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1-D AND 2-D CONSTRAINTS ON STACKING VELOCITY PICKING

Abstract. The interpretation of stacking velocity spectra is often done manually by expert seismic analysts because in most real cases many complex decisions and correlations have to be made. Automatic picking algorithms are not often able to take into account the numerous physical and geological constraints or include the a priori information that guides the human interpreter. The aim of this paper is to help to reduce the gap between the two results, introducing constraints in 1 and 2 dimensions (1-D and 2-D) that emulate the main criteria followed by seismic analysts.

INTRODUCTION

The interpretation of stacking velocity spectra is a critical step in the seismic processing sequence. It requires complex choices in order to identify multiple reflections, refractions, diffractions and lateral events. Furthermore, if VSP or well log data are available in proximity to the seismic profile, the solution should be guided by these measured values.

The interpretational complexity means that the geophysicist often prefers to work interactively or manually. Unfortunately, human intervention increases the cost and processing time, especially when a large amount of data has to be processed, as in 3-D prospecting. For this reason, we consider an automatic picking method which emulates the main criteria listed here which guide the interpretation:

1. since events with hyperbolic moveout produce significant peaks in the velocity spectrum, the path across it corresponding to the primary reflection velocity function should maximize the coherent energy;

2. the estimated local propagation velocity should be physically reasonable and consistent with laboratory and in situ measurements;

3. all the estimated velocity functions should be spatially consistent, leading to a geologically acceptable model of the considered prospect.

The first criterion has been studied by Toldi (1985, 1989), and a similar one is adopted in this paper also. Less attention has been paid until now to the second and third criteria and to their interactions, but recently Coppens (1989, 1990) proposed a solution based on expert systems. In the present paper, a deterministic approach is introduced which simultaneously takes into account the three mentioned criteria.

VELOCITY SPECTRA

The concept of velocity spectra dates back to Taner and Koehler (1969). Seismic traces

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OGS, Trieste, Italy.

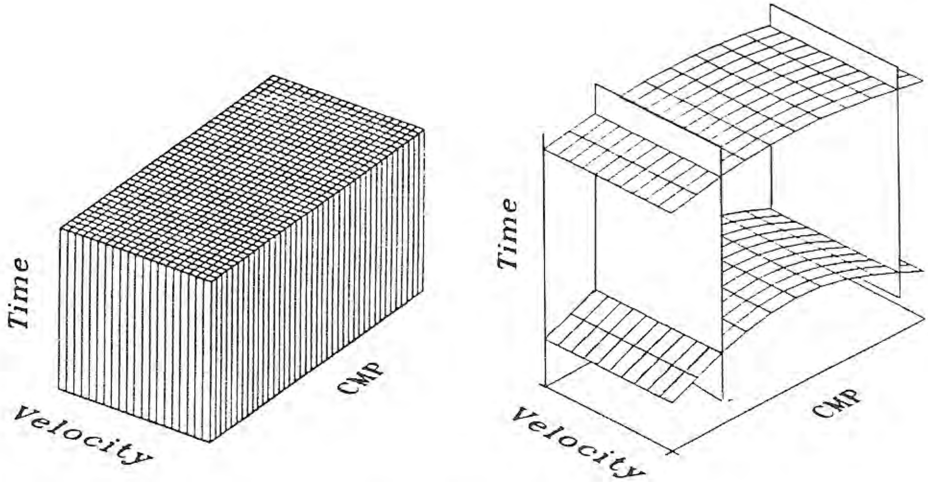


Fig. 1 — A coherency volume (on the left) and coherency spectra (on the right).

from one or more adjacent common mid-point (CMP) gathers are corrected for normal moveout using a set of trial velocities. The coherency between the traces is measured for all considered velocities v and arrival times t. Repeating this estimate for all CMP, we add a third dimension to the coherency field - the CMP coordinate x along the profile. We may represent it as a volume (Fig. 1). If we slice it at a given CMP, we get a conventional velocity spectrum, whilst if we slice it along a reflecting horizon, we obtain a continuous spectrum.

THE MAXIMUM ENERGY PRINCIPLE

An optimal path through the spectral peaks may be found iteratively by the conjugate gradient method (Fig. 2):

1. an initial guess for the velocity function is made and the gradient along it, which indicates the direction of steepest descent, is computed;

2. linearly combining the trial function and the spectrum gradient, an updated function may be obtained.

The two steps may be iterated many times and generally converge towards a well-defined solution. But the actual solution, unfortunately, may depend on the iteration number as well as on the initial guess, particularly if the coherency peaks are very flat or if many relative maxima with the same arrival time exist (Fig. 2A). To avoid this shortcoming it is necessary to apply the gradient method initially to a low-pass filtered spectrum, in order to estimate the major trend (Fig. 2B). Later, the band-pass range may be widened to get finer details around the major peaks, and finally, the whole spectrum is used to achieve the ultimate resolution.

If we accept that locally the dips of the reflectors may be neglected, we can use the Dix formula to estimate interval velocities, which can be better interpreted than stacking velocities. In particular, they can be more easily compared with well-log data, or velocity anomalies may be correlated with geological structures.

