Developing the long-term seismic strategy for Azeri-Chirag-Gunashli, South Caspian Sea, Azerbaijan

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At Azeri-Chirag-Gunashli (ACG), seismic activities have focused on static and dynamic imaging of the reservoir to reduce risk for appraisal and development drilling. Imaging and reservoir characterization constrain the “static” reservoir model, and 4D reservoir monitoring constrains the “dynamic” reservoir model. Over the last several years we have successfully tested and implemented prestack depth migration, 4-C OBS acquisition and processing, and towed-streamer 4D in various parts of ACG. Results from these technologies are being used to shape the longer-term (20+ years) seismic strategy of the development—in particular, how 4D seismic surveillance should be implemented across ACG.

Expected value delivered to ACG from 4D seismic surveillance has been based on proven benefits documented in other fields. Base production profiles and reserve estimates for Azeri and Gunashli include an expected benefit consistent with BP’s global experience from 4D seismic surveillance. The 4D benefits being banked are generally related to identifying bypassed oil and unswept zones to assist in targeting development and infill drilling. Other potential benefits (production acceleration, cost savings, risk mitigation) from more frequent time-lapse monitoring (>1 survey/year) have been evaluated, but at this time there is not a sufficient industry track record to provide confidence in magnitude or likelihood that these benefits can actually be delivered.

Because of the variable seismic data quality across ACG, the next cycle of seismic acquisition will help define the proper mix of seismic acquisition technologies (towed-streamer, temporary 4-C OBS, and permanent 4-C OBS) needed to maximize value from seismic surveillance. In areas where towed-streamer can deliver quality 4D results, it is preferred because it is significantly lower cost. In areas where 4-C OBS is essential to provide a reasonable static image, we need to prove the ability of repeat 4-C OBS (4-C/4D) for seismic surveillance in these areas. A key element in the evaluation of 4-C/4D will be a limited deployment of buried-cable “permanent” OBS which should provide a quality test of 4D noise levels and repeatability for this technology. Results from these seismic surveys will then be used to more clearly define the balance of seismic technologies implemented across ACG over the next 20 years.

Introduction. The Azeri-Chirag-Gunashli (ACG) megastucture, 100 km southeast of Baku in the South Caspian Sea, is a multibillion barrel oil accumulation in the early stages of development. Chirag Field, with a single platform, has been on production since 1997. The first of three Azeri Field production platforms delivered first oil in February 2005. Gunashli Field will be developed from a single production platform beginning in early 2008. More than 400 reservoir penetrations are expected from these five platforms.

The ACG structure provides a variety of challenges to seismic imaging which include: steep dips (>40°), structurally complex overburden, shallow gas, and mud volcanoes. Although the seismic data quality is variable, the seismic rock properties of the Pereriv and Balakhany reservoir sands are such that clear hydrocarbon fluid contacts and direct hydrocarbon indicators (DHI) are visible on a variety of seismic volumes.

Information from seismic data contributes to the ACG development in two fundamental ways. Static imaging provides the structural shape of the reservoir and potentially reservoir distribution and quality; dynamic imaging provides time-lapse monitoring of fluid movement or pressure changes in the reservoir resulting from production or injection.

The static seismic image (3D image) is critical for reducing risks associated with development drilling. A good static image is important for well positioning, depth prediction, and identification of shallow drilling hazards. The static image also provides the structural configuration, an important input for geologic and reservoir models. Many areas of ACG have structural dips in excess of 45°, so it is especially important to have an accurate structural model for planning development wells which are often highly deviated with nearly horizontal reservoir penetrations. The work over the last 4-5 years on depth migration of the towed-streamer data sets (1995 and 2002), and the 4-C OBS acquisition (2002) has provided a good static image over about 90% of the Pereriv hydrocarbon column (Figure 1). The remaining poor image areas are mainly limited to mud volcanoes and the crest of Chirag where 4-C OBS has not yet been acquired.

