

APPLICATION OF SEISMIC MODELLING TO VELOCITY STUDIES†

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ABSTRACT

It is well known that multiple coverage data can be stacked even when geological conditions do not allow true common reflection points to exist. However, this involves the use of stacking velocities which may differ considerably from the actual velocities of the subsurface formations.

This paper shows how interpreters can simulate such complex situations through seismic models and compensate for the effect on the stacking velocities of the anomalies of the seismic ray paths. Simplified and actual examples are shown to illustrate the method.

INTRODUCTION

One of the consequences of the success achieved by the multiple coverage method over the past fifteen years has been the extensive development of automatic velocity analysis techniques. Initially, such processes were essentially directed towards obtaining proper NMO control at discrete intervals so that the input data could be stacked successfully. As the progressive implementation of new hardware or software features decreased the cost of running velocity analysis programs, it became feasible to apply them on a continuous basis along entire lines, or even surveys, in order to attempt to extract more velocity information from the seismic records. When geological conditions involve gentle dips without sharp structural or stratigraphic variations, velocity analysis results may be directly related to the actual velocity of the rock formations. On the other hand, the existence of steep dips, facies variations, faults, fractures, or other tectonic or sedimentary features makes it much more difficult to correlate velocity analysis and geological data.

The purpose of this paper is to show how the use of seismic models can help the interpreter under this type of situation.

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BASIC PROBLEM

First, it is important to understand how velocity analysis programs work.

Theoretically, true "common depth points" do not exist in case of multiple coverage recording unless all beds are horizontal and the velocity is a function of depth only. (Figure 1)

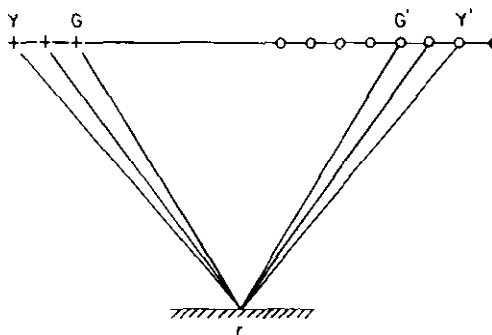


Fig. 1. Horizontal Reflector Case. Most velocity analysis programs assume the above geometry which corresponds to ideal common reflection point conditions.

Under these circumstances, the delta T correction for a trace located at an offset

X from the source and for a center time T is generally expressed by the well known formula

$$\Delta T = \sqrt{X^2/V_R^2 + T^2} - T \quad \dots(1)$$

where V_R = RMS velocity

Most velocity analysis programs use either the above or similar expressions to apply various sets of NMO corrections to the seismic data, and compute for each set, the value of some mathematical function (correlation, semblance, coherency, sum, . . .) the maximum of which should correspond to the "best" velocity.

Since the expression (1) represents the equation of a hyperbola when plotting Delta T versus X for given values of T and V_R one often refers to the set of NMO corrections which optimize the desired function as to the "hyperbolic fit".

When geological conditions differ significantly from the ideal case, common depth points may no longer exist in the strict sense of the term and expression (1) does no longer apply. However, it is still possible to obtain stacked sections by continuing to use this expression for both velocity analyses and NMO corrections, since the set of Delta T's which will optimize the criterium function should also yield the best stack of the data, as long as velocity analyses and move out corrections programs use the same basic format. Of course, the stack will not be the addition of groups of traces which originate from single points, but will involve the composition of reflection points scattered over a certain distance. The velocity V_R which gives the best "hyperbolic fit" is no longer the true RMS velocity of the geological formations, but only an apparent, or "stacking" velocity.

In some over-simplified cases, one can relate the "stacking" velocity to the true velocity through geometrical or analytical considerations. For instance, a dipping interface, overlaid by a constant velocity medium, will result in a stacking velocity equal to $V/\cos d$, where V is the velocity in the overburden and d the dip angle of the interface. (Figure 2).

For more complex situations, the use of seismic models may offer an easier way to correlate geological and stacking velocities.

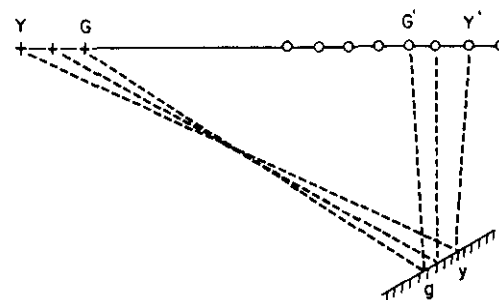


Fig. 2. Dipping Reflector Case. Although a true common reflection point does not exist, data can still be stacked successfully by applying NMO corrections corresponding to an apparent velocity of the reflector.

SEISMIC MODELLING

Seismic modelling constitutes a type of reverse approach to normal interpretation procedures. Instead of proceeding from the seismic results to some image of the earth section, the interpreter starts from a model of the subsurface and evaluates how well synthetic seismic data, generated from the model, match the actual field observations.

Before working on a modelling project, we first need to have a stack section of the line to interpret and the results of a continuous velocity analysis along the main horizons. The stack section alone cannot be sufficient, since it represents data reduced to a zero offset and consequently no longer contains the NMO information which existed on the original data. The velocity analysis output, on the other hand, or "velocity horizons" as we may call them, do retain this information.

The interpreter designs a model in the depth domain by defining the thickness and the interval velocity of each formation at various sample points along the line. A ray tracing program will then simulate the seismic travel paths which would be generated if a CDP survey using the field parameters of the actual line (recording geometry, stacking fold, . . .) were recorded on the model. Next, the resulting synthetic data are passed through the same routine processing modules as the original data, so that a synthetic stack section and synthetic velocity horizons can be generated.

By comparing the results from the model to the actual data, the interpreter can evaluate the accuracy of the model. He may then modify the original model and generate a new set of synthetic data, which hopefully will be closer to the desired responses than the initial attempt. Further modifications may be necessary to achieve an acceptable fit between simulated and observed results. (Figure 3).

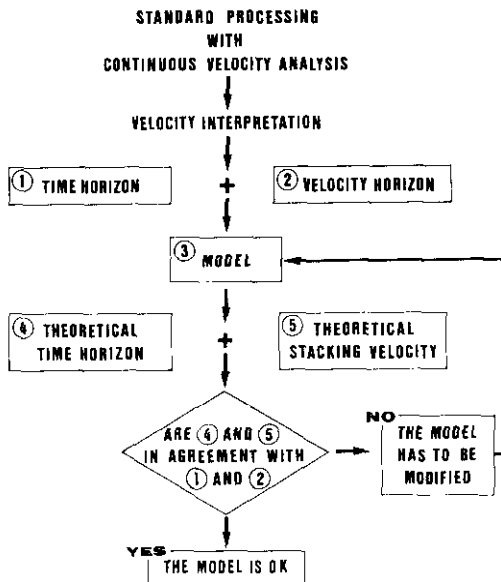


Fig. 3. Flow chart of the operations involved in iterative seismic modelling.

Since the depth, shape, thickness and velocity of a layer affect the travel paths of any seismic ray traversing this layer to be reflected on a deeper interface, one must proceed horizon by horizon from top to bottom, adjusting shallower boundaries first.

The use of an interactive terminal is quite suitable for this kind of operation, because it allows the interpreter to obtain an almost immediate response to any modification and drastically cuts the time necessary to achieve a proper fit.

The availability of a migrated time section, or even better, of a migrated depth section may also help the geophysicist in designing an initial model closer to the final solution.

We will now discuss some practical applications of seismic modelling.

THIN LAYER EXAMPLE

Before proceeding to more complex models, it is interesting to study the effect of some simplified anomalies on the velocity horizons.

Let us consider, first, a thin layer with a velocity lower than that of the adjacent formations. On Figures 4, 5 and 6, this layer is limited in one direction only, and located at increasing depths. We see that the stacking velocity varies by approximately the same amount in all three cases, but the horizontal extension of the anomaly decreases when the depth of the layer increases.

