Kadanwari Gas Field, Pakistan: a disappointment turns into an attractive development opportunity

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ABSTRACT: Kadanwari Gas Field, located in the Middle Indus Basin of Pakistan, was discovered in 1989. Lower Goru sands of Cretaceous age are the producing reservoir in this field. Initially, the structure was considered a relatively simple four-way closure with continuous sand. During appraisal, three wells were drilled and each of these tested gas. On the basis of these results 728 × 10^9 SCF of sales gas reserves were estimated and a processing facility was designed accordingly. Due to the corrosive and sour nature of Kadanwari gas, 22% chrome alloy was used in the well completion and surface facilities. Additional development wells and early production data indicated that the reserves were much smaller than originally estimated. After further studies, including reprocessing of seismic data, the reserves were revised downward to less than 200 × 10^9 SCF; by that time a total of nine wells had been drilled. Although the field was considered to be a disappointment, the subsurface studies continued and, as a result, the tenth well tested a new fault compartment, proving an accumulation of considerable reserves. As a result of detailed studies of the field, a number of other opportunities were also identified. Presently, the sales gas reserves are estimated at approximately 300 × 10^9 SCF and this has given a new life to the field. Some other independent fault-bounded structures in the field are now considered prospective and these have the potential to add sales gas reserves ranging from 100–500 bcf.

KEYWORDS: Pakistan, Kadanwari, field development

INTRODUCTION

The Kadanwari Gas Field is located in the northern area of Sindh Province, Pakistan, some 350 km NE of Karachi (Fig. 1). The field was discovered in 1989 and appraised by three wells in the period 1990 to 1991. Following approval of the development plan (1992) and successful gas sales and price agreements (1993), the Kadanwari Field was developed and was brought on production in May 1995.

The original 1992 Field Development Plan proposed the development of a crestal Core Area, followed by other low relief areas of the field. The Core Area was estimated to contain P50 reserves of 728 × 10^9 SCF of sales gas and was planned to be developed by up to 13 wells. These wells were expected to produce at rates of up to 50 × 10^9 SCF per day (SCFD), and the field plateau rate of 175 × 10^6 SCFD sales of gas was expected to be maintained for some 9 to 20 years. Other areas of the field were planned to be progressively appraised and developed as required to extend the production plateau.

The initial reservoir pressure and temperature of Kadanwari gas was 4900 psia and 340°F respectively and the gas consists of 2% N₂, 12% CO₂ and 35 ppm H₂S. The combination of high-pressure, temperature, CO₂, H₂S and the presence of condensed water make the Kadanwari fluids corrosive and sour in nature. To handle these fluids over the expected field life of about 20 years, 22% chrome stainless steel duplex pipelines, valves and other equipment were used in wells, flow-lines and in the central processing facility. The facility, designed to handle 175 × 10^6 SCFD of sales gas, consists of membrane units, H₂S polishers and hydrocarbon dew point control equipment in order to meet the sales gas specifications. Gas export is via a pipeline owned and operated by the gas purchaser SSGCL (Sui Southern Gas Company Limited).

After the project was sanctioned, prior to production start up, four development wells were drilled in 1994 and 1995. The wells K-5 and K-8 were disappointing, encountering the Lower Goru reservoir sand 100 m deeper than expected and wet, and non-reservoir quality, respectively. The potential need for down-hole sand control was also recognized. As P50 reserve estimates for the Core Area were being revised downward, the costs of the processing facilities were escalating. A further disappointment came in the performance of the processing plant when it became apparent that the membranes were being clogged with waxy condensate (C9+) leading to a reduction in processing efficiency and capacity.

Despite these problems and the challenges of operating and managing a complex reservoir and production facility, the subsurface and production teams continued to identify further opportunities and to reduce the operating cost (Linn 1998). This work resulted in recent successes in the northeastern fault block (K-10 area), and successful production being established from a shallower sand (F sand). The recognition of different gas–water contacts (GWC) in different fault blocks of the field...
and the potential prospectivity of shallower sand units has revived expectations of the asset.

LASMO Oil Pakistan Ltd (18.42% interest) operates the Kadanwari Field on behalf of its partners, OGDCL (50%), KUFPEC (15.79%) and Premier Kadanwari Development Co. (15.79%).

GEOLOGY

Tectonic setting

The Kadanwari Field is one of the southernmost gas fields in the prolific Middle Indus Basin (Fig. 1), and lies on the SE flank of the regional Jacobabad High (Dolan 1990; Kazmi & Jan 1997). The field consists of a number of low relief fault and dip closures. A loss of reservoir quality to the north provides a stratigraphic trapping component. The reservoirs are Cenomanian Lower Goru Formation shoreface sands, with transgressive marine shales providing the top seal. The trapping mechanism is a complex combination of structural dip, sealing faults and loss of reservoir quality to the north.