Significant value in the future for ACG is expected from time-lapse (4D) seismic monitoring of the reservoir depletion. 4D seismic surveillance provides one of many reservoir surveillance techniques that will be used to optimize recovery. The unique information that 4D seismic surveillance brings to reservoir management is the ability to see what is happening in the reservoir away from the wellbores. All other surveillance data is only gathered at the wells. Although Chirag has been producing now for seven years, the overall ACG development is really in its early stages. There are more than 5 billion barrels remaining to be produced and about 400 development wells and sidetracks remaining to be drilled. There is a huge peripheral waterflood around the margins of the field that will need to be optimized, as will a crestal gas flood in central Azeri (Figure 2).

The reservoir management of the field will be challeng-
ing and 4D seismic surveillance will have an important role to play in helping to optimize the development.

**Seismic cycle time versus major project stages.** Aligning seismic activities with the major field development decision points and stage gates has been an important challenge for the subsurface teams as the various phases of the ACG development have progressed. In presanction stages (before full financial commitment to develop the field), funding is often defined in 9-12 month segments. In these early project stages, a full range of field development options are evaluated (number of wells, number of platforms, type of platform, type of pressure support, expected fluid rates of oil/gas/water) and then reduced to one development plan. In the presanction stages, incremental improvements in the subsurface model may be incorporated—including refinements to the static model, revised structural configuration, improved faults, and new reservoir distribution. In these early stages of project planning, new or improved seismic data can contribute critical information about the static structural configuration and reservoir distribution which influence how the fields should be developed.

The seismic cycle time typically ranges from 12-24 months depending on whether the activity is reprocessing/remigration or new acquisition (Figure 3). This historical seismic time-lag, requires planning 2-3 years ahead to ensure that seismic deliverables are ready when needed. Therefore funding of major seismic activities (acquisition in particular) often must occur outside of or across the major project stage funding decisions. Postsanction, the project stages are longer, usually 2-3 years in duration. However, the project development activities shift towards shorter-term, faster-paced activities focused on early development well drilling. Seismic-related activities will be more focused on reservoir management (i.e., 4D seismic surveillance) as the field matures and understanding of fluid movements becomes more critical to development well targeting.

Although major financial commitments are related to each project stage, seismic projects do not easily fit into these stages. Significant advanced planning is needed to provide critical new seismic information in time for particular field development decisions. The various seismic activities are arranged on the chart (Figure 3) only to provide a general idea of when these types of seismic surveys are likely to be initiated. Repeat 4D surveys are not needed before production begins. Static image surveys, like 4-C OBS may be desired prior to sanction to better define structural models, but because of the time involved may not really be delivered until postsanction unless they are initiated very early in the project.

**Static imaging.** Since the acquisition of the first 3D towed-streamer seismic over ACG in 1995, geophysical activity has focused on improving the overall data quality. Primary, structural imaging is fundamentally important for appraisal and development well planning on this high relief structure. Large areas of the reservoir in central Azeri and Gunashli have been masked by complex structure and gas in the overburden. Improvements in imaging have been derived from reprocessing with improved migration algorithms, and application of 4-C OBS acquisition. Major imaging steps have included:

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**Figure 2.** Planned development for the Pereriv reservoirs in ACG.

**Figure 3.** Typical seismic project timelines experienced or expected in ACG compared to the major project stages in field development.
In Chirag, implementation of the first \(V(z)/V(xyz)\) depth migration significantly changed the view of the thrust fault geometry along the north flank of the structure. The changes in fault configuration transformed a large area that was unprospective because of structure, into a major production area for Chirag. Three producers and one injector in this area have produced as much as 30 000 b/d.

In Azeri, the \(V(z)/V(xyz)\) migration brought major changes to the configuration and location of the structural culmination. The shape and location of potential gas caps was changed significantly. As a result, the first predrill development well was redirected to prove the existence of large gas caps in several of the primary reservoirs in Azeri.