The next example (Figures 7, 8 and 9) show the effect of another thin layer, limited on both sides, this time, with a variable length and a constant depth. The results of Figure 9 are particularly worth noticing: while the total extension of the low velocity layer does not exceed one quarter of the length of the spread, it generates a strong anomaly in the stacking velocity, showing an apparent high at the very location where the true average velocity passes through a minimum, with an apparent low velocity extending on both sides beyond the limits of the layer. This type of anomaly is quite characteristic and could be used as a tool to detect small stratigraphic traps which would hardly show on the seismic sections themselves.

Figure 10 shows the results of similar modelling attempts, simulating a low velocity layer of various extensions deposited on the surface of the ground. Such studies can help geophysicists in understanding the effect of the existence of a weathering zone on the stacking velocity of deeper horizons, and in designing methods which can compensate for that effect.

SALT DOME EXAMPLE

Figure 11 depicts a model of a salt dome and Figure 12 shows both the time response (stack horizon) and the velocity response (velocity horizon) corresponding to the deeper interface on the model.

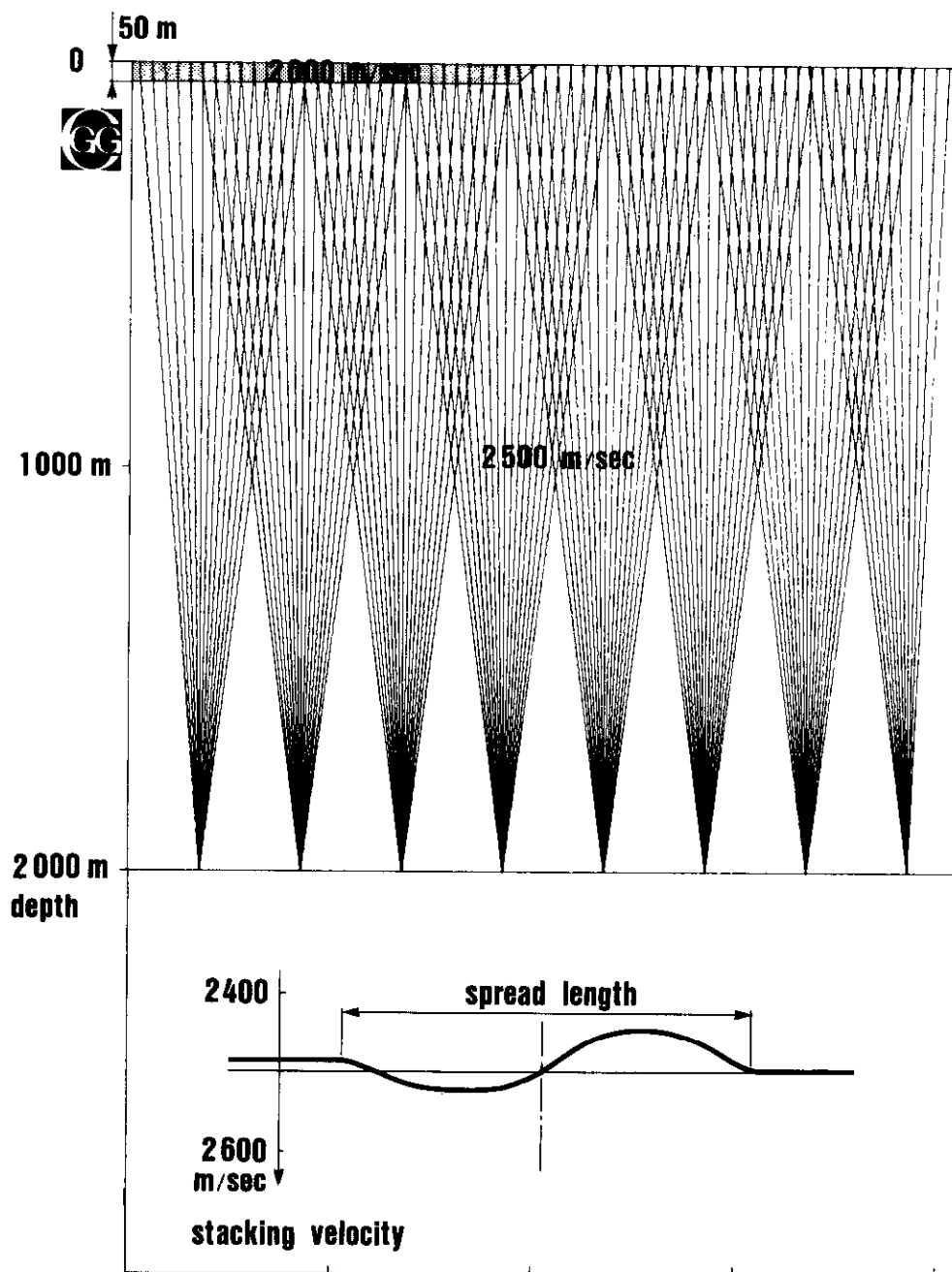


Fig. 4. Effect of the depth of a thin low velocity layer on the stacking velocity.

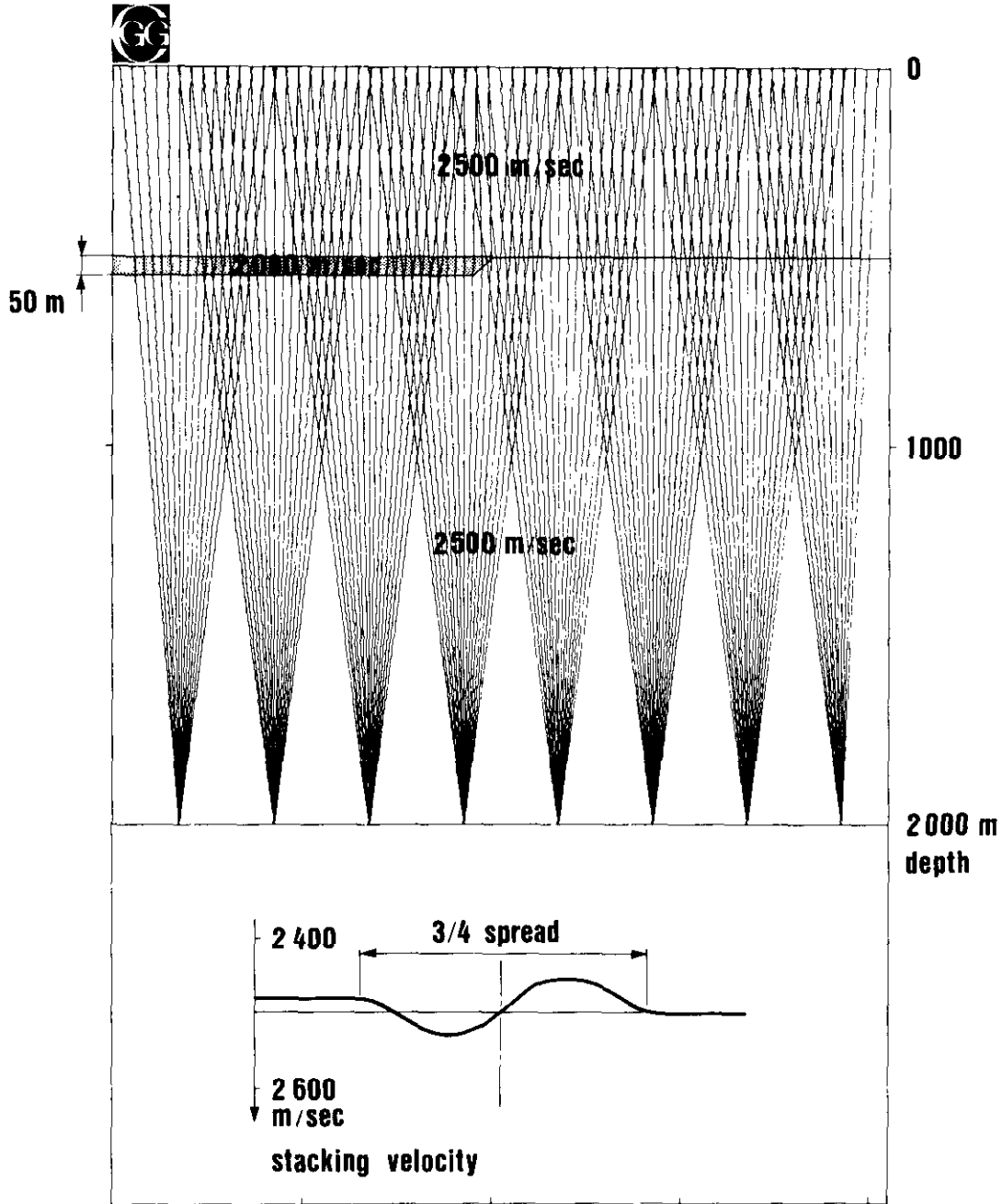


Fig. 5. Effect of the depth of a thin low velocity layer on the stacking velocity.

