that both must be perturbed simultaneously. We introduce a simple method of doing so.

These papers use a variety of input data: picked prestack traveltimes, picked prestack depth migrations, constant-velocity time migrations, picked stacking velocities, semblance panels, local slant stacks, and beam stacks. We illustrate our example with measured prestack traveltimes because we have optimized many of these alternative data as simple functions of traveltimes (e.g. best-fitting hyperbolas). See Harlan et al (1991) for another example.

OPTIMIZING COMMON-REFLECTION POINTS

We parameterize the slowness (reciprocal velocity) as a smooth function s(x,z) of horizontal and vertical coordinates x and z. Basis functions, splines, or smoothed grids serve equally well. An unoptimized slowness function will not allow a fan of modeled rays to share a common reflection point and satisfy the measured traveltimes at all offsets. Nevertheless, dynamic ray tracing, shooting, and relaxation can find reflection paths that fit measurements as well as possible. We prefer the powerful combination of explicit traveltime extrapolation (e.g. Vidale, 1990; van Trier, 1990; Moser, 1991) with Fermat's principle to estimate representative raypaths (Harlan, 1990). Measured spatial derivatives of surface traveltimes constrain the dip of reflectors.

Assume that we have identified M different common-reflection points, indexed by k. Each point reflects N_k raypaths with measured traveltimes T_{jk} at offsets indexed by j. If estimated raypaths are written as a function of distance a, then modeled traveltimes are integrals along the paths:
$$t_{jk} = \int s[x_{jk}(a), z_{jk}(a)]\, da .$$

In the vicinity of a reflection point, up- and down-going waves can be approximated as plane waves. Assume that a reflector has been displaced perpendicular to its dip until the measured and modeled traveltimes of a raypath agree. If the raypath reflects at an angle θ_{jk}, then the following error measures the effect of such a displacement on the zero-offset (normal-incidence) reflection time:
$$e_{jk} = (T_{jk} - t_{jk})/\cos\theta_{jk} .$$

See Stork and Clayton (1991) for a justification of the cosine. A revised velocity model need not drive these positioning errors to zero but should make the errors depend on the reflection point k alone. Let us then find the velocity model that minimizes the *variance* of these errors over offset:
$$\underset{s(x,z)}{Min} \sum_{k=1}^{M} \sum_{j=1}^{N_k} [e_{jk} - \frac{1}{N_k} \sum_{i=1}^{N_k} e_{ik}]^2 .$$

Analogously, prestack depth migration must create consistent images from different offsets, without constraining the depth of reflectors. This quadratic function of slowness lends itself to least-squares methods like conjugate-gradients or singular-value decomposition.

EXAMPLE OF DISCONTINUOUS REFLECTORS

Figure 1 shows the zero-offset time stack of a line from the North Sea which is unsuitable for a layered velocity model. Lower reflections are interrupted by salt which invades and compresses neighboring strata. A thick, relatively homogeneous chalk interval, below the strongest reflector, increases greatly in velocity with depth.

A cube of the unstacked data was viewed on a 3D interpretation workstation. Figure 2 shows the traveltimes of reflections picked from various constant-offset panels, after an approximate flattening of moveouts. In early iterations, when estimated raypaths and reflections were positioned poorly, the velocity model was perturbed smoothly to adjust regional trends. The final velocity model and reflectors (figure 3) fit the traveltimes to within picking errors. No reflections crossed or detected the salt directly, but velocities increase nearby from salt invasions or increased pressure. A prestack depth migration (figure 4) produced a consistent depth model and stacked coherently over offset.

CONCLUSIONS

Identifying common-reflection points improves the robustness and convergence of estimated interval velocities. Errors in modeled traveltimes can be converted into equivalent displacements of the reflection point for each raypath. An optimum velocity model encourages these displacements to be as consistent as possible, without attempting to preserve the original positions.

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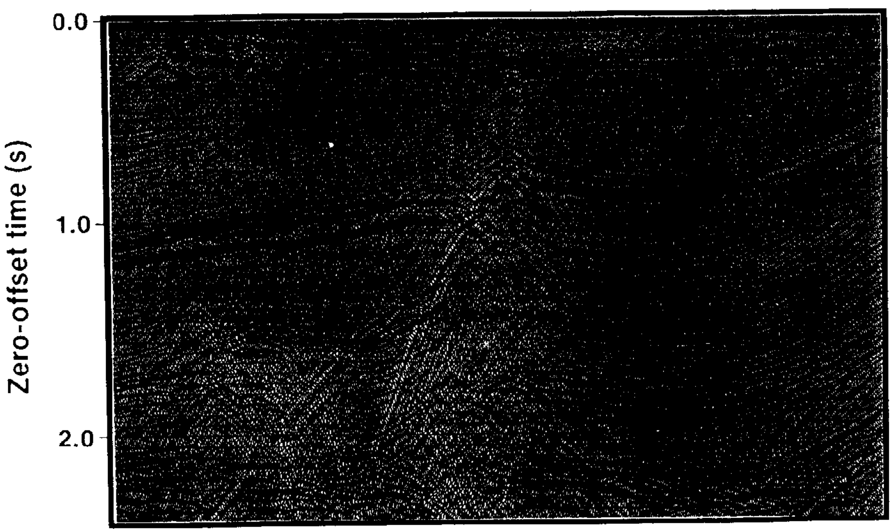

FIG. 1. Stacked North Sea time section. (All sections span 14 km of midpoints.)