Since reprocessing and improved migration of the towed-streamer seismic did not substantially change the extent of poor data quality in the crest of central Azeri and in Gunashli, we looked to 4-C OBS acquisition including PZ and PS imaging to further reduce the extent of poor data. In Azeri, OBS acquisition was justified on the reduction to drilling hazards for the 40% of Azeri wells that would have to drill through the seismic no-data areas.

PZ results from the Azeri OBS are demonstrating significant improvements in the image quality and a substantial reduction in the poor data areas in the crest of the structure. Although dramatic PZ improvements were not necessarily expected, the combination of seabed coupling, P + Z summation, azimuthal variation, and higher fold (250 fold versus 40 fold for towed-streamer) is providing major improvement.

The towed-streamer seismic data in ACG historically have not been of high enough quality to allow successful quantitative use of seismically-derived reservoir properties. The hydrocarbon-filled reservoir sands have distinctive and generally low impedance relative to the surrounding shales. However, there is enough variability in data quality, structural dip, and overburden that well-to-seismic correlations have been too low to be statistically useful for quantitative reservoir constraints.

The existing seismic data do, however, seismically resolve the two major Pereriv B and D reservoir sands which average 50 m and 30 m, respectively. Also, strong oil DHIs are evident on full-offset and partial-offset stacked volumes. These DHIs have been used with existing well control to map fluid contacts in several of the major reservoir sands.

Qualitative, soft-constraints from seismic have been provided for the more stratigraphically complex, and areally discontinuous Balakhany sands in the Balakhany VIII and X intervals. In Chirag and Gunashli, sand body maps have been used to help guide reservoir descriptions used for reservoir simulation models of the Balakhany VIII and X.

Recent analysis of the Azeri PZ-4-C OBS volumes is revealing significantly higher well-to-seismic correlations than seen previously from the towed-streamer data sets. The incremental improvements in signal-to-noise, image quality and, image positioning from the PZ-4-C OBS suggest that we are now getting close to data quality where more quantitative reservoir evaluation from seismic may be possible.

**Dynamic imaging.** Given the size of ACG, it was important to establish whether 4D seismic surveillance could be used to monitor production effects in the main reservoirs. In 2002, a 3D repeat towed-streamer survey over Chirag and Gunashli was acquired to provide the first time-lapse reservoir monitoring in the south Caspian basin. Core and petrophysical log-based feasibility studies determined that a significant 4D response from fluid changes should be expected. Acoustic impedance (AI) changes of 4-8%, depending on the magnitude of the saturation change, were expected from water sweeping oil, or gas replacing oil. Pressure effects might also be detectable with a 1000 psi pressure drop causing about a 2% change in AI.

An iterative, parallel processing approach that included extensive testing and velocity analysis was applied to the 1995 and 2002 data sets. Fast-track 4D products were delivered in about eight months and “final” volumes in 18 months. Although acquired with an identical line orientation, non-repeatable shooting direction changes in the 1995 acquisition caused spatial and timing shifts in relation to the 2002 data. As a result, there was significant acquisition-related amplitude stripping in the difference products. Effective application of high radon demultiple was also challenged by accurate discrimination of the multiple velocities. The steeply dipping primaries along the north flank (>40°) were susceptible to attenuation by the radon demultiple. To optimize positioning, a Kirchhoff \(V(xyz)\) prestack depth migration was applied to the final volumes.

The 1995-2002 4D difference results show the movement of the waterflood along the south flank of Chirag. Independent patterns of water movement in the two primary reservoirs (Pereriv B and D) have a generally good correlation to behavior expected from the reservoir simulation model. In detail, the shape of the water front does show differences to the simulation model and adjustments to the aquifer inputs are being tested. The 4D results indicate little or no aquifer movement on the north flank, again generally confirming results from the reservoir simulation model.

