Subsalt Depth Imaging Using 3-D VSP Technique in the Ras El Ush Field, Gulf of Suez, Egypt

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ABSTRACT

In 1995 oil was discovered in the pre-Miocene Matulla and Nubia Sandstones in the Ras El Ush field, Gulf of Suez, Egypt. The discovery was based on an aeromagnetic anomaly from a basement high. After drilling several delineation wells, based on a geological model, it became evident that the field is very complex as it is broken into tilted and rotated compartmental blocks by two perpendicular fault systems. Also the 2-D seismic data were of poor quality beneath the thick Miocene South Gharib Evaporite. Since part of the field lies below shallow-water, 3-D seismic was considered to be too costly. When a delineation well did not encounter the reservoir, due to an unanticipated fault, a 2-D walkaway Vertical Seismic Profile (VSP) was acquired. It clearly revealed the presence of a cross fault. The success of the 2-D VSP in imaging the fault led to the acquisition of the first Middle East 3-D VSP survey in the following well. A downhole, tri-axial, five geophone array tool was used to acquire the 3-D VSP. The 3-D volume of the final migrated VSP data provided the means for the reliable mapping of horizons beneath the South Gharib Evaporite. These maps improved the definition of the field and helped detect previously unrecognized prospective blocks. Four further successful delineation wells confirmed the 3-D VSP interpretation.

INTRODUCTION

The Ras El Ush (REU) field was discovered in 1995 in the petroliferous Egyptian Gulf of Suez (Figure 1). This complex, fault-bounded, structural trap was first suggested by outcrop geology and subsequently delineated from an aeromagnetic anomaly which corresponds to a basement high. Shortly after its discovery, the offshore REU field was delineated with five deviated wells which were drilled from onshore. These wells indicate that the reservoir occurs in a rotated block, bounded by normal and strike-slip cross faults. Delineation well REU-5 missed the reservoir entirely due to fault complexity, and this led to a re-evaluation of the development drilling strategy.

Seismic 2-D imaging in the Gulf of Suez, as in the case of the REU field area, is hampered by the thick Miocene South Gharib Formation (Figure 2). This formation consists of a thick sequence of evaporites interbedded with thin clastics, which produce severe multiples that mask the reflections from the underlying reservoirs. As part of the REU field extends into shallow-water, 3-D surface seismic was considered to be too costly.

In some areas, 2-D Vertical Seismic Profiles (VSP) can resolve reservoir geometries near the wellbore (Christie and Dangerfield, 1987; Badri et al., 1997). Therefore, a 2-D walkaway VSP was acquired in one of the REU wells and it clearly imaged a cross fault. This led to the acquisition of a 3-D VSP in the following development well which was the first 3-D VSP survey acquired in the Middle East. This paper describes how the 3-D VSP survey was acquired, processed and interpreted.

RAS EL USH FIELD BEFORE 3-D VSP

The reservoir zones in the REU field are approximately 1,000 meters (m) deep and occur in the Cretaceous Malha and Matulla formations. The average thickness of the Matulla Formation encountered
Figure 1: Ras El Ush field is located in the southeastern part of the Gulf of Suez, Egypt. Several development wells were drilled from onshore before the 3-D VSP was acquired. Note REU-5 missed the productive reservoir.
| STAGES          | ROCK UNITS            | LITHOLOGY | THICKNESS MAX (Feet) |
|-----------------|-----------------------|-----------|----------------------|
| PLEISTOCENE-    | POST MIocene          |           | 4,000                |
| QUATERNARY      |                       |           |                      |
|                 |                       |           |                      |
| MIOCENE         |                       |           |                      |
|                 | Upper                 |           |                      |
|                 | South Gharib          |           | 2,300                |
|                 | Hammam-Farun          |           |                      |
|                 | Middle                |           |                      |
|                 | Feiran                |           | 1,400                |
|                 | Shagar                |           | 1,000                |
|                 | Baba                  |           |                      |
|                 | Rahmi                 |           |                      |
|                 | Asl/Ayun              |           |                      |
|                 | Yusr                  |           | 2,500                |
|                 | Bakr                  |           |                      |
|                 | Khoshera              |           |                      |
|                 | Sudr                  |           | 1,200                |
|                 | Nebwi                 |           |                      |
|                 | Ras Matarma           |           |                      |
| OLIGOCENE       |                       |           |                      |
|                 | Abu Zenima            |           | 450                  |
|                 | Tayiba Beds           |           |                      |
| EOCENE          |                       |           |                      |
|                 | Upper                 |           |                      |
|                 | Tanka Beds            |           | 1,400                |
|                 | Gypseous Marl         |           |                      |
|                 | Green Beds            |           |                      |
|                 | Caroita Series       |           |                      |
|                 | Eocene Limestone      |           | 2,000                |
|                 | Thebes                |           | 1,400                |
| PALEOCENE       |                       |           |                      |
|                 | ESNA                  |           | 300                  |
|                 | Oweina                |           |                      |
|                 | Sharwuna              |           |                      |
| CRETACEOUS      |                       |           |                      |
|                 | Upper Senonian        |           |                      |
|                 | SUDR                  |           | 1,000                |
|                 | Chalk                 |           |                      |
|                 | Brown Limestones      |           |                      |
|                 | L. Senonian           |           | 400                  |
|                 | Turonian              |           | 250                  |
|                 | Cenomanian            |           | 85                   |
|                 | Abu Qada              |           | 500                  |
|                     | Nubia 'A'             |           | 575                  |
|                     | Nubia 'B'             |           | 825                  |
|                     | Nubia 'C'             |           | 2,000                |
|                     | Basement              |           |                      |