Three tectonic events are responsible for the structural configuration of the field, namely, Late Cretaceous uplift and erosion, Late Paleocene wrench faulting, and Late Tertiary to Recent uplift/inversion of the Jacobabad High.

Seismic data in the Kadanwari area show events in the late Cretaceous section truncated by the Base Tertiary unconformity due to a Late Cretaceous uplift. The degree of uplift is uncertain, but in the Kadanwari area, several hundred metres of section is estimated to have been eroded. The axis of uplift appears to be the Jacobabad–Khairpur High. This is an important event as it has effectively placed the distal parts of the Lower Goru depositional sequences at structurally higher elevations than the more proximal, and better reservoir quality, shoreface top-sets. This enables combination stratigraphic and structural traps to occur along the flanks of the present day high (Milan & Rodgers 1993).

Reservoir geology

The oldest Cretaceous strata in the Kadanwari area are the organic-rich shales of the Sembar Formation, which is the presumed source of much of the gas in the Middle Indus Basin. This is overlain by the sandy Lower Goru and the shaley Upper Goru formations (Fig. 4). The Lower Goru Formation in the Kadanwari Field has been informally subdivided into six sand-bearing members, B to G, the units from C to G are shown in Figure 5 with the main reservoir interval being the E sand. From 1999 additional production was achieved from the shallower and thinner F' sand.

Approximately 517 m of core have been acquired in the Kadanwari Field. The cores vary in thickness from 0.5 to 2 m. The most significant is the F sand, which is apparently capable of withholding pressure differentials of 3500 psi during production.

Seismic coverage

The Kadanwari Gas Field is located in the remnant part of the old Tajjal exploration concession. The initial seismic data in the Cretaceous section rarely extend above the Base Tertiary unconformity. These are basement-rooted, right-lateral wrenches and have generated the dominant structural style in the Cretaceous section. Although the magnitude of horizontal displacement is small, the faults show frequent reversal and have a "flower"-type cross-section (Fig. 2). These wrench faults are particularly significant since they divide the Kadanwari Field into five known reservoir compartments (K-7/K-9 and K-4 in the south, and K-3, K-1/K-6 and K-10/K-11 in the north, Fig. 3). A number of additional compartments within the production area have yet to be tested. Fault seal is believed to be due to cataclasis and is apparently capable of withholding pressure differentials of 3500 psi during production.

The final tectonic event to have a major impact on the Kadanwari area is a Late Tertiary to Recent inversion of the Jacobabad–Khairpur High. This is an important event as it has effectively placed the distal parts of the Lower Goru depositional sequences at structurally higher elevations than the more proximal, and better reservoir quality, shoreface top-sets. This enables combination stratigraphic and structural traps to occur along the flanks of the present day high (Milan & Rodgers 1993).
Tajjal Concession were acquired with a regional spacing of 6–7 km in 1987/88. The lines are generally east–west, with some north–south ties. Prospective areas were subsequently in-filled with more data; the Kadanwari Gas Field is one of them. In Kadanwari, the central area was considered more prospective than the western area. In 1989, a NE–SW oriented, 2 km spaced seismic grid, with a shot point interval of 50 m and 60-fold coverage was acquired. This was extended in 1990 to the west, but with a 25 m shot point interval and 120-fold coverage. In 1991, the Core Area and part of the East Kadanwari Block were infilled to 1 km spacing, using the same parameters as in 1990. All of the c. 2000 km of seismic data are 2D and have a vibroseis source (Fig. 8). The area is generally covered by sand dunes of the Thar Desert.

Seismic statics model

After early development drilling, it became apparent that processing of the seismic data was not ideal and significant static effects remained. A series of lines were reprocessed in 1995, but their static correction was also problematic. In 1996 a rigorous refraction static solution was designed and, using this model, 389 km of seismic data from the central part of the field were reprocessed. Current interpretations and maps for the central area are based on these seismic data (see Fig. 2 for an example of the data quality).

The new static model was based up on a three-layer spatially consistent refractor overburden velocity/depth model from uphole data, and it was used as an integral part of the delay time analysis. The delay time of each layer was computed and subtracted from the total delay time of the refractor and the depth of the refractor was computed from the residual delay times. Previously a one-layer refractor overburden model was used, which was not supported by the uphole data. The geometry of the newly picked refractor was completely different from previous attempts.

The success of K-10 and the recognition of greater prospectivity in other parts of the field has led to reprocessing of a further c. 483 km of seismic data, with proper static correction in these areas.