CONSTRAINED PICKING IN 1-D

A completely automatic process sometimes produces an unsatisfactory solution due to the fact that both multiple reflections and refracted events may have greater energy than the primaries. The first introduce apparent low interval velocities whereas the second produce the opposite

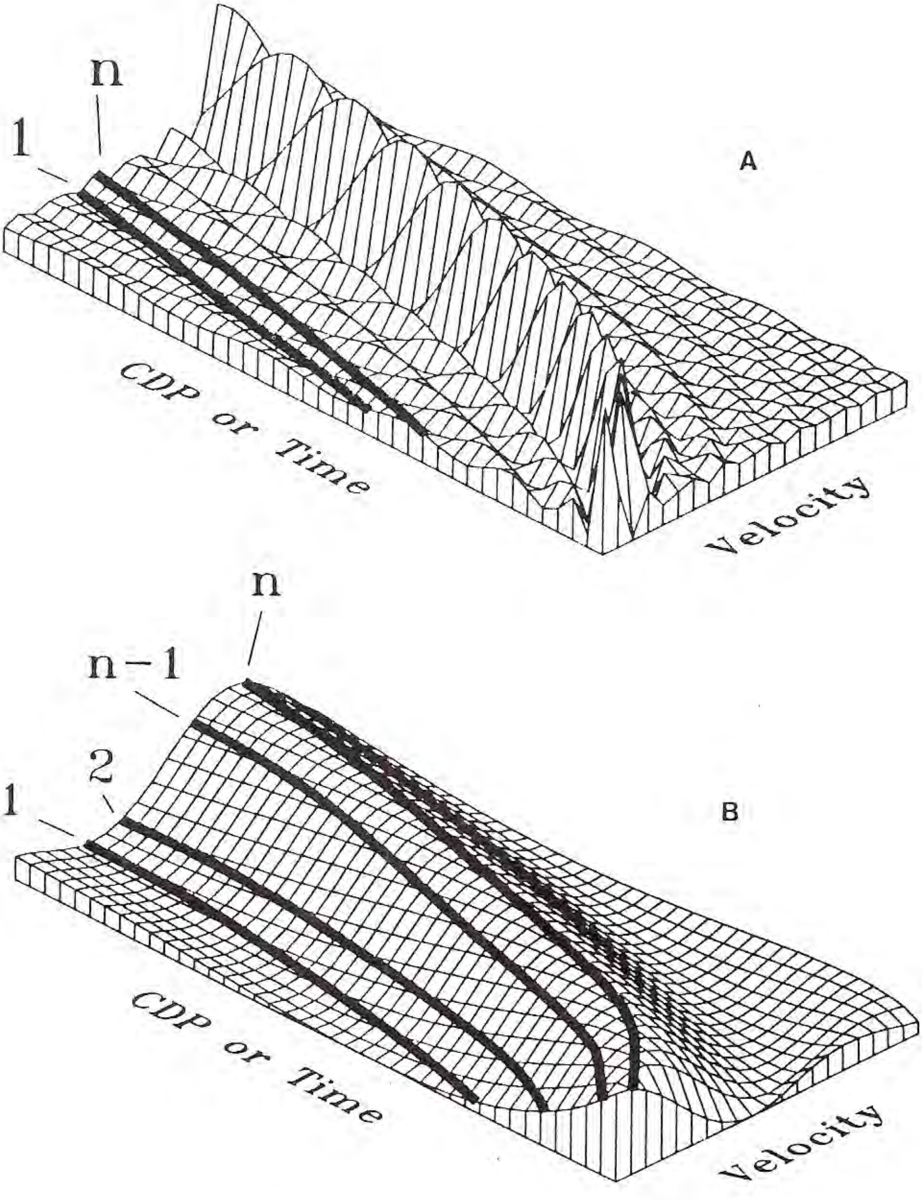


Fig. 2 — A trial velocity function at an iteration of the gradient method, operating on the whole frequency band of the frequency spectrum (A), and on a band-pass filtered copy of it (B).

effect (Fig. 3). Therefore, it is useful to constrain the automatic computation by user-defined bounds, which should include all available a priori information, e.g. knowledge of the main geological features of the region, or a velocity range as a function of depth suggested by laboratory and in situ measurements. Four criteria have been identified in this context.

1. *The initial function used in the first iteration of the gradient method.* Due to the iterative nature of the algorithm, the final result may depend on the initial conditions, especially in flat regions of the coherency spectra where the gradient tends to zero, and the convergence may be very slow or zero. Generally, a suitable initial choice is the expected regional trend of the stacking velocity.

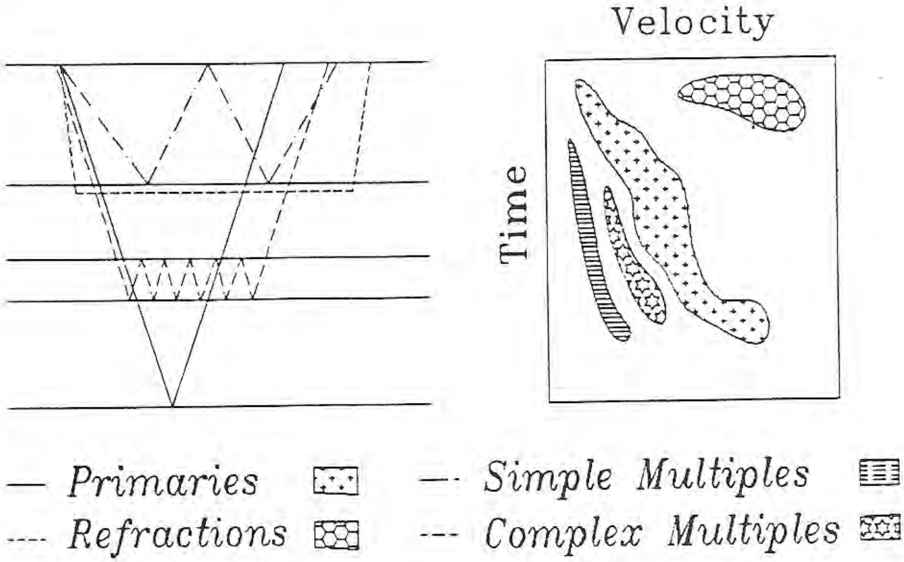


Fig. 3 — Primaries, refractions, simple and complex multiples produce characteristic high energy zones in coherency spectra.