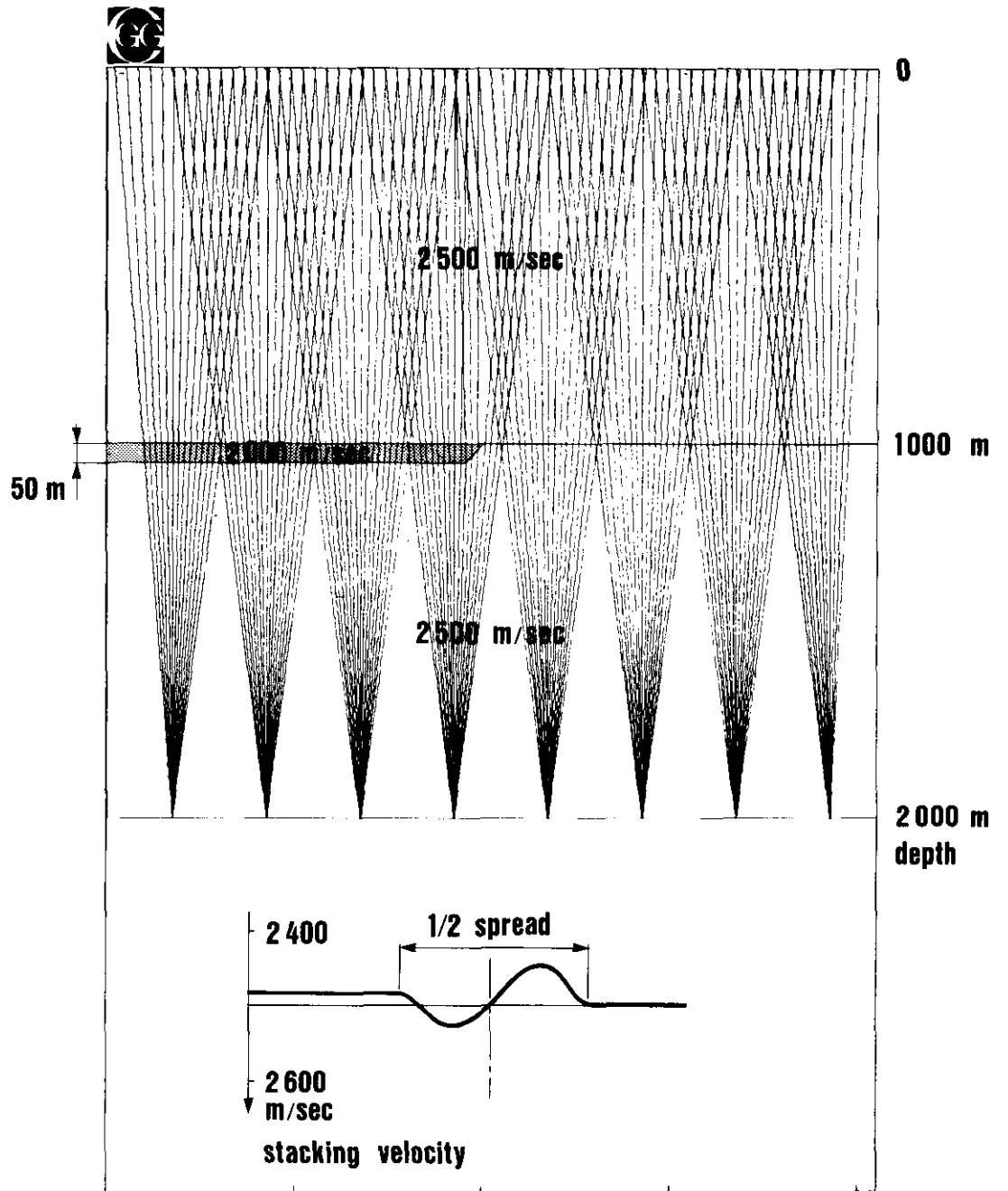


Fig. 6. Effect of the depth of a thin low velocity layer on the stacking velocity.

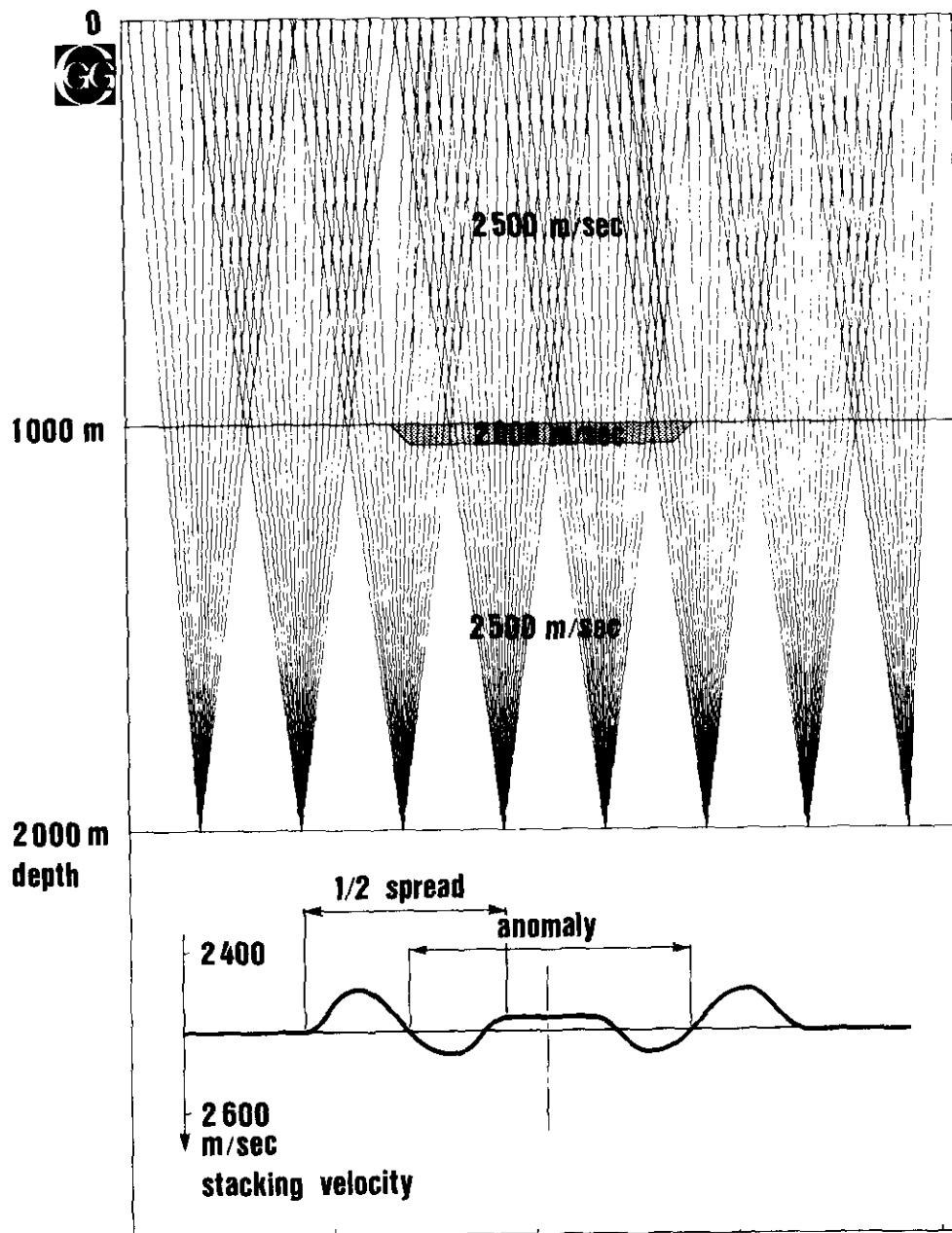


Fig. 7. Effect of the horizontal extension of a thin low velocity layer on the stacking velocity.