Figure 2: Stratigraphy and petroleum systems of the Gulf of Suez (Egyptian General Petroleum Corporation, 1996). Flags indicate source rock and green dots reservoirs.
Figure 3: Geological cross-section showing the structural and stratigraphic complexity across the Ras El Ush field (see A-A' in Figure 1 for location).
in the drilled wells is about 100 m (true stratigraphic thickness, TST) with average porosity of 22% and water saturation 42.5%. The depositional environment of the Matulla Sandstone is interpreted as tidal.

The Nubia Sandstone Member of the Malha Formation encountered in the wells is about 350 m (140 m TST). In the REU field the porosity of the Nubia Reservoir is about 18% with water saturation of about 24%. The depositional environment of the Nubia Sandstone is interpreted as fluvial.

Based on dipmeter, borehole seismic, and drilling data from the delineation wells, a geological model was derived for the REU field (Figure 3). The reservoir is broken into compartmental blocks with normal faults trending northwest-southeast, parallel to the Gulf of Suez. A major northwest-southeast trending normal fault seals the reservoir with the South Gharib Evaporite to the northeast (Figure 3). Down-hole dipmeter measurements indicated that the Nubia Sandstone dips at approximately 42° to the southwest and strikes northwest (Figure 3).

The 2-D seismic data are of limited use for mapping the sub-evaporite reservoirs. Figures 4a and 4b show examples of 48-fold, 2-D surface seismic sections, acquired in 1985, along the dip and strike.

Figure 4a: 2-D seismic dip line, acquired in 1985, shows the imaging problems beneath the South Gharib Evaporite. The location of the line is shown in Figure 1. The data was acquired with high pressure air guns and 96 receiver groups (48 channels). Source and receiver group interval is 12.5 meters.
Figure 4b: 2-D seismic strike line, acquired in 1985, shows the imaging problems beneath the South Gharib Evaporite. The location of the line is shown in Figure 1. (1) Top Matulla Formation (2) Top Nubia Formation. Data acquisition parameters as in Figure 4a.
The data quality generally improves eastwards where the water is deeper. Although the South Gharib Evaporite is adequately imaged, the sub-evaporite reservoir shows no clear reflectivity.

Figure 5 shows a structure contour map of the top Nubia Sandstone reservoir derived from 2-D surface seismic and well data before the acquisition of the 3-D VSP. Two major faults trending NE-SW and two more NW-SE sub-parallel normal faults constitute the boundaries of the field.
3-D VSP TECHNIQUE

3-D VSPs have generally proven to be effective where 3-D surface seismic data interpretation has limitations (Dangerfield, 1992). To determine whether faults in the vicinity of the REU wells are better imaged with a 2-D or a 3-D VSP, ray tracing was performed for several source lines and various receiver depth positions.

The 2-D velocity models were based on well measurements and tested for sensitivity to velocity variations of ± 10%. The dip of the sub-evaporite target was 42°. Several source-receiver geometries were considered to determine the survey parameters that would adequately delineate the faults. Source far-offsets in the updip, downdip and strike directions were taken into consideration in terms of incidence angles at the target level.