2. *The maximum variation frequency of the velocity function.* Although we know from sonic logs that very sharp and sudden variations are present in the propagation velocity, the rather low vertical resolution of reflection seismics due to the Fresnel zone size should not be forgotten. For this reason, high frequencies changes in the estimated function should be rejected as noise. It should be emphasized that this limit is to be considered both in time (conventional spectra) and in space (continuous spectra).

3. *A corridor for interval velocities.* It is well known that compaction phenomena and increasing hydrostatic pressure determine a systematically increasing velocity as a function of depth trend. Therefore, the corridor of acceptable interval velocities must depend on arrival times. This corridor is particularly effective in rejecting multiples, diffractions, and lateral events. However, such a corridor may be applied only to conventional spectra, since a Dix-like formula for transforming stacking to interval velocities does not exist for continuous spectra.

4. *A corridor for stacking velocities.* Sometimes, due to a mispick (e.g. a short lag intrabed multiple), the apparent interval velocity is not large, so that direct interaction with the picking algorithm is needed to guide the choice towards the desired solution.

The first couple of tools do not have substantial effects, and therefore are generally referred to as soft constraints, whilst the second couple are indicated as hard constraints, because the constraint shape may often be distinguished in the obtained solution.

The practical implementation of criterion (1) is straightforward. To reject the highest frequency changes in the picked function (criterion (2)), the temporary solution of the gradient method is bandpass filtered after each iteration. The range limits of the interval velocities (criterion 3) require a conversion of the estimated stacking velocity to interval, at each iteration, a clipping of the values exceeding the limits and, finally, a conversion back of interval to stacking velocity. The limits on stacking velocities (criterion 4) may be imposed very simply by zeroing the coherency spectrum in the forbidden regions.

REAL DATA EXAMPLES

In Figs. 4 to 7, some application examples of the constraints in the two kind of spectra obtained from real data are shown.