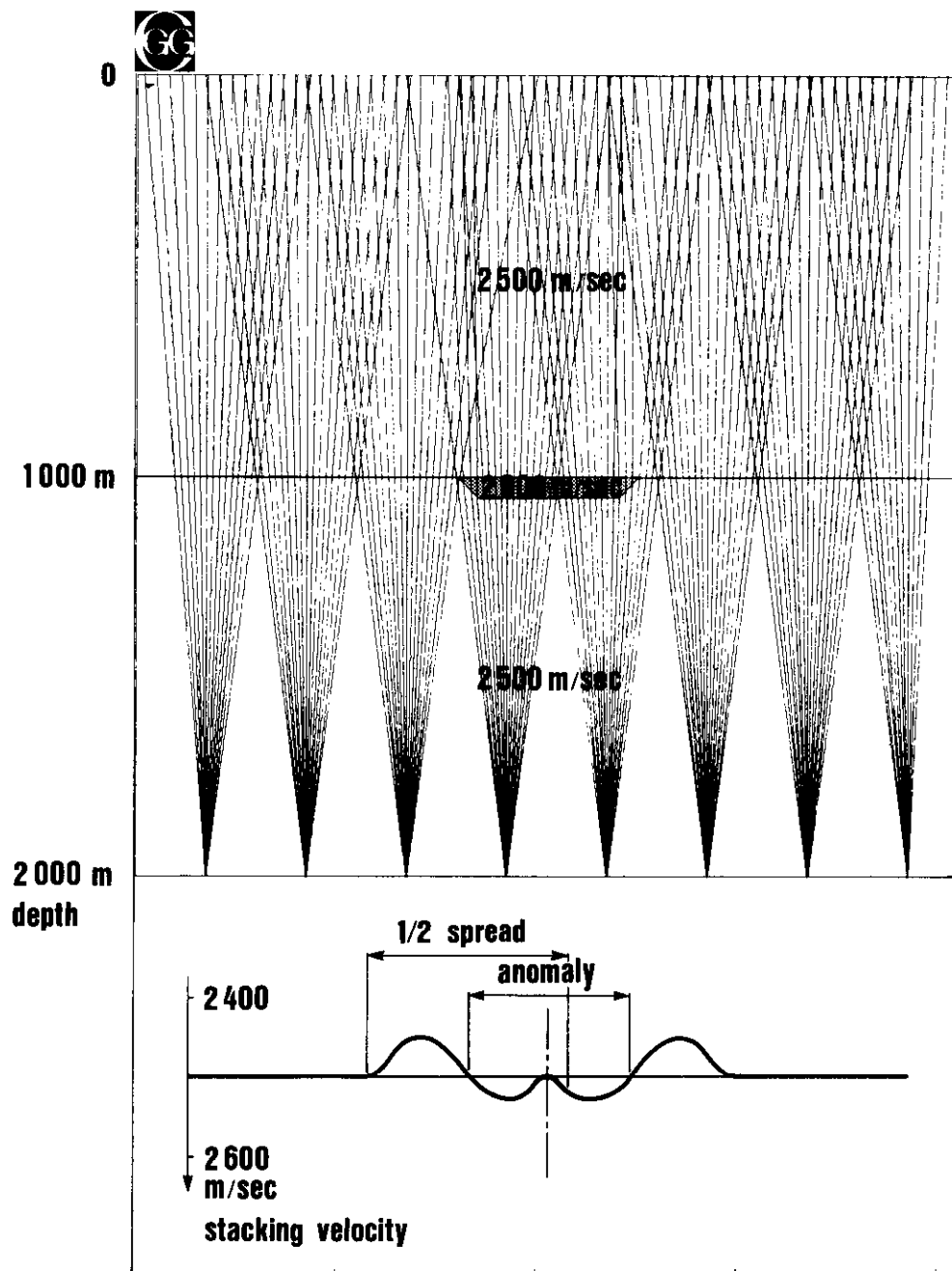


Fig. 8. Effect of the horizontal extension of a thin low velocity layer on the stacking velocity.

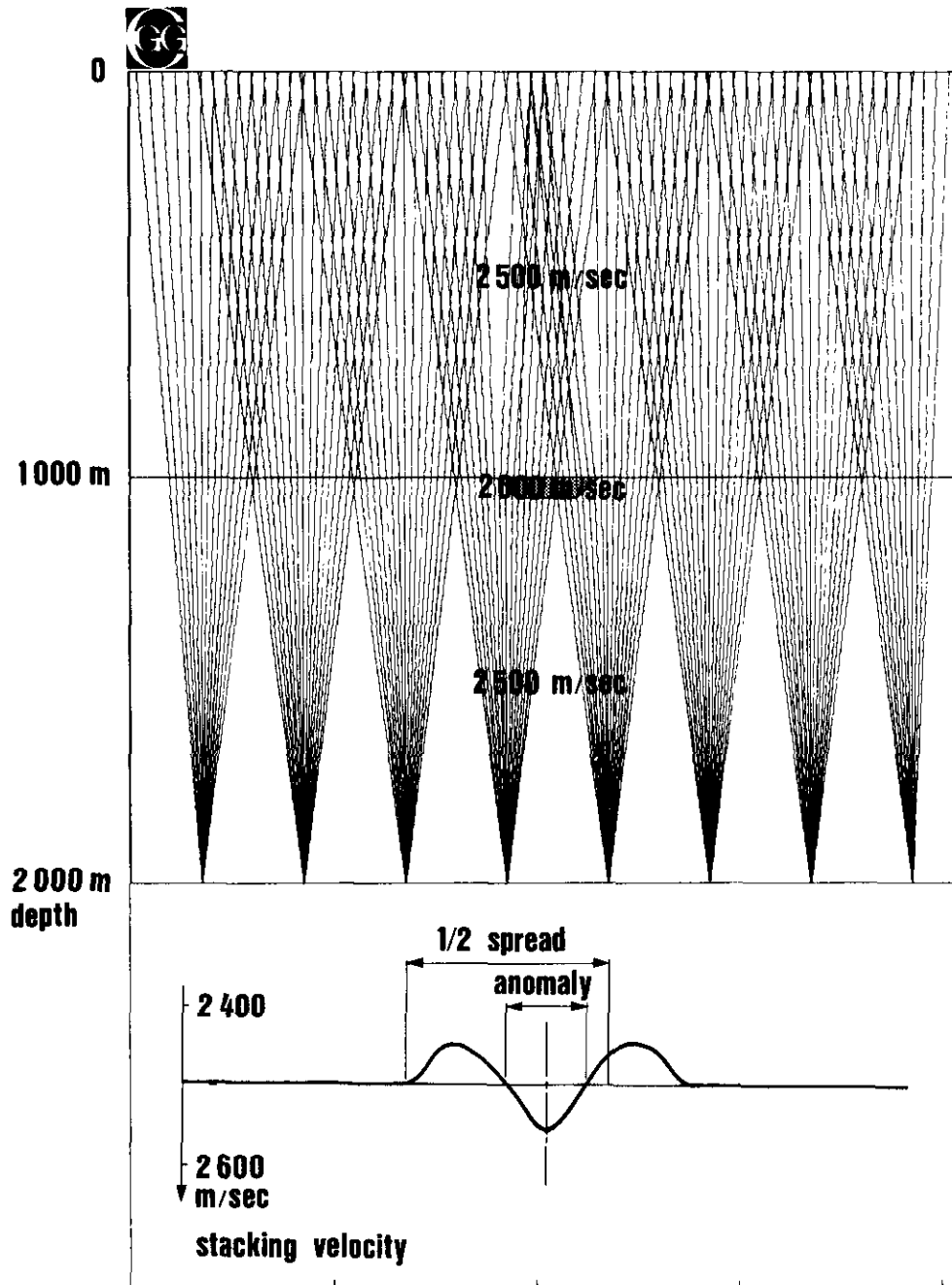


Fig. 9. Effect of the horizontal extension of a thin low velocity layer on the stacking velocity.