After a detailed analysis, it was concluded that simple 2-D VSP configurations would not achieve the objective in this complex structural setting. 3-D modeling supported the requirement for a 3-D VSP survey. This is due to the high-velocity evaporite layer and the complex geometry of compartmented blocks.

3-D VSP ACQUISITION

A tri-axial downhole seismic array tool was used to acquire the 3-D VSP. The well was deviated by approximately 60° in a northeast direction and encountered steeply-dipping pre-Miocene beds to the southwest with an angle of about 42°. Twenty parallel Walkaway VSP profiles were acquired using a cluster airgun source mounted on a special triangular frame. The cluster consisted of three 150 cubic inch guns pressured to 3,000 pounds per square inch (psi). Each profile was assigned a corresponding downhole receiver array position. Five downhole geophones were used with a spacing of 15 m. The distance from the wellbore to the target horizon varied with depth since the well was deviated.

Figure 6 shows the field acquisition configuration of the 3-D VSP survey. This geometry minimizes out-of-plane reflections (i.e. along the dip direction). Each walkaway acquisition profile was recorded

Figure 6: Acquisition procedure for the 3-D VSP survey in Ras El Ush field.
with the downhole geophone array placed in the same plane as the source line. Spacing between lines was 50 m with a tolerance of 10 m and source point spacing of 25 m. Profile lengths were approximately 4 kilometers (km) with 160 shots per line. The horizontal distance between the two wells where the 3-D VSP surveys were acquired was 1.2 km (Figure 1). The 3-D VSP survey was acquired in a remarkably short time of 24 hours thereby keeping rig time to a minimum.

3-D VSP DATA PROCESSING

Data processing began by checking the 3-D VSP survey geometry. The data was sorted and gathered with control over source positions along a given shooting line. Waveforms were sorted into common receiver gathers. An editing procedure selected shots with high signal-to-noise ratio which fell within the accepted shot position tolerance. Travel time picking and residual source static corrections were performed on each receiver gather.

Figure 7 shows representative raw common-receiver gathers from one shot profile. The true vertical depths of the gathers is 983 m, 974 m, and 965 m in well REU-5. The profile is not symmetric due to the presence of shallow reefs to one side. The first arrivals represent the downgoing waves in the vertical source-receiver plane. The first arrivals on the northwest segment were clearer than the ones on the southeast which may be caused by scattering from faults. The travel times from the source to receiver forms a hyperbolic moveout as the source moves away from the receiver-well trajectory vertical plane.

Another important application of VSPs is the identification of multiples using the downhole wavefields recorded at the receiver array. In the Gulf of Suez strong multiples are generated by the South Gharib Evaporite above the reservoir.
Before the 3-D VSP data was migrated into Common Depth Point (CDP)-depth domain several processing steps were performed. These included true amplitude recovery to account for spherical divergence, wavefield separation using a median velocity filter to separate the downgoing and upgoing wavefields, predictive deconvolution to suppress multiples, and finally zero-phase waveshape deconvolution. This procedure was applied on each line separately. At each processing step, several tests were run to choose the optimum processing parameters which preserve data integrity.

**DEPTH VELOCITY MODEL BUILDING**

In general, 3-D model building is based on simple layering without faults. However, because of the complex structure of the REU field, a special 3-D velocity model building application was developed. This application is based on geometric tetrahedral elements which represent formation boundaries and faults. A unit can be assigned properties such as velocity, density and dip. Therefore the velocity model is defined by layer velocity and reflector geometry.

Interval velocities for the tessellated layers were determined from calibrated sonic logs from six wells. These were assigned to each subvolume and stored at each corner of every tetrahedron. Ray tracing was then performed for several lines and reflection points were saved and viewed with color coding to show the reflection angles of rays and their locations on the reflecting surface. Travel time tomographic analysis was performed in order to optimize the velocities above the receiver position. The tomographic analysis was based on direct arrival tomography. This approach is superior to 3-D surface seismic in terms of providing a better control on velocities with depth (Chapman and Pratt, 1992). Lookup tables were generated which were required for the subsequent 3-D Kirchhoff depth migration.

**TRAVEL TIME INVERSION AND MIGRATION**

To establish a preliminary validation for the velocity model, the initial 3-D VSP migration pass employed a depth-velocity model based on 2-D geological and seismic data. This model was built with accurate well control and from geological models derived in the area. The initial 3-D volume model was built from eight depth surfaces and corresponding velocity fields. In addition to the main geological horizons, five fault planes were also included. The 3-D macro model was subsequently tessellated with all volumes in the model filled with tetrahedra.