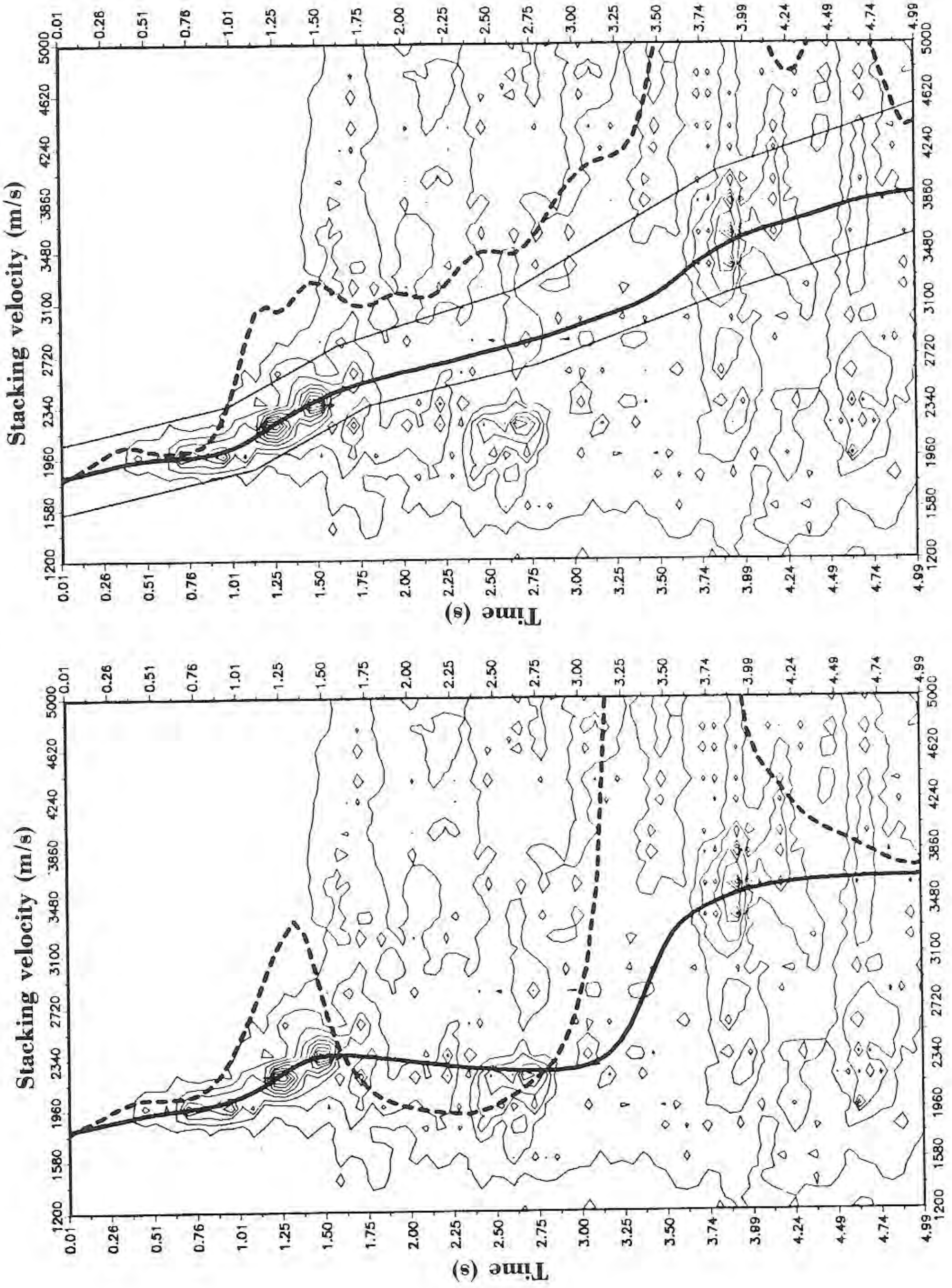


Fig. 4 — Stacking (thick continuous lines) and interval velocities (thick dotted lines) estimated without constraints (on the bottom), and using a corridor for stacking velocity (on the top), in a conventional spectrum.

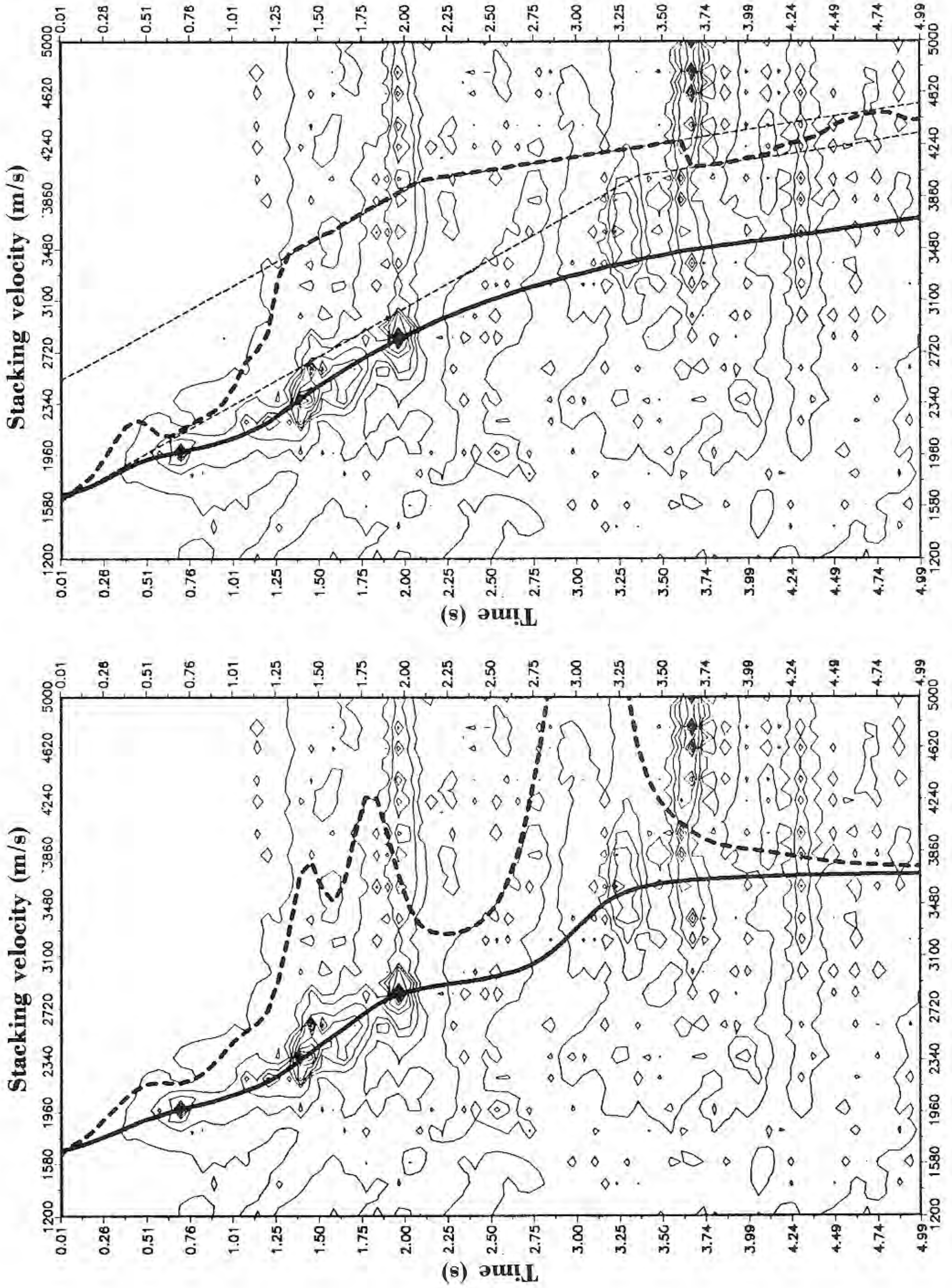


Fig. 5 — Stacking (thick continuous lines) and interval velocities (thick dotted lines) estimated without constraints (on the bottom), and using a corridor for interval velocity (on the top), in a conventional spectrum.