SURFACE ANOMALY

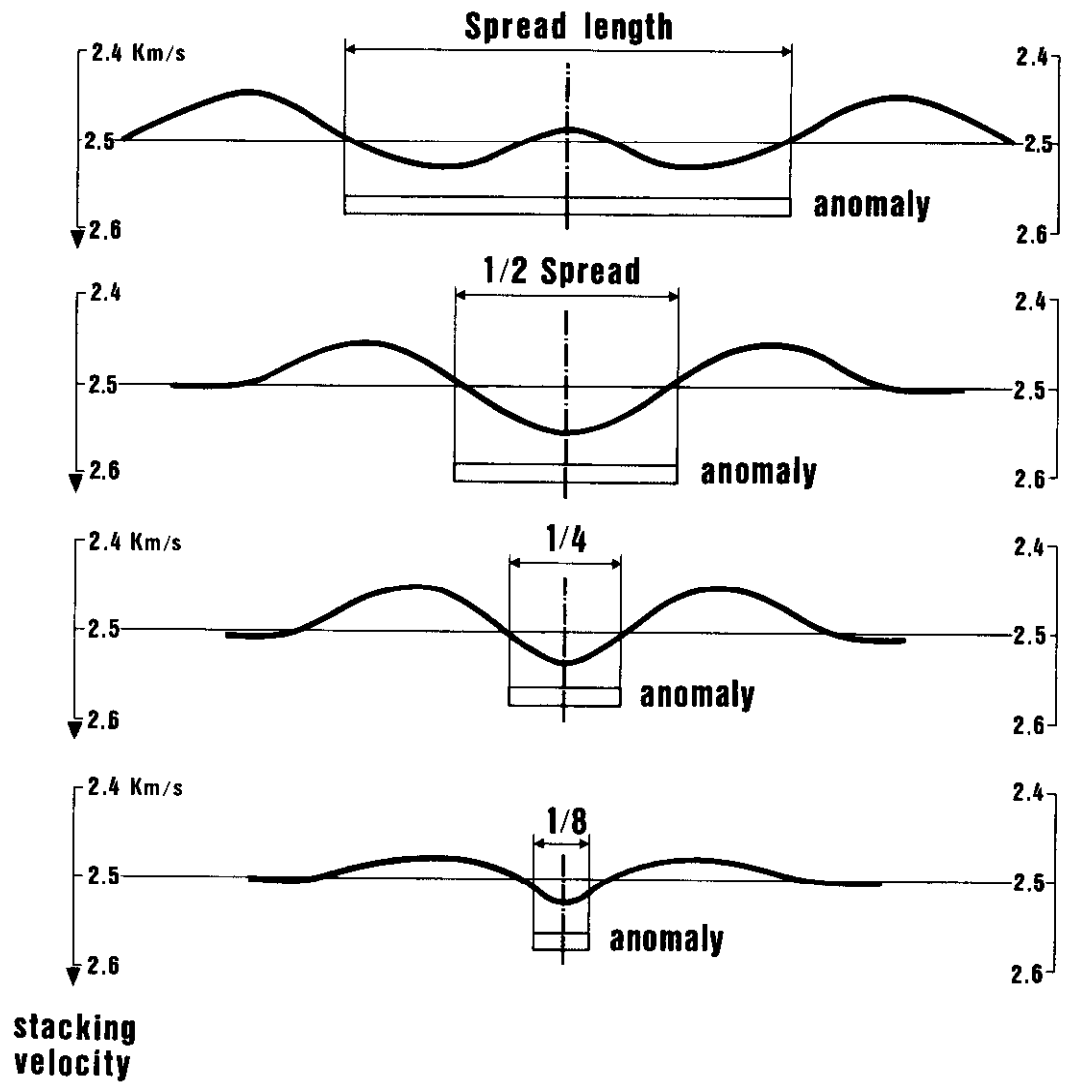


Fig. 10. Comparison of the effect on the stacking velocity of various extensions of a weathering layer.

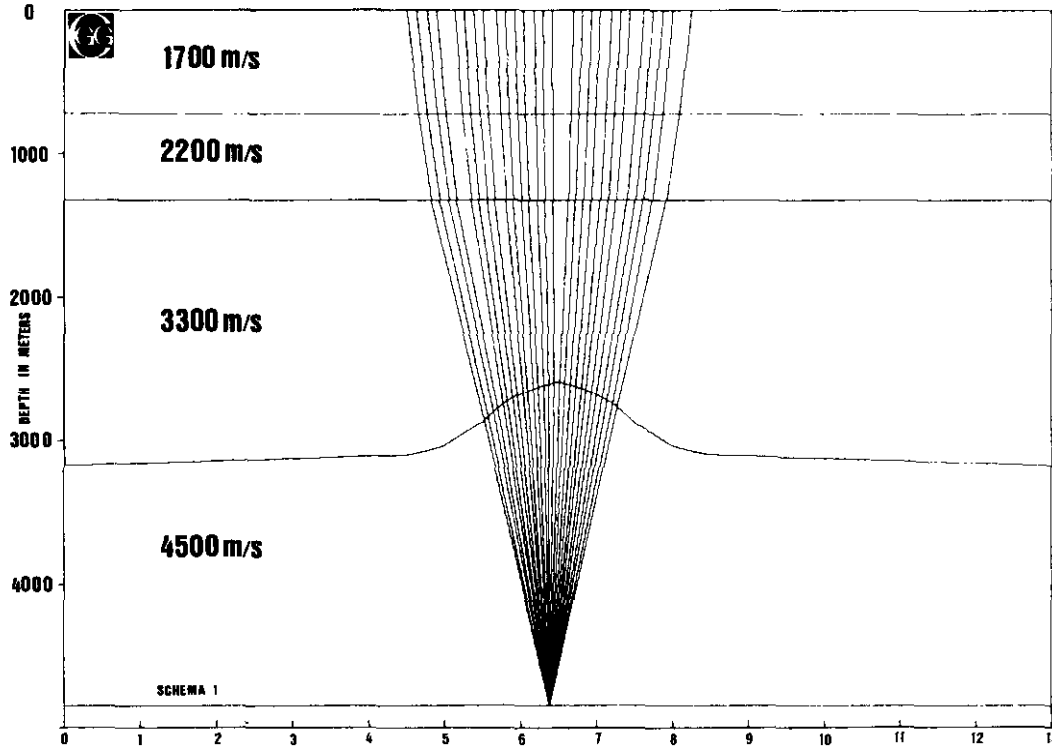


Fig. 11. Salt Dome Example.

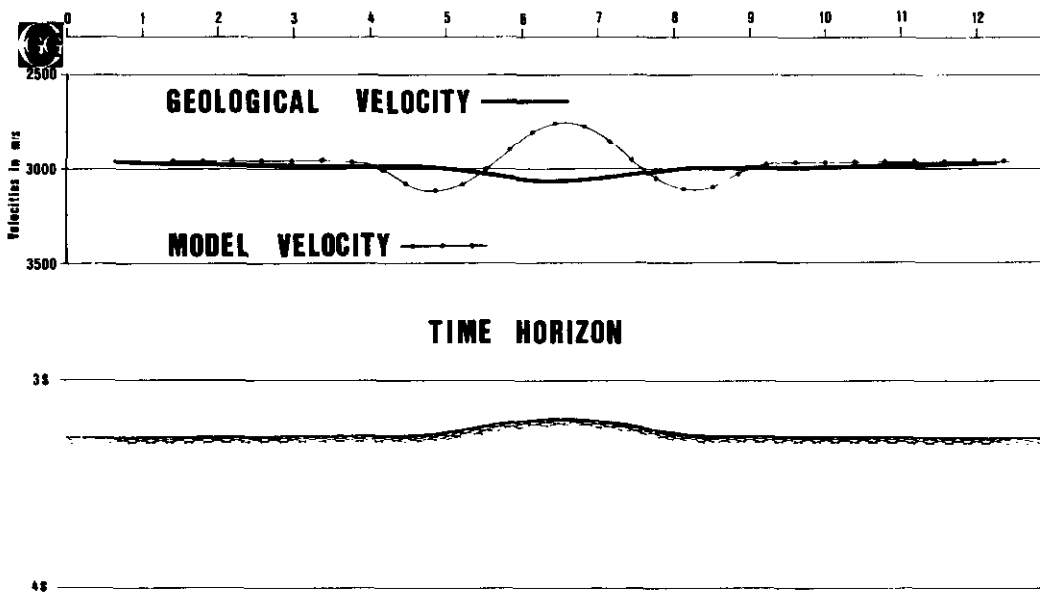


Fig. 12. Time and Velocity responses of the model shown on Figure 11.

