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Depth Imaging in Deep Waters: A Case History

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Abstract

The paper outlines the methodological approach followed to solve a complex problem of depth imaging in the Nile Delta, offshore Egypt. The original time image was thought as being distorted not only by sea bottom variations (from few hundred to a thousand meters) but also by the presence of large scale (thick Pleistocenic sequence at high velocity) and smaller scale velocity anomalies (low velocity shales and high velocity evaporites).

In the study area the possible target Miocene reservoirs lie below a thick sequence of Plio-Pleistocene sediments and are sealed by an evaporitic sequence of varying thickness. Moreover the Miocene sequences have low but almost uniform velocity, thus causing poor reflectivity and hence a poor signal-to-noise ratio.

An exploratory well (Well-1) did find an unexpected thick layer of relatively high velocity Pleistocene instead of prognosed low velocity Pliocene. This caused a complete rethinking of the depth conversion approach followed so far. It was decided to use the most up-to-date technologies, like Pre-Stack Depth Migration (PrSDM), to attack the problem. Since there were constraints either in term of budget and time, it was decided to use 2D PrSDM along 22 inlines to determine the velocity field and then perform a full 3D Post-Stack Depth Migration (PoSDM) of the entire volume. This would have allowed a good compromise in terms of cost - benefit ratio. The final depth volume showed quite clearly that a double culmination present in time turned out to be a single culmination, yet to be drilled. A strict integration between depth imagers and the geologists and geophysicists acquainted with the complex area proved to be one of the winning factor in the succesfull completion of the study together with the use of PrSDM tools in the construction of the velocity volume.

INTRODUCTION

The Nile Delta basin, which the study area belongs to, lies on the North external margin of the African Plate and is an important hydrocarbon province with a quite complex geological setting (M. Sarhan et al., 1996).

The Mesozoic and Early Cenozoic sequence shows in the deeper part shallow marine features turning to deep marine facies in the upper part. Open marine sediments were deposited during Early Oligocene, while the Late Oligocene is characterized by generalized eustatic sea level fall with a strong erosive phase, represented by a regional unconformity. During the Late Oligocene and the Earliest Miocene a marine environment was re-established. The sediments testify continental-nearshore conditions (Southward) and slope and deep marine environments (Northward).

The basin can be further divided into two parts, separated by a hinge zone: Southward a steady platform developed, while Northward, in the distal part, a subsident basin developed. Transgressive conditions persisted until the Middle Miocene uplift. Erosion (Serravallian-Tortonian unconformity) and low-stand turbidites deposition took place in the Serravallian. The Tortonian is characterized by a relative sea level rise.

The end of the Miocene is marked by a general sea level fall, with fluvio-deltaic sediments and by the typical Upper Messinian evaporitic deposition in the basinal part of the area.

Starting from Early Pliocene, open marine condition were re-established. The high subsidence and the strong Nile River sedimentation led to the presence of a very thick Plio-Pleistocenic sequence in the distal part of the basin. The contemporary presence of basal plastic levels (evaporites and shales in overpressure condition) led to important gravitative movements and to the development of syn-depositional structural features.

In the basin it is possible to distinguish several tectonic phases linked to the Neo-Tethyan opening (Early Triassic to Early Jurassic) and closing (Late Cretaceous to Late Eocene) and to the stages of the Suez Rifting development from Late Eocene.

The study area is located in the Northern part of the basin, where a very thick Pliocene-Pleistocene sequence overlies the Messinian evaporitic complex (Rosetta Fm.) and the Miocene sequence. This part of the basin is located beyond the regional hinge line; because of this reason, in the study area the Pre Miocenic horizons, main targets of the hydrocarbon exploration, lay at remarkable depths.

From the seismic standpoint, the imaging of the subsurface is made difficult by the complexity of the structural scenario. The Pliocene-Pleistocene sequence is characterized, in the study area, by widespread growth geometries and listric faults, starting from the evaporitic complex. During this period the sedimentation rate was very high: the Well-1 did not find any Pliocene, proving the Pleistocene to be more than 2 kilometers. Gas accumulations, marked by amplitude anomalies, are known to exist. This section with its dense faulting, rapid lateral variations in lithology and the frequent steep dips of the geological formations, causes strong distortion of the ray paths and frequent lateral variations of the velocity.

The Messinian evaporites with their high velocity and their irregular shape cause scattering and absorption of the seismic energy which cover the underlying sequences. The Miocene section, where the target horizons are located, has itself a complex framework with high dips and faults which certainly complicate the ray paths. Moreover, in this section the seismic velocity is generally low with almost no vertical contrasts, thus causing an overall poor reflectivity. In the study area the Pre-Messinian sequence shows indeed a simple structural framework, characterized by the presence of a structural high with a double culmination in the time domain (fig. 1).