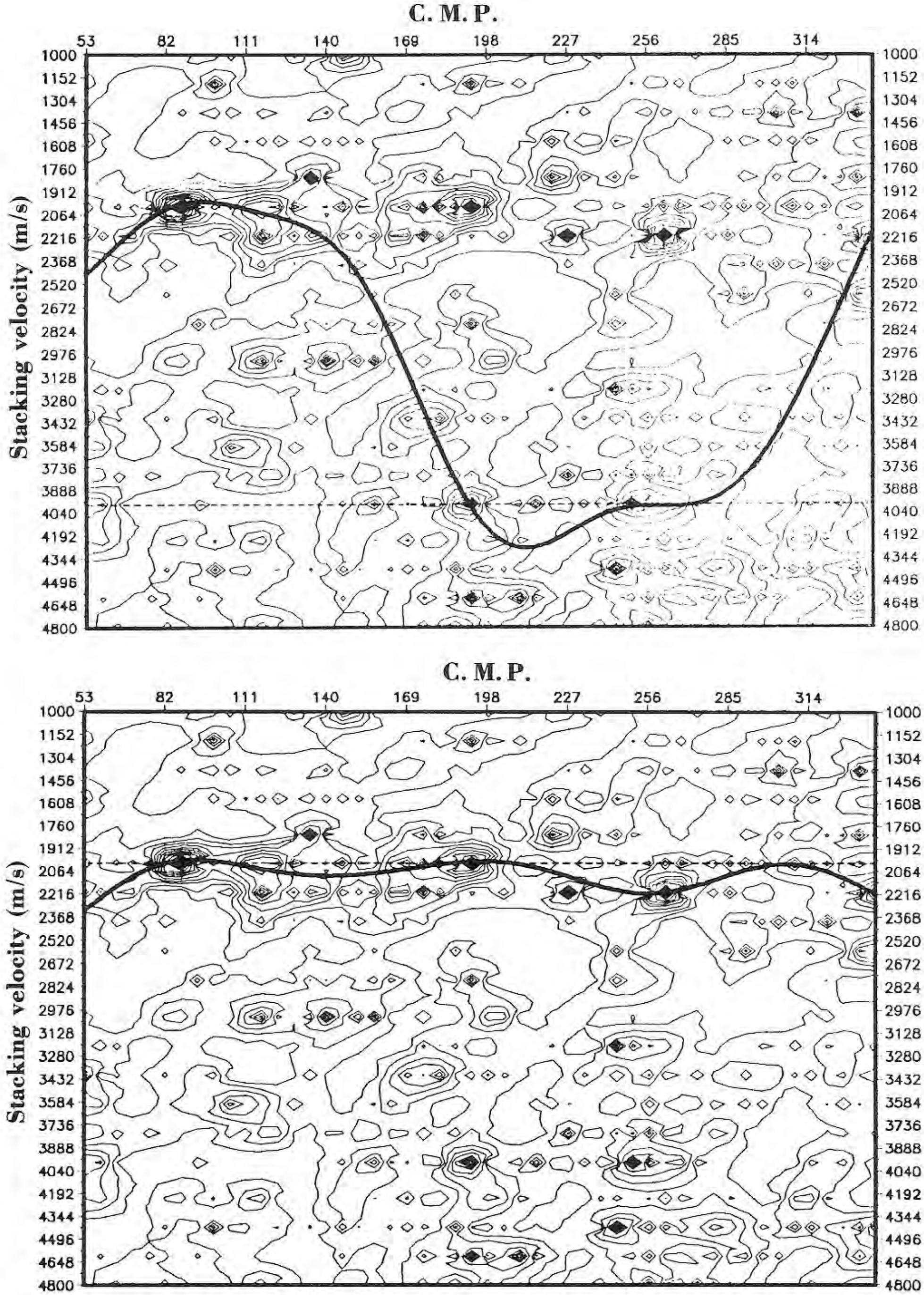


Fig. 6 — Effect of two different initial curves (thin dotted lines) on the final solution (thick continuous lines) of automatic picking of a continuous spectrum.