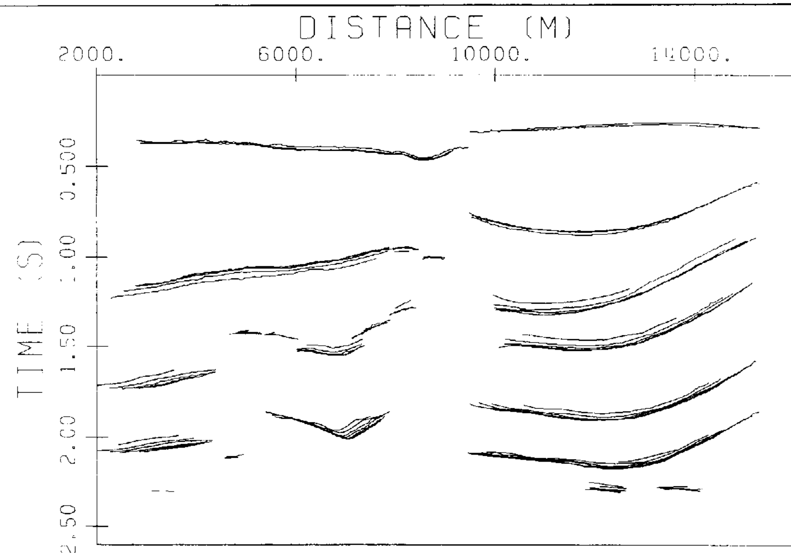

FIG. 2. Picked multi-offset reflection times, after approximate NMO corrections.

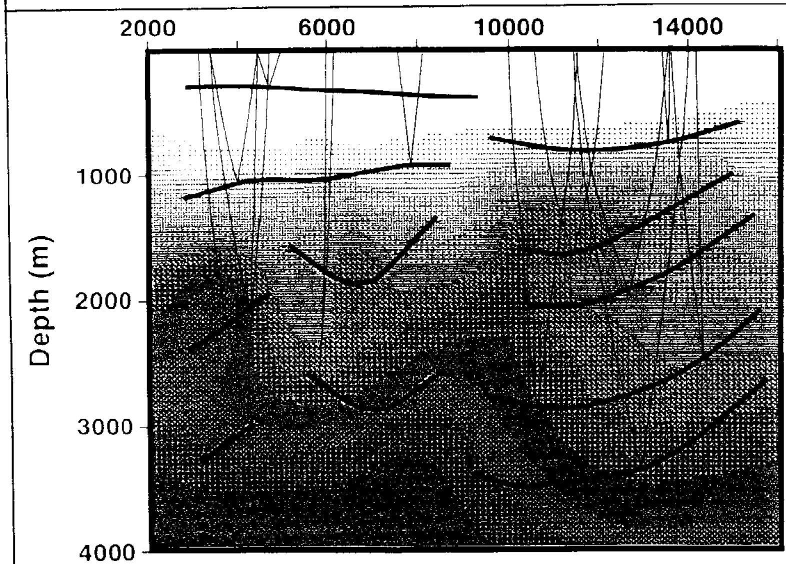

FIG. 3. Estimated reflectors and transmission velocities (gray levels increase from 1550 m/s to 5950 m/s).

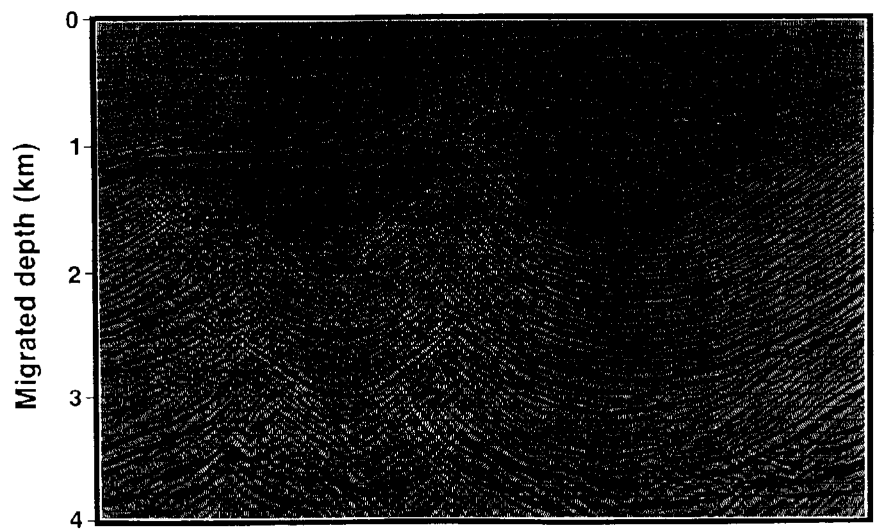

FIG. 4. Prestack depth migration using estimated velocities. Stacks coherently over offset. Consistent with figure 3.