The actual vertical RMS velocity has also been plotted on Figure 12. One can see that the stacking velocity (as indicated by the dotted line) passes through a minimum at the apex of the dome, while the geological velocity exhibits a slight increase at the same position as could be anticipated. The higher values for the stacking velocity have been rejected on both sides of the dome.

ACTUAL EXAMPLE

The next set of figures (Figure 13 through 18) show the various documents which may be required or generated during a seismic modelling process. Figure 13 is a display of the stack section of the line under investigation, where two horizons of interest have been identified respectively as "C" and "f". Figure 14 shows the velocity horizons

relative to the same "C" and "f" events, i.e. a representation, in section form, of the output generated CDP by CDP along the two horizons by a continuous analysis program.

Figure 15 is the result of a depth migration process applied to the stack section of Figure 13. This display helped the interpreter to build the seismic model which is shown in Figure 16. Then the ray tracing program simulated seismic data which were in turn input to processing modules, resulting in the synthetic time horizons, shown on Figure 17, and in the synthetic velocity horizons, shown on Figure 18, superimposed on the actual velocity horizons. The correlation between synthetic and real data appears to be quite good and the seismic model probably represents a fair picture of the geological reality along the line.

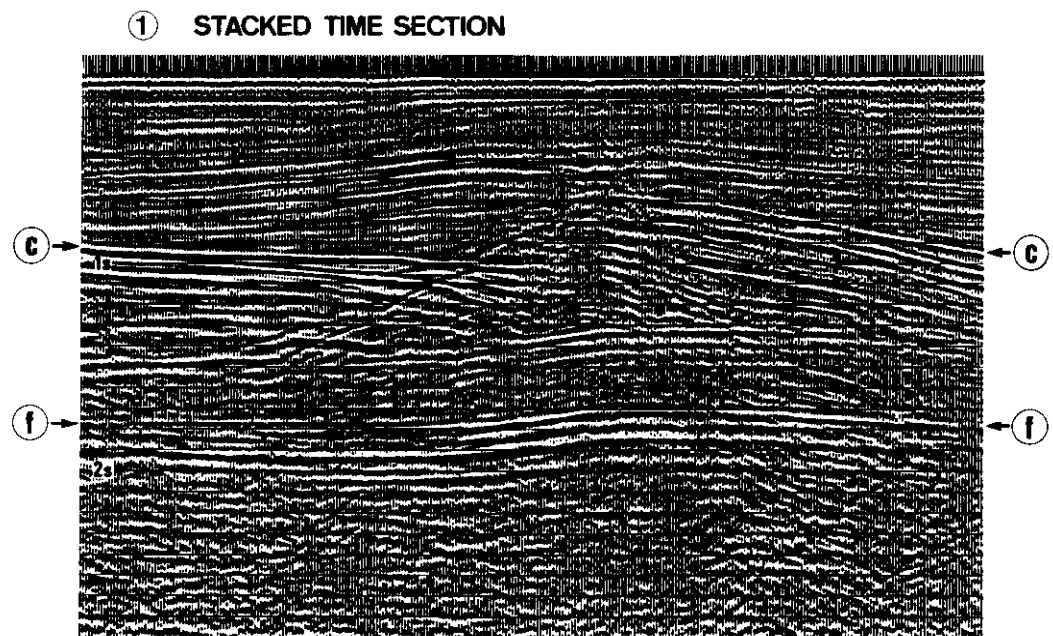


Fig. 13. Conventional stack section showing horizons "C" and "f".

② VELOCITY HORIZONS

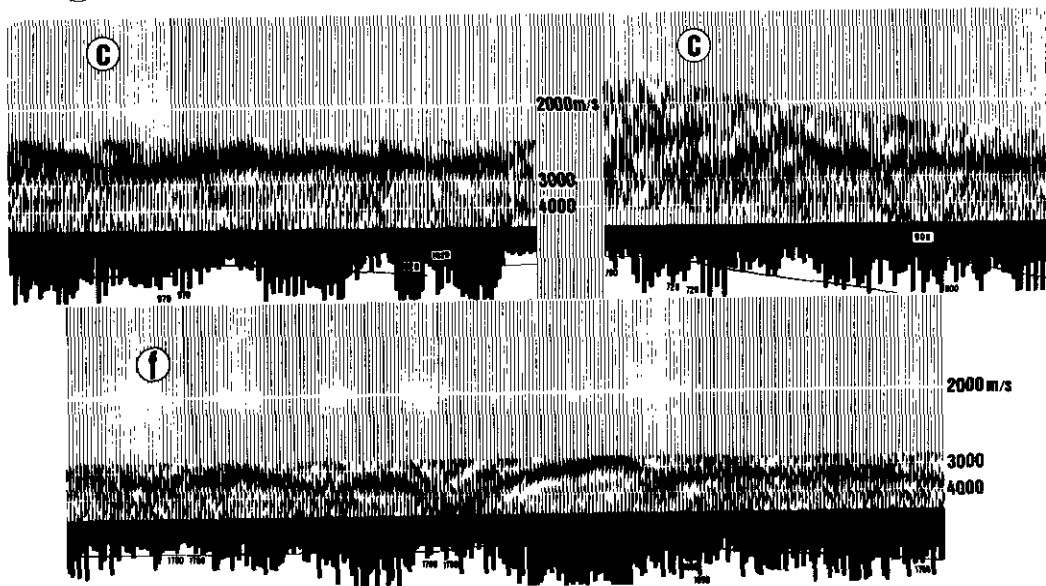


Fig. 14. Velocity horizons along events "C" and "f" of the sections shown on Figure 13.

③ MIGRATED DEPTH SECTION

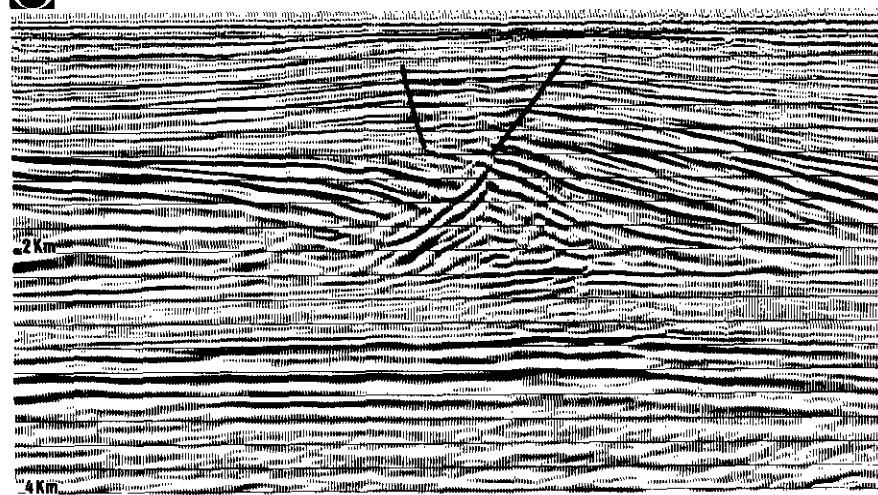


Fig. 15. Results of a depth migration process applied to the conventional section shown on Figure 13.