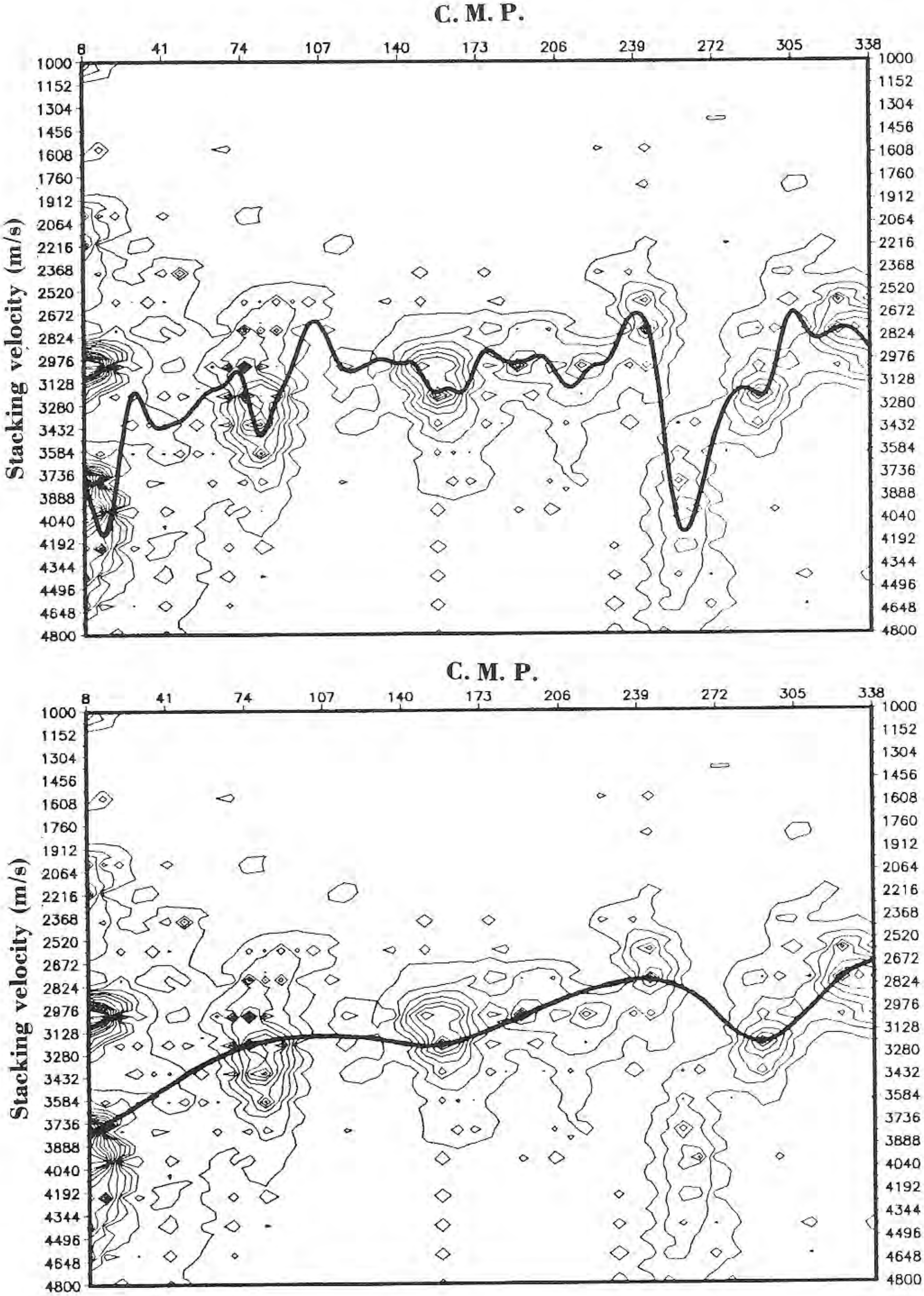


Fig. 7 — Effect of two different maximum spatial frequencies in a continuous spectrum - higher at the top, lower at the bottom.

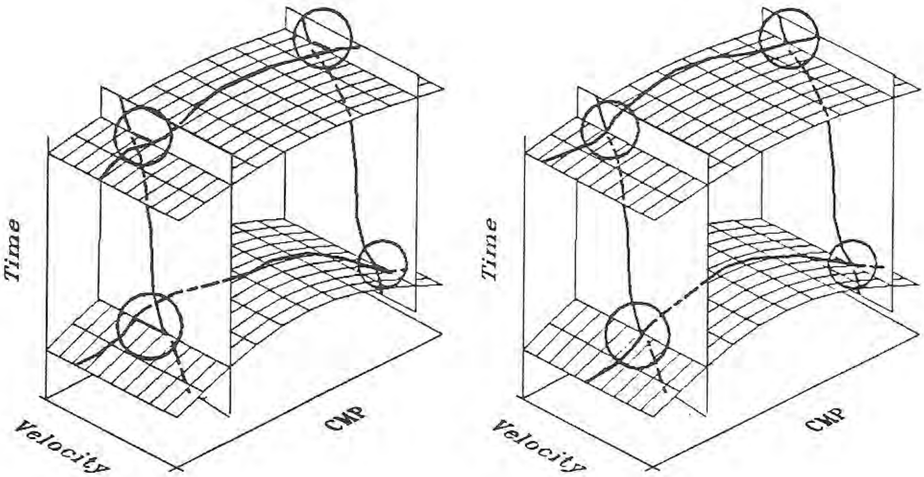


Fig. 8 — Velocity functions (thick lines) picked in continuous and conventional spectra, independently (left) and in a coupled manner (right). Circles highlight differences at intersections.

In Fig. 4, on the bottom, the result of unconstrained picking on marine data is shown. The continuous thick lines indicate the estimated stacking velocity, the dotted thick ones the interval. Between 0 to 1.5 s, the solution is satisfying since primaries have the dominant energy. Between 1.5 and 3.5 s, short and long period multiples become stronger than primaries, and the solution in that region is incorrect - very low interval velocities are detected. Later, particularly at 4 s, a significant peak probably due to a deep primary has been correctly chosen. To exclude the multiple zone, a corridor has been introduced (thin piece-wise straight lines), as seen on the top, giving a more regular and reasonable interval velocity.

In Fig. 5, another example shows the effect of a corridor for interval velocities. The velocity function estimated by unconstrained picking (on the bottom) is acceptable from 0 to 1 s, whilst between 1 and 3.5 s instabilities occur in the interval velocity, mostly due to a coherency zone at 2.5 s corresponding probably to multiples. The clipping effect of the corridor on interval velocities is evident (on the top), as well as a smoothing of the corresponding stacking velocities.

Fig. 6 illustrates the effect of the initial guess on the final solution. A high coherency zone is situated at 2000 m/s in a continuous spectrum. If the initial function (thin dotted line) is far from that zone, e.g. at 4 m/s, only the highest coherency peaks are reached by the algorithm, and local maxima at 4 m/s force the solution to unreliable values between CMP's 170 and 300. Using a better initial guess (at the bottom), we get a solution which is much more stable and acceptable.

