3D Seismic Surveys in Complex Sub-Surface Areas

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ABSTRACT : We have discussed the problems of designing a 3D seismic survey in complex subsurface areas. The various factors were examined in detail:

Geophysical Factors
Physical Influcences
Processing Considerations and
Budget Considerations.

The most important factors can be summarized as:

Acquisition – honor spatial continuity as much as possible.
Processing – build in the topography to NMO, PSTM and PSDM.
Budget – be prepared to spend some money!

There is nothing as expensive as a 3D that cannot be interpreted!

A 3D seismic acquisition survey in a complex sub-surface area is challenging. The most important factors that the designer must take into account may be grouped as follows:

GEOPHYSICAL FACTORS

Adequate fold (and hence S/N).
Frequency of signal available at the target.
Resolution.
Aperture (both individual shots and survey dimensions).
Spatial continuity of recording geometry.
Multiplicity of ray-paths.
Adequate offsets.

PHYSICAL INFLUCENCES

Access problems
Limitations on the design imposed by topography
Limitations imposed by other environmental factors such as weather, wildlife, security of personnel and equipment, etc.

PROCESSING CONSIDERATIONS

Once the data are collected, can the processor perform such processes as:

Noise removal (shot noise, multiples)?
Removal of near surface effects (statics)?
Analysis and application of velocity from topography (surface NMO)?
Successful imaging from topography– either by DMO plus post-stack migration,
pre-stack time migration (PSTM) or pre-stack depth migration (PSDM)?

BUDGET CONSIDERATIONS

And the biggest question of all – Can we design a 3D that deals with the factors above and still meets our budget?

Geometry plays a crucial role in dealing with each of these factors. In this paper, we will consider the types of geometries best suited to meeting the constraints imposed by each of the factors outlined above.

GEOPHYSICAL FACTORS

Adequate fold (and hence S/N)

Normally S/N may be specified prior to the 3D design. This is typically based on the needs of an interpreter to identify structure times – and amplitude anomalies which may help in identifying the presence (or absence!) of hydrocarbons. When nothing is known about the area a useful rule of thumb is to require that S/N=4. Any lower level on a final migrated stack will normally mean that the interpreter will have severe difficulties in identifying potential targets. Any higher level can be noted as an added bonus. Once S/N of typical raw data from the area can be established, the desired fold of the survey follows as a simple calculation:

$$\text{Fold} = (\text{S/N of final migrated stack} / \text{S/N of raw data})^2$$

Frequency of signal available at the target

If VSP's are available, they can be used to determine attenuation (Q factor). Otherwise some approximation must be made from geologic models and the constituent rock properties. In carbonate areas high values of Q should be expected – 300 or more. In areas of fast deposition (e.g. Gulf of Mexico, parts of Indonesia), values of Q are lower – typically around 200.

From the expected Q value, graphs (an example is shown in Figure 1) may be constructed showing available frequency vs time or depth. These are determined by taking into account spreading losses, transmission and reflection losses – and inelastic attenuation (Q). Once a signal has fallen to 110dB below its near surface amplitude, it can be considered lost, since the 24-bit recording system has a total dynamic range of only 138dB (signal is 5 bits or less than 30dB).

Resolution

Resolution is an attribute of the sub-surface. Basically it depends on the velocity of the over-burden and the frequency available at the target. Once the resolution available is calculated, the 3D designer has a choice: make the bin size equal to the horizontal resolution and therefore acquire the highest resolution survey that is possible – or make the bin size less than the available resolution and therefore discard information in the upgoing wavefield that describes the finer details of the sub-surface. Selecting a smaller than required bin size does not provide us with any additional information.

Aperture (both individual shots and survey dimensions)

Each shot creates a wavefield which travels into the sub-surface and is reflected upwards to be recorded at the surface. Each trace must be recorded for enough time so that reflections of interest from sub-surface points are captured – regardless of the distance from source to sub-surface point to receiver. Also, the survey itself should be spatially large enough so that all reflections of interest are captured within the recorded area(migration aperture) and for steep dips one has to expect to add significantly to the outline of the 3D survey area. For complex areas, this step may require extensive 3D modeling.