④ MODEL

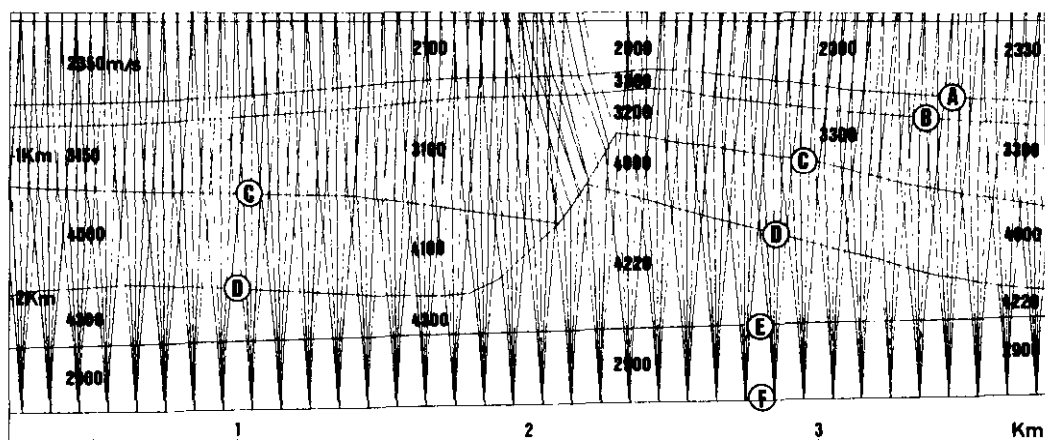


Fig. 16. The final model obtained by the interpreter after several iterations.

⑤ THEORETICAL TIME SECTION

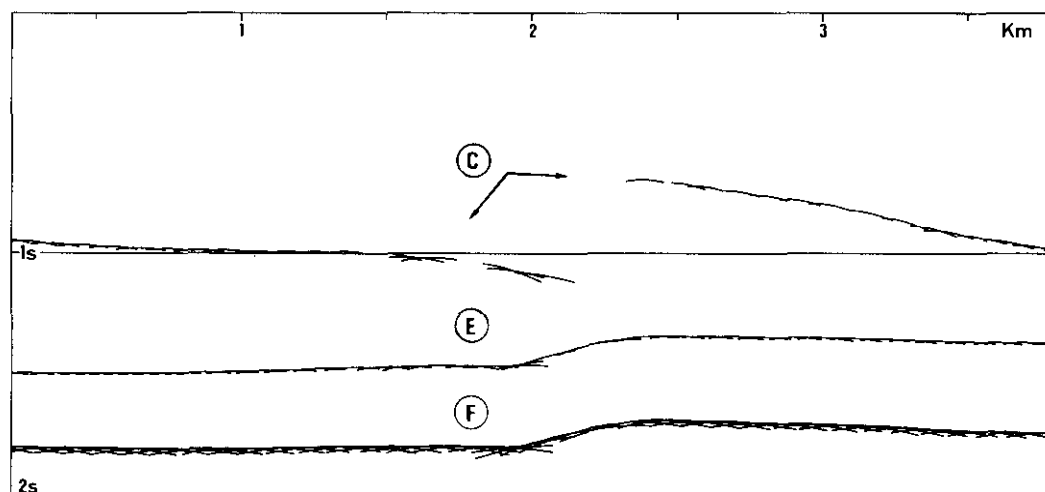


Fig. 17. Time response of the model shown on Figure 16.

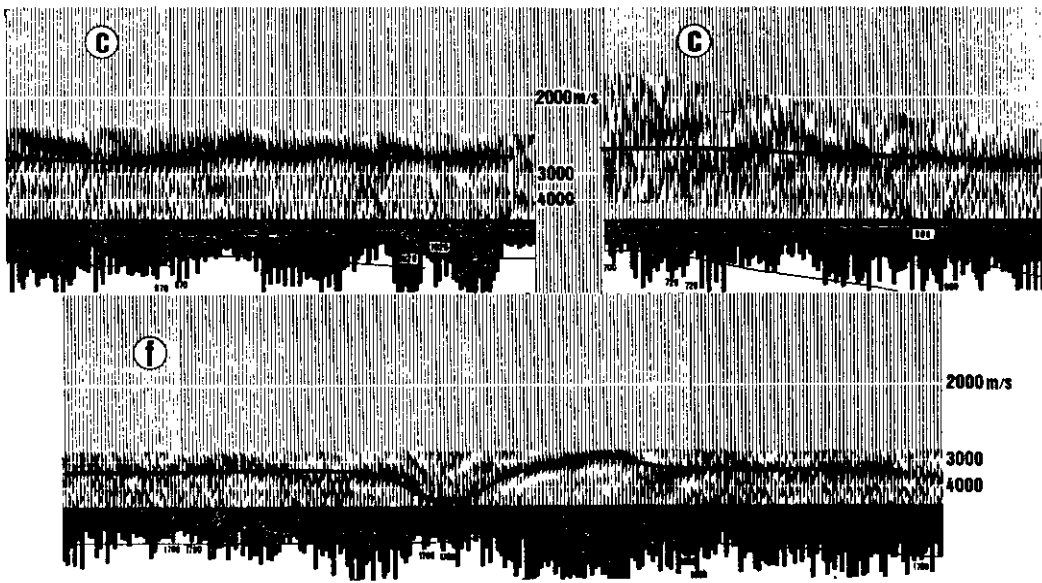

THEORETICAL STACKING VELOCITY


Fig. 18. The black line indicates the velocity response of the model shown on Figure 16, superimposed on the actual velocity horizons as shown on Figure 14.

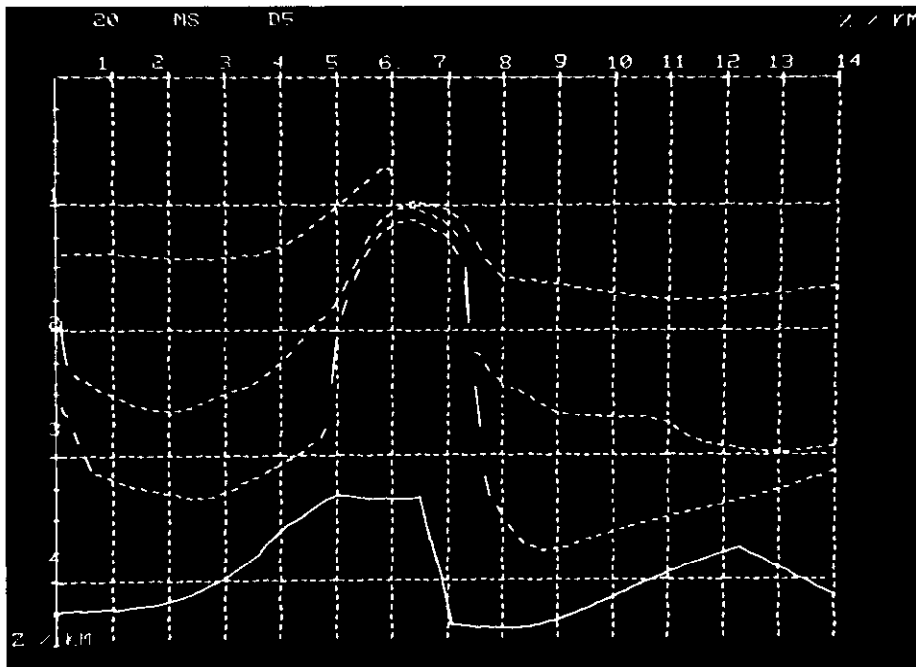


Fig. 19. Photograph of the CRT screen during interactive seismic modelling. The picture shows the model as built by the interpreter up to this stage. The solid lines representing the deepest horizon means that the interpreter is currently attempting to model that particular interface.