Fig. 7 compares the effect of two different upper limits for the spatial frequencies in the picked curves in a continuous spectrum. Finding a good choice for this parameter is not trivial. Very sharp lateral changes in velocity should not be allowed if the solution is to be used as input for migration or inversion programs. On the other hand, excessive smoothing can hide real significant changes in the earth.

CONSTRAINED PICKING IN 2-D

Continuous and conventional spectra define intersecting surfaces in the coherency volume (Fig. 1). If each spectrum is interpreted independently, differences occur almost always at the intersection points between the velocity estimated by the continuous and the conventional spectra (Fig. 8). This fact is for three main reasons.

1. User-defined constraints may be not fully compatible between the different spectra.

2. One of the two intersecting spectra may have a well-defined dominant trend, whilst the

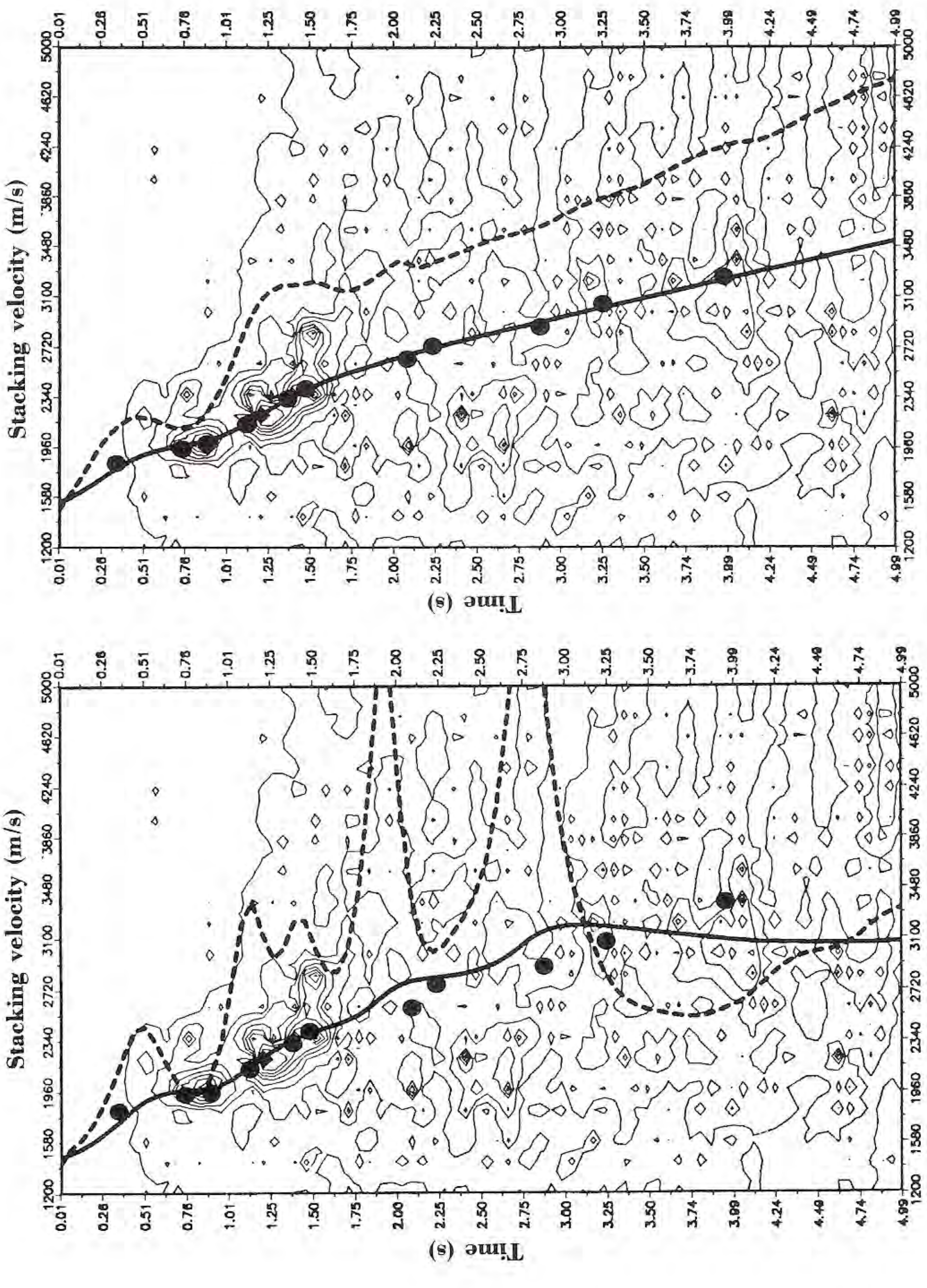
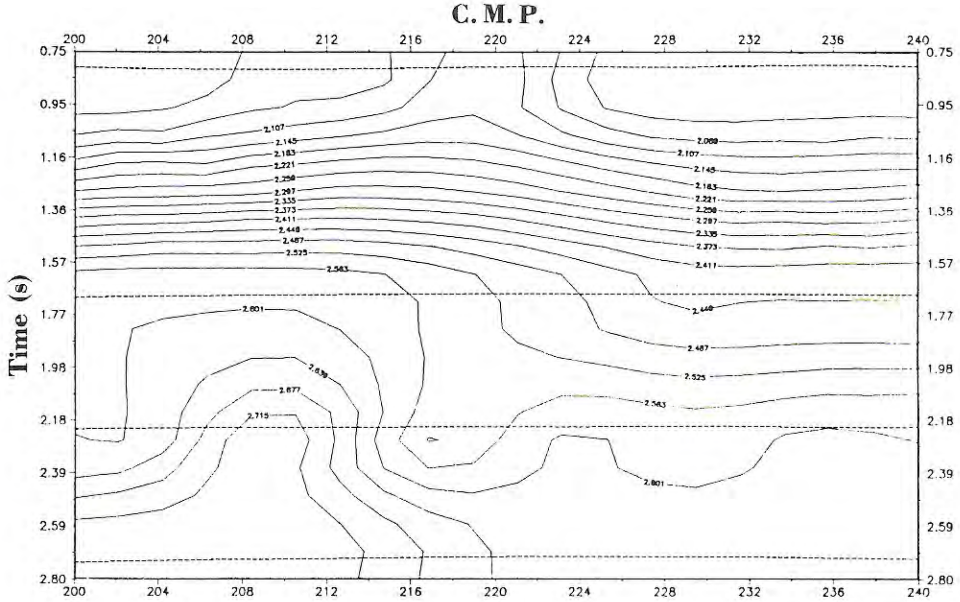