The 4D difference has also revealed an area of distributed high gas saturation in eastern crestal areas of Chirag. The location and extent of secondary gas was not as expected from reservoir simulation results, where a consolidated gas cap was predicted. Integrated evaluation and iterative analysis of the 4D results with other reservoir surveillance data and the reservoir simulation model has brought improved consistency to the reservoir model.
However, there are still significant inconsistencies with the
4D results as there are areas where crestal wells produce large
amounts of gas, but the seismic is not detecting high gas satu-
ration. Because of variable image quality, and the limitations
of repeatability imposed by the 1995 baseline survey, reliable
4D results for the 1995-2002 time-lapse may be possible only
in the best data areas. We expect that repeatability of future
towed-streamer 4D surveys could be improved because it
should be easier to match the acquisition to the 2002 geometry.

**Defining a life of field seismic strategy.** The learnings applied
from recent experience with depth migration, 4-C OBS, and
towed-streamer 4D are helping to define our seismic strategy
as we look ahead. We need to prepare for the massive devel-
opment of Azeri Field (nearly 300 penetrations, and peak oil
rate of 800 000 b/d), ongoing drilling and production in Chirag,
and the future Gunashli development (Figure 4). To date, the
static imaging results from the seismic have delivered signif-
ificant value to the assets through definition of the reservoir con-
figuration, and accurate depth prediction for well targeting.
In the future, seismic surveillance is expected to provide major
additional value to the ACG development through improved
understanding and optimization of field depletions. The spe-
cific depletions plans and pace of development in each ACG
field will dictate the appropriate level of 4D seismic surveil-
ance that may be required.

Finding the right balance between towed-streamer and 4-
C OBS is one major question. Our experience in the Caspian
Sea reveals approximately a 1:5 cost differential between them
but we also need to consider the suitability of each acquisi-
tion method for 4D seismic surveillance. Thus, we need to bal-
ance the potential imaging benefits of 4-C OBS against the
lower cost of towed-streamer to maximize value. Because 4-
C OBS is much more expensive, we need to employ towed-
streamer wherever we are confident it can deliver reasonable
quality results. Four-dimensional towed-streamer now has
an extensive track record across the industry, while 4-C/4D has
been implemented in only a few places. In the next four
years, ACG production will increase about seven fold. It is crit-
ical in the next couple of years to determine what mix of seis-
mic technologies will be used to deliver 4D seismic surveil-
ance. The next cycle of seismic acquisition will be target-
ed to establish the relative balance of the two acquisition
technologies employed for seismic surveillance.

Based on towed-streamer experience, ACG can be divided
into three general areas of data quality. The eastern end of Azeri
has some of the best seismic data quality, and there is high
confidence that towed-streamer seismic should be completely
adequate for 4D monitoring (Figure 5). On the other end of
ACG, in Gunashli, the opposite is true. Most of Gunashli is
characterized by poor quality towed-streamer data and 4-C
OBS will be required over the entire area. The third area which
covers Chirag and west and central Azeri, has a full range of
data quality from good over Chirag to very poor in the crest
of central Azeri. There are also large areas, primarily on the
north flank, where it is unclear how well towed-streamer 4D
will work (Figure 5, orange areas). It is in this third area where
better matched towed-streamer acquisition may bring
improved 4D repeatability, raising confidence in the useful-
ness of these methods in these areas. Because of the signifi-
cant cost differential, it is important that we determine where
towed-streamer is adequate for seismic surveillance, and
where 4-C/4D is required. The next cycle of seismic acquisi-
tion on ACG is being designed to establish a reasonable “tech-
nical limit” for towed-streamer 4D, and to demonstrate and
establish the potential of 4-C/4D. To date, there is no repeat

*Figure 5. Major regions of ACG divided by the likely 4D acquisition
method. Towed-streamer 4D is expected to deliver good results in green
areas. In red areas, towed-streamer data quality is poor and 4-C OBS is
almost certainly required. Orange areas are uncertain for towed-streamer
4D, since improvements in 4D repeatability through better matched
acquisition could improve its potential in these areas.*

4-C OBS survey on ACG. As part of the 4-C/4D evaluation,
a small permanent 4-C OBS array may be installed to deter-
mine the 4D noise levels and repeatability of buried cables.
Results from the permanent 4-C array at Valhall suggest that
the best repeatability and lowest 4D noise levels can be
achieved with buried cables.