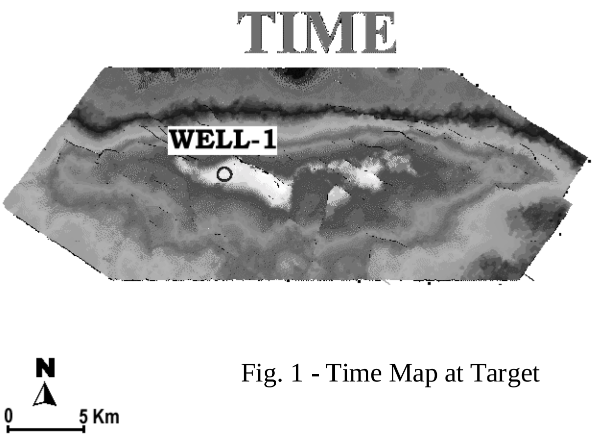

Fig. 1 - Time Map at Target

After the drilling of Well-1 and its unexpected results it was clear that the depth image of the structure still remained questionable. The solution to this problem was thought to be a 3d Post-Stack Depth Migration (PoSDM) of the whole 3d seismic volume, roughly 750 kmsq that could take care of both the focusing and depth imaging problems. These two tasks required necessarily the best possible velocity volume that was obtained via a Pre-Stack Depth Migration (PrSDM) of 22 inlines, treated as 2d lines.

VELOCITY ANALYSIS SEQUENCE

3D Post Stack Depth Migration (3D PoSDM), commonly applied in imaging beneath complex structures, was performed in order to get a reliable image of the subsurface. The process required the definition of a correct Migration Velocity Volume. The creation of the velocity and depth migrated volumes developed simultaneously and in an iterative manner from the shallowest to the deepest portions of both volumes (L. Pizzaferri et al., 1998).

At the beginning of the process the velocity of the shallowest reflector was analysed along the 22 in-lines applying 2D Pre Stack Depth Migration (2D PrSDM) techniques, both Migration Velocity Analysis and Reflection Tomography in depth were applied. Subsequently, the velocity field was laterally harmonised using geostatistical tools and the velocity map for the relevant reflector was built. The velocity map was then extended to the half space below it and, after running the 3D PoSDM iteration, the horizons were directly interpreted in depth. Finally, the 3D depth interpretation was extracted along the 22 velocity lines and was imported in the 2D Pre Stack Velocity Study Project.

The same process started again and it was performed layer by layer for the 8 selected reflectors, moving from the 2D Pre Stack Velocity Study to Geostatistics and to the 3D PoSDM iteration. At that point the whole volume was filled with geometries and velocities and the final 3D PoSDM could be performed.

The velocity analysis was performed along 8 horizons that were selected for their geophysical (good seismic response) and geological significance: Sea Bottom; Two geophysical horizons (Vertical Gradient 0.39 sec^{-1} and 0.3 sec^{-1} respectively); Possible Plio-Pleistocene Interface (Vertical Gradient 0.5 sec^{-1}); Top and Bottom of the Evaporitic Complex; Tortonian-Serravallian Unconformity; Top Qantara Fm.

The two geophysical markers (Horizons 1, 2) were chosen to better define the velocity fields in the shallowest parts of the seismic. Moreover, it was used a vertical gradient in the velocity field determination of the overburden to take into account compaction. Their geometry, that clearly showed a general shape similar to the sea bottom, was characterised by the presence of a structural low, marked by normal faults.

In the zone tested by the Well-1 the Post-Messinian section was entirely represented by Middle to Upper Pleistocene, because of the intense subsidence inside a wide trough, bounded by listric faults, where the Pliocene is absent. The third horizon corresponded then in large part to the tangle of the growth faults surfaces, that are often very well defined. On the shoulders of the huge trough this interface had no well tie and must be merely considered as a geophysical horizon. The integration between the velocity study and the seismic interpretation in depth led to better define the surface and helped to identify some low velocity bodies.

The Top of the Evaporites was quite well defined and normally rather easy to be identified because of the strong acoustic impedance contrast between the Plio-Pleistocene clastic sequence and the Messinian evaporites. No interval velocity analysis was performed along the Bottom of Evaporitic Complex owing to the thin TWT thickness (average value less than 100 msec) of the evaporitic layer. A constant value (3670 m/s) was chosen, consistent with the well data of surrounding areas.

The interval velocities of Messinian targets were mainly derived from well data and checked with the geophysical tools, partly because their depth were greater of the maximum offset of the seismic data.

For each of the three shallowest horizons the vertical gradient was laterally constant and was computed from the Sonic Log acquired in the Well 1.