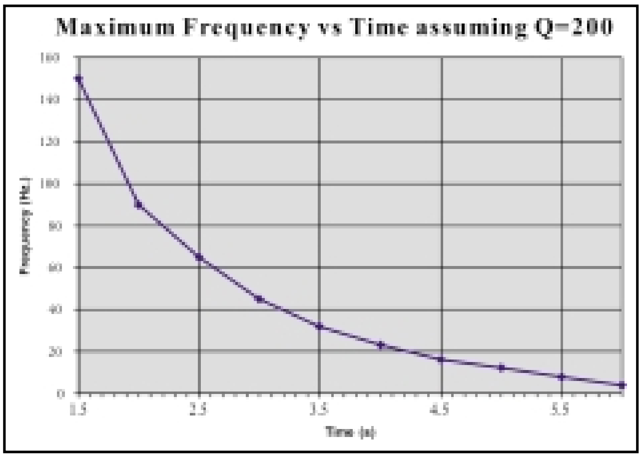

Figure 1

Figure 2 shows an example of a model built for a complex subsurface area. The section shown is an "in-line" display. The cross-lines showed the true three-dimensional nature of the model. Such models can be ray-traced to create synthetic 3D data volumes. The complex data resulting from such raytracing can be created with the correct times and amplitudes. This enables an investigator to observe the effects of processing – particularly PSDM from topography.

By such means, the degree of illumination on any chosen target can be determined. In complex sub-surface areas, ray-tracing like this can establish the "visibility" or otherwise of a target for any specified 3D acquisition geometry.

Spatial continuity of recording geometry

Because we measure wavefields in a spatially discrete fashion (created at shot positions and recorded at geophone positions), we must ensure strict mathematical spatial continuity, since we wish to reproduce these wavefields in all

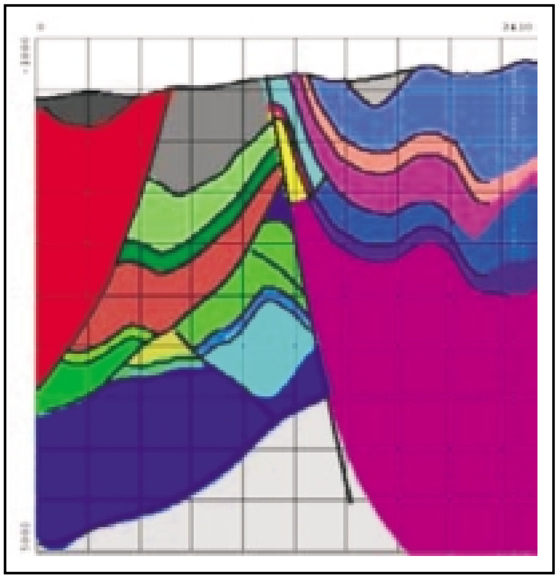

Figure 2

their complexity – for all wavelengths greater than the spatial Nyquist (alias). If this condition of strict spatial continuity is satisfied then the properly recorded wavefield may be used to reconstruct the subsurface reflectors to a degree of accuracy equal to the Nyquist wavelength.

This means that it does not matter how complicated the sub-surface is. From our properly sampled surface measurements we can reproduce every sub-surface wrinkle (up to Nyquist) so long as we have spatial continuity. So what can go wrong?

Shots and receivers are normally laid out in some form of orthogonal grid. The sampling interval along both the shot and receiver direction determines the spatial Nyquist wavelength. Any deviation from the spacing affects the spatial continuity. Thus, for example, deleting a shot introduces a break in spatial continuity. This will manifest itself in the final migrated section as an "edge" effect which will give rise to migration noise in the area of the missing shot (diffractions).

Great attention must be given to preserving spatial continuity. Thus where obstacles are encountered, the lines (shot or receiver) must be moved smoothly around them. Any sudden changes of direction will become an "edge" with the unfortunate added migration noise.

Multiplicity of ray-paths

The downgoing and upgoing wavefields can travel in very complex ways through the sub-surface. It is possible that some areas of the sub-surface may only be illuminated by portions of wavefields that have to travel great distances from source to receiver. As a result, some portions of the sub-surface may not be illuminated as well as other portions. To help with this problem the 3D designer must try to ensure that every sub-surface area of interest receives similar illumination. Extensive 3D modeling is necessary to investigate this illumination question.