**Supporting base production with seismic surveillance.** BP
has been using 4D seismic methods for reservoir monitoring
for more than seven years. More than 20 fields worldwide have
had 4D surveys recorded. With this experience, BP has devel-
oped and tracked the benefits from time-lapse surveillance
(Marsh et al., 2003; Whitcombe et al., 2004). BP’s experience
to date has shown a documented reserve increase of 3% on
average. Other companies are reporting similar contributions
to reserves and recovery from 4D seismic.

In fields where more than one repeat survey has been recorded, the typical time-lapse interval has been 1-2 years,
with most fields adopting an average interval of about two
years. The time-lapse interval is usually determined through
reservoir simulation predictions of 4D changes in the reser-
voir, combined with the scheduling of development drilling
campaigns.

The surveillance plans developed at project sanction for
Azeri and Gunashli included 4D seismic as an important sur-
veillance data set for field development and reservoir man-
agement. The sanction production profiles and expected
recovery are therefore supported by the benefits of 4D sur-
veillance. We have assumed, in our base case going forward,
a 3% contribution to reserves over field life from regular 4D
monitoring. The benefit is tied only to the reservoir manage-
ment benefit from seismic surveillance with a proven track
record, namely identification of bypassed and isolated oil for
targets of development and infill drilling. In these base assump-
tions, the time-lapse interval between surveys has not yet
been firmly determined, but is generally expected to be at least
every few years similar to the historic application of 4D across
the industry. We also have not yet specified which acquisition
method will be used, but are looking at full-cycle economics
to help us understand the differences in value that might be
delivered from towed-streamer or 4-C OBS (temporary or
permanently deployed). It is expected that a mix of tech-
nologies is likely because of the variability in seismic data qual-
Evaluating the unproven upside potential from short-interval time-lapse monitoring. Although our base evaluation of the 4D seismic surveillance contribution to the ACG development is built around proven benefits of 4D, we do recognize that there is another group of reservoir management benefits that might come from 4D monitoring on significantly shorter time-lapse intervals. Our recent experience with image quality improvements from 4-C OBS acquisition has raised interest on the benefits of permanent OBS implementation (known as life of field seismic or LoFS). Logistically, short-interval time-lapse or “seismic-on-demand” would be much simpler with a permanently installed array. We completed an economic evaluation for the Azeri Field development of the potential benefits from a range of possible 4D options. The major elements of the evaluation included:

- repeat towed-streamer versus LoFS
- comparison of 4D benefits for different time-lapse intervals (two years, one year, three months)
- pace and timing of 4D implementation for a new field

The benefit mechanisms that were evaluated fall into four general classifications—reserves increases; production acceleration; cost savings; and risk mitigation.

Two key assumptions were used to evaluate the possible benefits from different time-lapse sampling intervals. First, time-lapse seismic improves knowledge of fluid distribution and compartmentalization that, in turn, improves development well positioning. The optimized well positioning potentially results in higher recovery, fewer sidetracks, and fewer overall development wells. Second, more frequent time-lapse reservoir monitoring should result in incremental improvement in overall recovery and reduce the number of sidetracks and total development wells. The challenge to the evaluation is to properly estimate the size of the incremental improvements because there is no real track record for 4D monitoring more often than 1-2 years at this time.

We did not consider using towed-streamer acquisition more often than once a year because of the logistical and cost limitations of the method. LoFS potentially provides significantly greater acquisition flexibility since scheduling of a large seismic vessel is not required. “Seismic-on-demand” as needed in response to the reservoir behavior should be possible with LoFS. Once the permanent cables are in place, acquisition cost per survey should be reduced by an order of magnitude compared to towed-streamer. Also, significant improvements in processing turnaround should be possible since the survey geometry is effectively fixed, survey repeatability improved, and data handling direct to the processor would be streamlined.