A preliminary velocity model was computed from stacking velocities through the Dix formula and was used as input to the first Kirchhoff 2D-PrSDM iteration. Afterwards, reflectors were directly interpreted in the depth domain since the following Residual Horizon Velocity Analysis (RHVA or Depth Delay) was focused on the relevant reflector.

Depth Delay sections along the horizons were computed in order to analyse how the reflectors were flattened in the CRP domain. Depth Delays showed, for each CRP gather along the seismic section, the maximum reflector depth difference between the first and last offset. The Depth Delay sections were interpreted and then the velocities were updated in order to flatten the reflector that showed the picked delays. Although the Depth Delay section is a powerful tool, (f.i. the analysis is performed continuously along the horizon) it was interpreted with care and monitoring the CRP gathers.

After updating the velocity a new model was computed, a new 2D-PrSDM iteration was run and a new Depth Delay section was computed as well. This allowed to check the results of the previous velocity corrections (in term of better reflector flattening). If the improvements were considered satisfactory then the analysis along the relevant horizon would have stopped; otherwise a new velocity update of the same horizon would have been carried out.

Moreover, due to the high structural complexity, the velocities were also updated following a tomographic approach in the depth domain. This approach had the great advantage to take into consideration, during the updating process, the complete model instead of the relevant reflectors only.

The picked delays along the Depth Delay sections were automatically transformed into travel time difference (Δt) between the true and the actual travel times (calculated by CRP ray tracing on the preliminary velocity model). An inversion algorithm refined the slowness (inverse of velocity) in order to minimise Δt using the standard formulation of reflection tomography (C. Stork, 1992). Velocities were then updated according to the tomographic corrections.

GEOSTATISTICS AND VELOCITY VOLUME

After having computed the final Initial velocity (V_0) distributions along the 22 in-lines, the velocity fields were spatially harmonised following an approach based on kriging estimation. The geostatistical tool GEOVEL (Eni-Agip Division proprietary software) was used (P. Ruffo et al., 1997). Kriging is a methodology to estimate the value of a variable at non-sampled locations based on a weighted average of a small set of nearby known control points. First, the experimental variogram of the data distribution (that describes the spatial correlation among the data) was automatically computed. Then, the experimental variogram was fitted with a model function. This function was then used to calculate the weights to be given to the input data in the kriging estimation.

The kriging estimation was performed on a lattice with a 500 meters grid interval (250 m for the layer between Horizon 3 and the Top of Evaporitic Complex in order to preserve the widespread local anomalies). The final grids were used to create the velocity maps that were input, as half space velocity, to the 3D PoSDM iterations.

Eventually all velocity maps and depth interpretation wera assembled to prepare the velocity volume (fig. 2) used for the final 3D PoSDM. All 3D PoSDM iterations ran on a 24 nodes machine (massive parallel processing mode) using a Phase Shift Plus Correction algorithm (5-60 Hz frequency range).

The input 3D Stack Volume consisted of $2.3 \ast 10^6$ live traces (2885 cross-lines by 1062 in-lines, 4 ms sample rate and 1625 samples per trace), covered an area of 750 sqkm. The final 3D PoSDM iteration down to a total depth of 6500 m (depth sample 5 m) took about 6 days of elapsed time to be completed.