Some raypaths in complex sub-surface areas can be troublesome. In Figure 3, an example of a raypath associated with so-called "prism waves" is shown. These waves exist in complex sub-surface areas and cannot be treated by any normal processing steps (NMO, PSTM, PSDM, etc.). Nonetheless the seismic record will contain such reflected energy – which will appear as noise after normal processing. The author is aware of some research in this area and there are migration codes that have been written to solve these very specific problems. However these migration codes require

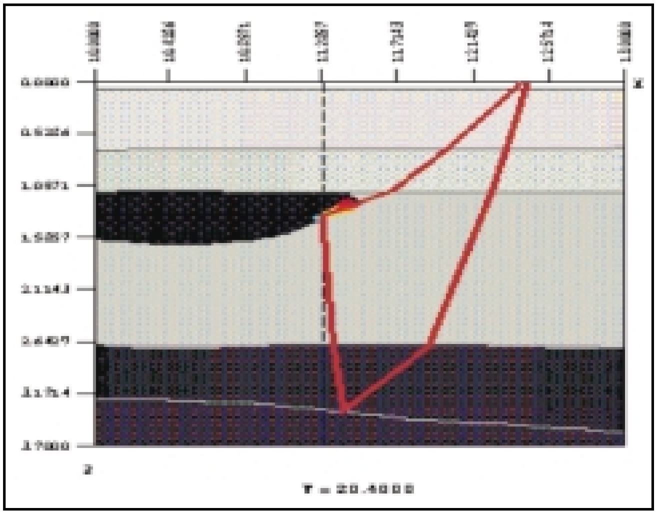

Figure 3

the velocity function corresponding to the "answer" before they will work – thus potentially limiting their usefulness.

Adequate offsets

Offset energy can serve two main purposes: firstly we use offset traces to help in determining subsurface velocity. Because the source energy travels to a far offset trace by a longer path than a near offset trace, we can examine migrated stacked images (PSTM or PSDM) that have been created using different velocities. The image that is focused most sharply will tell us that the velocity we have used to correct both the near and far traces is correct. Figure 4 shows an example of such image analysis. The second purpose for offsets is when we use amplitude vs offset behavior as an indicator of hydrocarbons. In complex structures this can be enormously

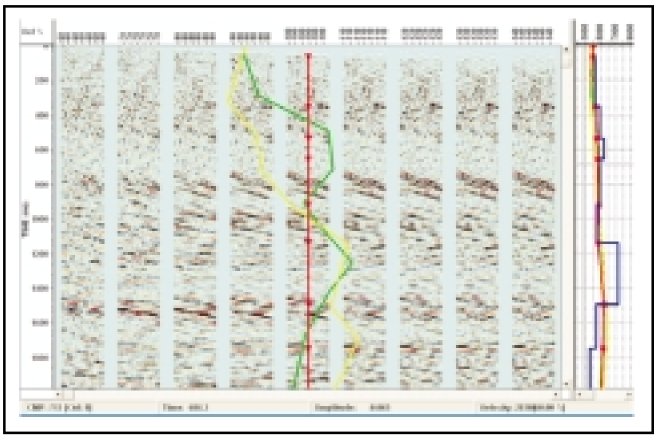

Figure 4

difficult – simply because the target of interest (a channel sand) may lie on a severely tilted bedding plane where all ideas of angle of reflection become chaotic.

PHYSICAL INFLUCENCES

Access problems

Limitations on the design imposed by topography

Limitations imposed by other environmental factors such as weather, wildlife, security of personnel and equipment, etc.

The 3D designer must do the best job possible to avoid introducing any spatial discontinuity to the basic design. The physical influcences above will clearly impose limitations on spatial continuity. The impacts of those factors should be minimized in order for us to be able to deliver the best image possible. Some migration modeling can show the designer the expected effects of severe shot and/or receiver movements.

PROCESSING CONSIDERATIONS

Noise removal (shot noise, multiples)?

Here is a brief list of the various types of noise:

Linear shot noise

This includes air blast, ground roll and other near surface waves traveling horizontally from shot to receiver.

Backscattered shot noise

Near surface scatterers can cause each of the linear noise waves to be reflected. Thus the waves travel by a path from shot to scatterer to receiver. Backscatter can often be the single largest noise component in recorded seismic data.

Multiple energy

surface and interbedded

The nature of offset distribution and azimuth distribution and how they change with depth is crucial in studying the noise problem. On the question of noise attenuation algorithms, the jury is still out. New processing algorithms often appear to make a substantial difference to individual shots (or receiver line components of shots). But the CMP stacks with and without the noise removal algorithm often look distressingly similar, leading to the conclusion that CMP stacking is still the best weapon in the antinoise armory.

Removal of near surface effects (statics)?

Delays in travel times caused by near (or even far) surface anomalies can be a source of noise. The simple perspective is that if such static delays cannot be removed they will diminish the signal content. 3D geometries differ in their ability to resolve 3D static delays. A useful rule of thumb is that the recording patch itself must be large enough to span any expected static anomaly. If a near surface static anomaly is larger than the recording patch it will be virtually impossible to remove in conventional processing.