Our 4D benefits evaluation suggests that for frequent monitoring (>1 survey/yr) the reserve increases contribute about two thirds of the value, while the other mechanisms (production acceleration, cost savings, risk mitigation) combined provide remaining one third (Figure 6). For less frequent monitoring (two-year time-lapse), the production acceleration, cost savings, and risk mitigation are reduced substantially, leaving reserve increases (essentially the industry proven 4D benefit) as the only significant benefit.

Reservoir simulation models at both full-field scale (coarse) and sector scale (fine) were used to help define the magnitude of potential benefits when applicable. In particular, potential reserve increases from peripheral well positioning, and possible acceleration and risk mitigation benefits were developed with constraints from reservoir simulations.

Challenges for permanent OBS (LoFS). There is interesting potential at ACG from LoFS for delivering significant value through improving 4D time-lapse seismic data quality and cycle time. Aside from unproven benefits, there are also several major technology issues that need to be addressed both in ACG and the wider industry before large-scale implementation can occur. These include:

- large upfront initial investment for the technology
- early field-life 4D benefits not widely established
- differential benefits for short-interval 4D not established
- once installed, a particular LoFS technology is locked in (trenched in)
- operational life of the LoFS cables not established
- data management and integration of large volumes of rapidly acquired seismic data

Widespread implementation of LoFS will not occur until these concerns are largely reduced or eliminated. The results from the Valhall LoFS experience are beginning to build a track-record of benefits and impacts from permanent OBS.

Establishing the long-term plan for seismic surveillance at ACG. In 2002, both 4-C OBS and 4D towed-streamer acquisition provided key tests of these two important seismic technologies. The results have shown that PZ 4-C OBS can deliver major improvements to static imaging, where towed-streamer fails. The results from the Chirag 4D have also demonstrated that we can use 4D seismic surveillance to monitor reservoir depletion at ACG to help optimize recovery. Although there are inconsistencies and uncertainties with regard to secondary gas detection, it is recognized that improved 4D sensitivity may be possible with better matched seismic acquisition.

The next cycle of seismic acquisition (expected in 2006), will be focused on determining what the proper mix of 4D acquisition technologies should be long-term to maximize value for ACG. An additional towed-streamer 4D at Chirag, with better matched acquisition parameters, would provide an improved test of the sensitivity of this method at ACG. This additional 4D survey will be important to understand how extensively the lower-cost towed-streamer technology could be used for seismic surveillance. In addition, we need to test repeat 4-C (4-C/4D) to ensure that 4-C OBS will deliver the quality 4D results anticipated from the improvements seen in static imaging. Based on experience from the Valhall LoFS, we expect the best 4-C/4D sensitivity and repeatability will be achieved from buried cables. A small, pilot permanent 4-C array is being planned to allow a clear demonstration of the
capability of 4-C/4D for seismic surveillance. Given the significant area of ACG where 4-C will be required for 4D seismic surveillance, it is important to verify the technology as soon as possible.

**Conclusions.** The ACG subsurface teams have adopted a strategy that has focused on using seismic data for static and dynamic imaging of the reservoir to assist in optimizing this major development. Progress in the last 3-5 years in implementing prestack depth migration, and 4-C OBS acquisition and processing has substantially reduced the structural uncertainties and risks associated with development drilling. Furthermore, successful 4D seismic surveillance has been demonstrated at Chirag through the use of repeat towed-streamer seismic surveys. Looking ahead toward the next 20 years of the development, 4D seismic surveillance is expected to contribute to the base production profiles and reserves. Because of the wide variation in seismic data quality across ACG, we are now evaluating what is the proper mix of seismic acquisition technologies (towed-streamer, temporary 4-C OBS, and permanent 4-C OBS) needed to maximize value from future seismic surveillance.


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