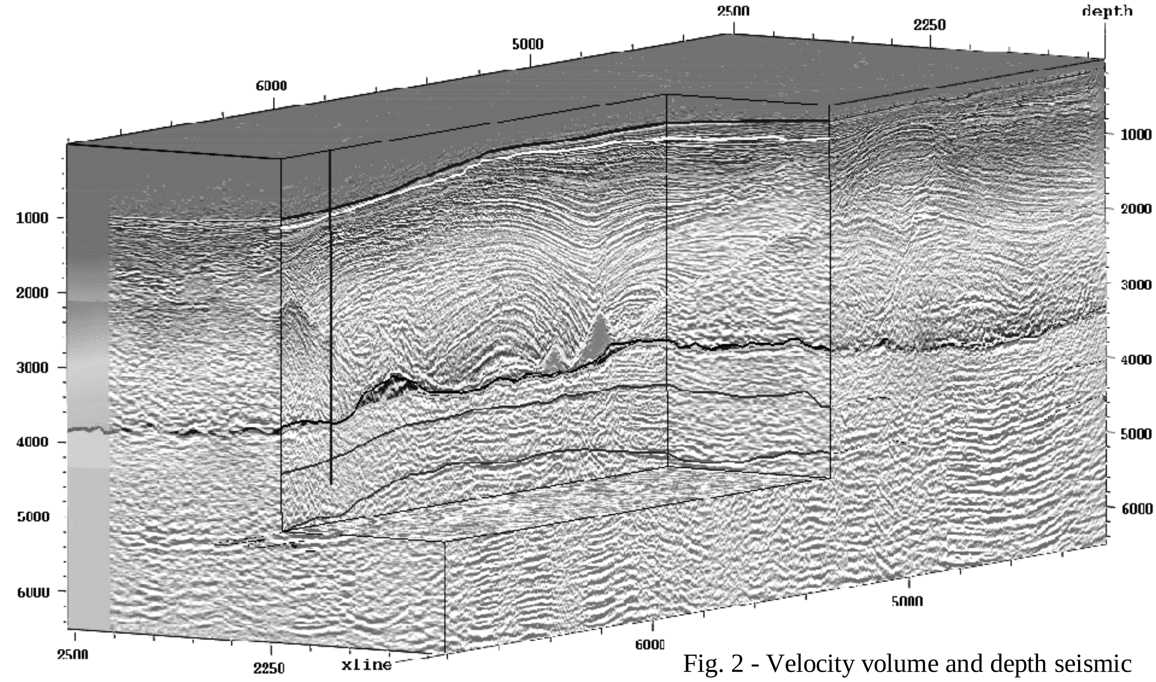

Fig. 2 - Velocity volume and depth seismic

DEPTH INTERPRETATION

The 2D PrSDM Velocity Study highlighted three main features: at a large scale the deep waters (sea bottom ranging from 300 m to 1000 m), the existence of localised high velocity anomaly related to a thick Pleistocenic succession that filled a huge through and whose geometry is now defined in detail; at a local scale the presence of both low and high velocity bodies, related to squeezing phenomena that affected the Pliocenic sediments and the Messinian evaporites; the existence of a rather homogeneous velocity fields in the pre-evaporitic stratigraphic sequence.

The velocity anomalies that were detected in the overburden (at large scale due to the deep waters and the Pleistocenic sequence and locally due to low velocity bodies) affected the real geometry of the deepest surfaces to be defined: the Serravallian-Tortonian Unconformity and the Near Top of Qantara Fm (fig. 3). Their shapes showed, in the time domain, a double culmination that turned to be a single one in depth (cfr. fig. 3 with fig. 1). Most pull-down effects were removed also in the deeper part of the. Wherever the Top of the Evaporitic Complex showed an evident hump it was decided to interpret a flat Bottom of the Evaporitic Complex. This choice was supported by the results of various 3D PoSDM test performed both with a constant evaporitic layer and with small diapiric bodies; the pull up effects evident in the former model disappeared in the latter.

The outlined characteristics of the velocity fields had a great influence on the real shape of the deepest reflectors: the double structural high that was present in time turned out to be a single one in depth while the pull-down effects were almost completely solved.

The structural model, that is consistent with the geometries defined in depth, was interpreted as the result of a sequence of events that developed from the Pre-Messinian in the study area.

The final depth migrated volume was not calibrated to the Well-1 since the error in depth between seismic and well data was about 50 m (2%). This result can be considered impressive since the scientific literature would credit similar studies with a possible error of 5-6%, considering the depth of the target, the maximum offset and the wavelength of the target itself (O. Uzcategui, 1997).

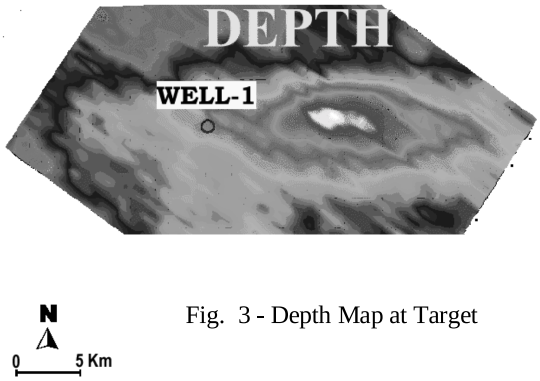

Fig. 3 - Depth Map at Target

CONCLUSIONS

The construction of the Velocity Volume using Pre-Stack depth Migration tools and the complete 3D PoSDM of the time Volume turned out to be a successful strategy in order to get a reliable image of the subsurface in the study area. Although both the detected large scale and the local velocity anomalies were located in the upper stratigraphic sequence, they had a great impact on the real geometry of the deepest reflectors as compared with the time image. First, the double structural closure, that was evident in time, turned out to be a single one in depth, Eastward from the location of the original Well-1. Besides, the pull-down phenomena almost disappeared in depth.

Furthermore, the general improvement of the depth image led to the detection of possible prospectable levels in the pre-evaporitic stratigraphic sequence.

These results confirmed the importance of a detailed definition of both velocities and geometries in the overburden in order to get a realistic image of the deepest portion of the volume. The successful tools applied in the study were the horizon based pre stack velocity analysis, the tomographic approach, the choice of a vertical gradient, the lateral harmonisation of the velocity fields with geostatistics and the definition of a consistent structural model of the overburden.

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