Analysis and application of velocity from topography (surface NMO)?

In complex sub-surface areas, the surface topography is often highly variable. There can be very large elevation changes between shots and receivers. In such cases, the normal methods for dealing with such problems (floating datum etc.) can not be used reliably. Instead other methods should be used which honor the different paths from shot to subsurface and from sub-surface to receiver.

Successful imaging from topography– either by DMO plus post-stack migration, prestack time migration (PSTM) or pre-stack depth migration (PSDM)?

Aperture is crucial – both the aperture recorded by single shots and that of entire surveys. And multiplicity of ray-paths is also crucial. Some conclusions are clear. First that resolution varies throughout a survey – becoming larger near the edges and near the end of recording time (in this context, larger resolution means less ability to distinguish two adjacent sub-surface features). Second, that the size of a bin can determine resolution because of anti-alias criteria. Thus large bins set the limit on resolution and therefore on the maximum useful frequency. To put it another way, additional high frequencies have no effect on resolution when it is set by the bin size.

The debate about combining individual shots – or components of shots (e.g. offsets) to form a complete pre-stack time migrated volume is the subject of much current work. Vermeer (SEG Convention, 2000) showed how common offset vector tiles (formed from symmetrically sampled orthogonal geometry) could be used to create a continuous migrated volume with minimal “edges”. The answer to the same question for other geometries is still unresolved.

Just as NMO must be modified to take account of severe topography, so any imaging algorithm must also be modified to account for the different source and receiver raypaths.

Imaging in the early days was all done post stack – typically through 3D Kirchhoff or FK migration. Later, other post-stack methods were added to the arsenal – Finite difference, Phase Shift and other more exotic variants. Post-stack depth migration has also made an appearance over the years.

In the pre-stack domain, DMO has been the algorithm of choice for many years (and still is in many parts of the world). Recently many practitioners have noted that geometry can dramatically affect the output of DMO. In particular, wide towed marine streamer data (multi-source, multi-streamer) after DMO had a very striped appearance. This was also predictable from theory and has been remarked on by a number of authors. In the past few years there has been a decline in the use of DMO.

Recently there has been an ever increasing emphasis on pre-stack time migration and prestack depth migration. An improvement of the focusing of the seismic reflector image is achieved by being able to determine the velocity better. In some areas of the world, like e.g. the Gulf of Mexico, other geophysical methods are supporting the efforts of the seismic industry to derive the geological model.

BUDGET CONSIDERATIONS

The primary goal of any 3D is to achieve the desired S/N at the target! In complex areas, feasibility studies are routinely done to establish suitable parameters of a 3D seismic survey and calculate an initial budget.

To ensure the best image, the best sampling method that can be used to recreate the various spatial wavelengths in X, Y and Z must be chosen. Vermeer has published a compendium on this approach and it involves symmetric sampling – whatever is done to shots must also be done for receivers.

Noise attenuation may be just as important as recording the signal. The “best” geometry is the one that addresses the specific local problems of improving signal at a chosen target, while identifying and reducing the various sources of noise. It is worth remembering that if the CMP stack for one geometry attenuates the noise by 6dB when compared to the CMP stack for another geometry, the fold has been effectively quadrupled. This can have a dramatic effect on the budget!

Today’s best geometries for noise attenuation seem to be wide azimuth slanted geometries with 18 degrees often emerging as the winning angle. The small departure from orthogonal (18 degrees instead of zero) does not dramatically affect the imaging properties.

For noise reduction (both linear, backscatter and multiples), many authors have noted that wide azimuth surveys will be better than narrow – simply because of the preponderance of long offsets. Other factors like unequal shot and receiver line spacing and slanted lines are currently under investigation.

Arrays are also making a comeback. Since 2D gave way to 3D, arrays have been largely ignored. All too often bunched phones and single holes have been the norm. Recently many acquisition geophysicists have made attempts to reduce linear and backscatter noise before it reaches the recorder. While there is no shortage of anecdotal knowledge, there is still a lack of broadly based experiential knowledge about the use of arrays in 3D.

We must also remember that arrays play a crucial role in wavefield filtering and resampling to the group interval. In the absence of a geophone array, the wavefield samples collected at each surface station (group) will be aliased for all wavelengths less than the group interval. The geophone array will essentially “filter” the wavefield prior to sampling and remove this spatially aliased energy.