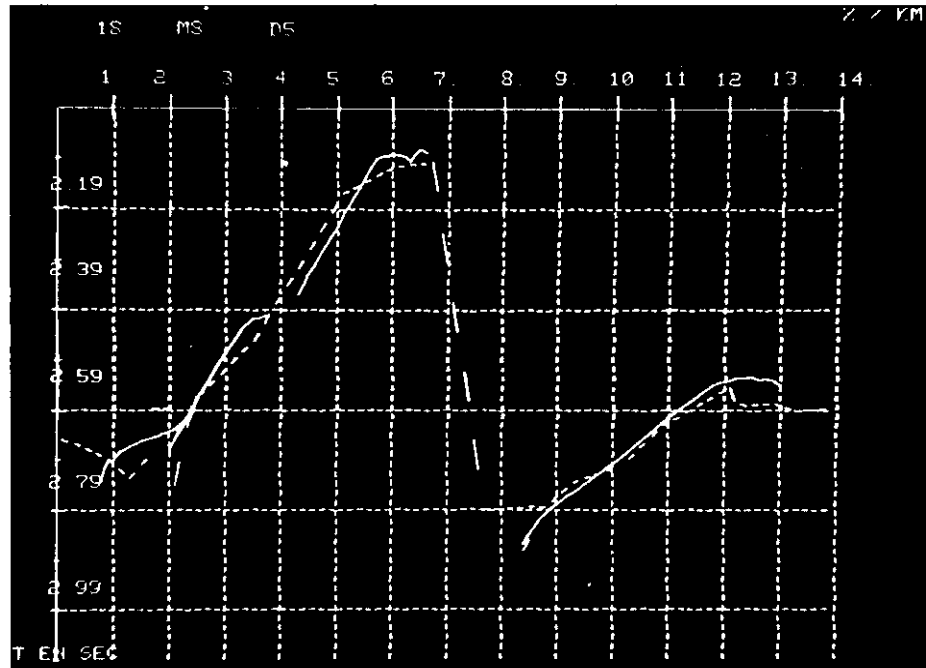


Fig. 20. Photograph of the CRT screen during interactive seismic modelling. The picture shows the time response (solid line) of the above model. The horizon section is shown as a dotted line.

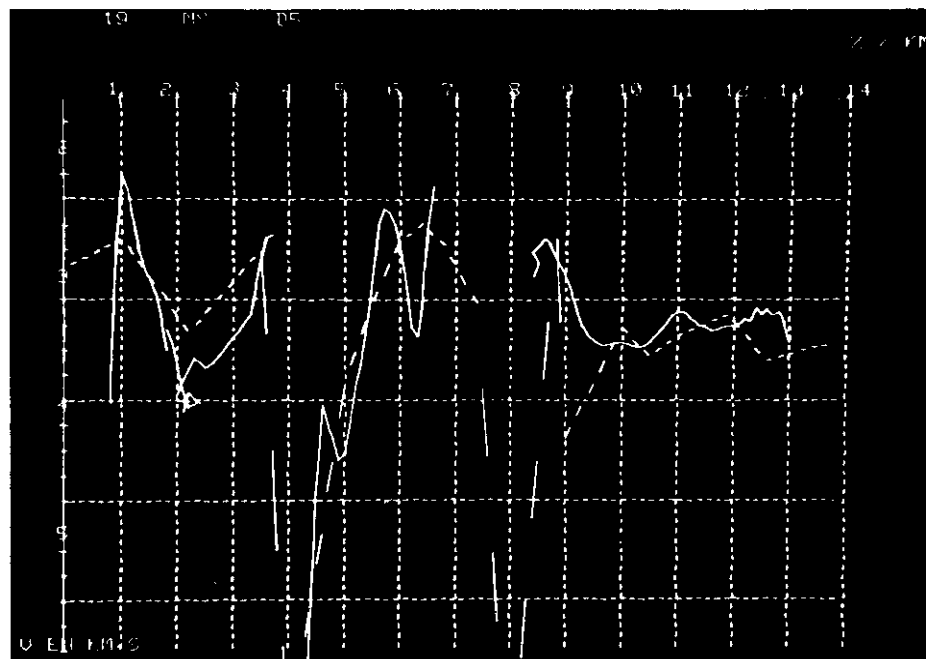


Fig. 21. Photograph of the CRT screen during interactive seismic modelling. The picture shows the velocity response (solid line) of the model shown on Fig. 19. The dotted line represents the velocity horizon obtained from the actual data by continuous velocity analysis.

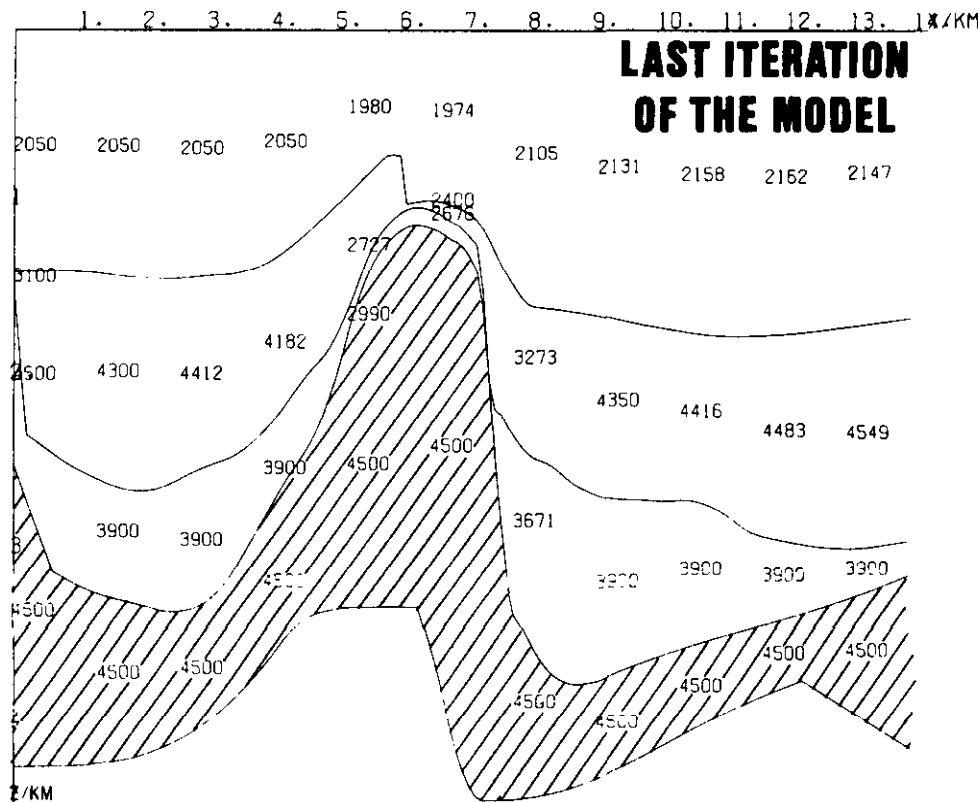


Fig. 22. The final model as obtained by the interpreter after several iterations.

INTERACTIVE MODELLING

Figures 19 through 22 give some idea of how seismic modelling can be performed in interactive mode. The interpreter uses a CRT screen to visualize either the model itself, or the corresponding time or velocity responses and their deviations from the actual observations selected as references. The three displays shown on Figures 19, 20 and 21 are actual photographs of the CRT screen. The first picture (Figure 19) corresponds to the model currently under investigation; all interfaces are indicated by dotted lines, except the one on which the interpreter is working, displayed as a solid line. The next two photographs (Figures 20 and 21) are the comparison between the responses of the model (solid lines) and the actual result as picked from the seismic section (dotted lines).

The agreement appears to be quite good both for the time response (Figure 20)

and for the velocity response (Figure 21). It is interesting to note at this stage that the variations of the stacking velocity along the horizon under investigation are large.

The interpreter can modify the model as many times as he may feel necessary and observe the effect of his modifications in terms of time and velocity. When he is satisfied that he has achieved a good fit between real and synthetic data, he may obtain a Calcomp output of the final model as shown in Figure 22.

CONCLUSION

Stacking velocities, as determined by velocity analysis programs, make it possible to complete stack sections even when true common reflection points cannot exist in the subsurface. Such stacking velocities may exhibit anomalies far beyond the variations which could be expected from lateral and/or vertical velocity changes.

This is due to the fact that routine velocity analysis programs assume horizontal bedding geometry with variable vertical velocity and consequently express travel path anomalies in terms of velocity functions. By simulating the same process on a seismic model, the interpreter may generate synthetic sections and synthetic velocity

horizons which will then be adjusted by successive steps until they fit closely with the field observations.

This approach can remove the effect of the seismic ray path geometry on the velocity determinations and yield a closer estimate of the actual interval velocities.