Figure 8 displays a 3-D model of the tessellated layers with geological boundaries and faults incorporated. The model dimensions were 3.7 km by 1.5 km. The magnitude of geologic dips and boundary orientation geometries were carefully preserved in the model. The next step was to run ray tracing and compute travel times, which were then compared to observed travel times for all shot and receiver configurations. The inversion process is based on a velocity update at each node of the tessellated model adopting an iterative procedure. In the inversion process, the difference between the measured and modeled travel times is minimized in a least square sense, yielding a revised velocity field for each iteration. The final velocity model was then used in the final 3-D migration.

In a 3-D VSP survey, seismic waves are recorded in the source-offset and one-way time domain for the upgoing waves. Migration, in this context, is the process which converts this domain into CDP and depth domain. The migration algorithm used is based on the Generalized Radon Transform (GRT). In this process, each point in the offset-depth (x,y,z) domain is regarded as a potential velocity anomaly and therefore capable of scattering seismic energy from the source (Miller et al., 1987). In the source-receiver-time (S,R,t) domain, each point is based on the contribution of scattered energy from points along an isochron (surface) in the (x,y,z) domain.

In a constant velocity medium the isochrons are ellipsoids with source and receiver points as foci. The scattering phenomenon provides symmetry between the earth and data spaces. Points in earth space lead to travel time curves in the data space which in turn lead to curves (isochrons) in the earth space. Any data point whose isochron passes through a given point in the earth must be used in the migration process to reconstruct the image at that point.
Figure 8: 3-D model showing tessellated layers with geological boundaries and faults. The interval velocities and layer depths are stored at each corner of 64,000 tetrahedra in 40 subvolumes.
Figure 9 illustrates the principle and shows an isochronal surface for a geometry consisting of two reflection-time surfaces in a 2-D case where the velocity is constant, the source position is fixed and receivers lie along the surface. In the presence of laterally varying velocity, the shapes of the isochrons are distorted. The local structural dip in the model is represented by a tolerance cone (aperture) with an axis normal to the expected dipping planes. The aperture of that dipping cone constitutes the accepted uncertainty of the local structural dip in the model. The final migration parameters were selected and the 3-D VSP data volume was migrated and loaded into an interpretation workstation database.

**INTERPRETATION**

The final migrated 3-D volume of the walkaway VSP survey was 3.8 square kilometers (sq km) in size (1.4 km x 2.73 km). The survey was loaded on a workstation and interpreted. Figure 10 shows a 2-D section from the 3-D VSP volume along the dip direction and a depth slice at the top of reservoir. Major horizons are marked on the display. Faults are visible in both the dip section and in the horizontal plane slice.

Three key horizons and major faults were picked and mapped. Figure 11 shows the top Nubia Sandstone depth map with the dominant faults bounding the reservoir. The map reveals the NW-SE normal and NE-SW cross fault trends. The NE-SW fault pattern was difficult to identify from surface seismic data. The intersection of these two fault trends forms the horsts and grabens that define the oil traps.

Based on this map four development wells were drilled in the field, namely, REU-7 to REU-10, which increased production from 8,000 barrels of oil per day to 14,000 barrels of oil per day. REU-10 encountered the fault mapped from the 3-D VSP survey.
Figure 10: Vertical (left) and horizontal (right) slices from the 3-D VSP volume. The horizontal time slice is near the top of the Nubia Formation.
SUMMARY

The steeply-dipping reservoirs, in the Ras El Ush field, are found in fault-bounded compartmental blocks. These are difficult to map from 2-D surface seismic data due to the presence of the overlying thick evaporite section and shallow water acquisition problems. The 3-D VSP survey imaged the reservoir successfully. The 3-D VSP survey, including acquisition and processing, costs about one-third of an equivalent 3-D surface seismic survey making it cost-effective.

Initial estimates for the acquisition and processing time of the 3-D VSP was 9 months to one year. The acquisition was completed in one day. The processing and migration were completed in about three months. This short time for the processing turnaround was critical for the placement of development wells. In comparison, a 3-D seismic survey would have required 12 to 18 months to acquire and process.

Figure 11: Depth map of the Nubia Formation derived from the 3-D VSP. Wells drilled after the 3-D VSP are also indicated. Fault planes indicated in gray.
The structure maps derived from the 3-D VSP data helped in placing successful development wells. It reduced the risk of missing the target reservoir. The 3-D VSP survey also identified additional prospective blocks.

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