Fig. 9 — Stacking velocities (thick continuous lines) picked in a conventional spectrum, independently (bottom) and in a coupled manner (top). Black dots indicate velocity values evaluated at intersecting continuous spectra.



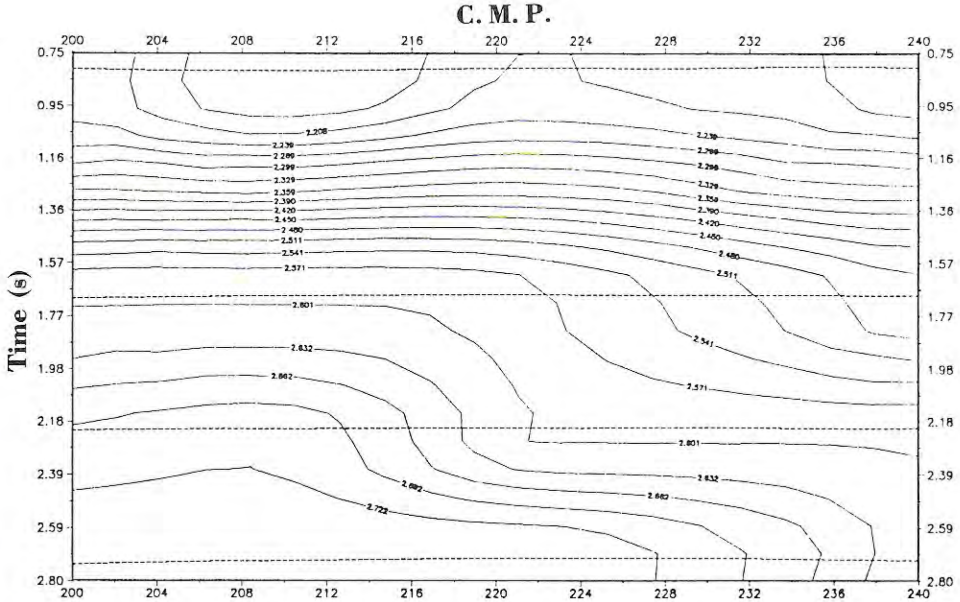


Fig. 10 — Stacking velocity field obtained by automatic picking, independently (top) and in a coupled manner (bottom). Thin dotted lines indicate the arrival times of continuous spectra.

other may be very noisy or flat, thus leading to unstable picking.

3. Undesired organized noise such as multiples or diffractions may be effectively avoided only if sufficient discrimination exists between their apparent velocity and that of the primaries; and this does not always occur.

Whilst the first problem can be eliminated by an accurate bound choice, the other two depend on data quality. If we require that the final solutions coincide at intersection points, we get additional constraints for the picking algorithm.

From a practical point of view, we can exploit the iterative nature of the gradient method. We start the first iteration by picking the various velocity spectra independently. Then, from the second iteration on, the solution is affected by the intersections of the previously estimated curves in the crossing spectra proportionally to the weight of their coherence. Proper corridors are applied to guide the solution towards the position of the prevalent values. The iterations continue until the differences between estimated velocities at intersections are all smaller than a chosen threshold. In this way, we finally get a grid of stacking velocity functions in which all intersections agree closely with the corresponding ones in the other spectra.

FURTHER EXAMPLES

Fig. 9 shows the difference between 1-D and 2-D picking in a conventional spectrum. On the bottom, the black dots indicate the stacking velocity values obtained picking the intersecting continuous spectra. The mismatch is pretty large in certain cases. A global approach in 2-D reduces the difference below a chosen threshold after four iterations. The interval velocity is now stable and reliable, and is obtained without any constraint except the required agreement at intersections.

The total field estimated along the whole profile is displayed in Fig. 10. If each spectrum is considered independently (top), the spatial consistency is pretty good, but it increases in the global approach (bottom). It should be emphasized that the smoothness obtained is not due to a spatial filter but to the picking algorithm itself.

CONCLUSIONS

Automatic picking can become an effective and reliable tool in standard processing only if proper constraints are used to emulate the complex integrated interpretation done by an experienced seismic analyst. General geological and physical knowledge may thus be incorporated into the picking algorithm, as well as VSPs, well logs, and other additional information.

The constraints become particularly effective if they act in two dimensions, i.e. space and time, leading to a robust global solution. In this way we exploit redundancy in the data due to the generally slow lateral variations of the velocity field.

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