Time-to-depth conversion

Time-to-depth conversion on Kadanwari is critical because of the thin reservoir target and the generally low-relief structures. A few metres off-prognosis, at depths of 3300–3350 m, can make a significant impact on the performance of a well. Four different methods have been used to convert seismic time maps to depth. In the first method, the average velocity map (pseudo-velocity) has been applied, taking depths from wells and time from seismic sections. Pseudo-velocity was used because the well to seismic tie was not good. In the second, a layer-cake depth conversion method used many layers, but was complex to undertake and did not tie the wells closely.

The third method is considered to be the most effective. The depth and time to the base of the weathering zone is calculated separately from the static correction work. The depth conversion from the base of the weathering zone to the reservoir uses...
an average velocity map based on well information. The two thicknesses are then added together. This method continues to be the favoured one for depth conversion. The fourth method uses a single average velocity and an error map, and is also quite effective, as there is relatively little velocity variation away from fault zones.

**RESERVOIR PERFORMANCE**

**Rock and fluid properties**

A comprehensive petrophysical review has recently been completed for all wells in Kadanwari. Varying geology, complex mineralogy and borehole washouts make log interpretation far from straightforward. Some high GR ‘hot sands’ have good porosity and permeability (K-7 and K-9 F sands), whereas others are tight (E3 interval). Petrophysical sums and averages are dependent on the cut-offs applied and can give a misleading indication of reservoir potential. Indeed, many intervals are gas bearing, but lack sufficient permeability to produce at commercial rates. Typically, porosity has to exceed 18% and permeability to be >2 mD for a sand to produce gas at commercial rates in Kadanwari. The petrophysical review has resulted in an evaluation model to use for new wells in the field, a consistent set of results to use in estimating volumetric gas-in-place, and an ability to rank recompletion opportunities in the D, F and G sands in the existing wells.

The fluid contacts evaluated from logs are consistent with the free water levels (FWLs) established from RFT/MDT data (Fig. 9). The FWL for most of the compartments in the field appears to be 3284 m subsea (mss). Initial gas pressures in the K-10 block were 60 psia higher than the rest of the field. If a normal hydrostatic water gradient is assumed, as appears most likely, then this would imply a deeper FWL of around 3330 mss for the K-10 area. An important element of data gathering in the recently drilled K-11 was to obtain water pressures from the deeper sands in the K-10 block. Although several attempts were made, unfortunately, not a single valid point could be obtained.

The distribution of hydrocarbons, cores and tests in the C–G sands of Kadanwari is illustrated in Figure 6. Of interest is the slightly higher 13% non-hydrocarbon gas content of the southern wells (K-4, K-7 and K-9) compared with the northern wells (11%, K-1, K-6 and K-10). K-3 E sand and the K-7 and K-9 F sand have compositions intermediate between the two areas. H₂S occurs in concentrations up to 32 ppm, considerably less than the 100 ppm anticipated in the development plan of 1992.

**Reservoir performance**

Figure 10 illustrates the field production performance to date, dominated by the contributions from wells K-6, K-7, K-10 and K-11.

In terms of E sand reservoir performance, the field can be divided into two parts, southern and northern, resulting from
the differing thickness of the E4 sand and the differing structural relief of the accumulations. These two parts are further divided into separate blocks by sealing faults. The low-relief southern blocks, with the thickly developed, poorly consolidated E4 reservoir, produce under aquifer drive and normally require sand control (Fig. 7). The northern blocks generally produce under depletion drive and sand control can be avoided. These blocks are discussed below.

Southern blocks. Wells K-7 and K-9 were initially completed on the E sand. Although the wells had gravel pack completions, they had very good deliverability (about $50 \times 10^6$ SCFD each). The drive mechanism of this pool was strong aquifer influx which, along with very high permeability, was the reason for the high-sustained rates from these wells. K-9 watered out in November 1998 and K-7 in October 1999. The two wells recovered $67 \times 10^9$ SCF wellhead gas from this block, equating to a probable recovery factor of <50%.

A wireline perforation job was carried out on the F sand in K-7 in October 1999 and the well flowed gas at rates of up to $23 \times 10^6$ SCFD. This was restricted somewhat in the absence of sand control and lack of production experience from F sand. After this success, a rig work-over was carried out in May 2000 to complete the F sand in K-9 (and remove gravel pack equipment which prevented the simple perforation of this zone). The K-9 F sand was found depleted by 1100 psi compared to K-7, for reasons which are unclear, though pressure data and an interference test indicate that wells are not in communication at F sand level. The fault mapped between them in Figure 3 appears to be sealing the thin F sand. Material balance for K-7 F sand suggests a gas initially in place (GIIP) of $10.5 \times 10^9$ SCF, and there is insufficient data at this time from K-9 for an estimate to be made of its volume. The performance of K-9 F sand is somewhat disappointing and the sand was re-perforated in July and may subsequently be considered for stimulation.

K-4 produces from a down-flank location in a separate fault block in the south. It has a 7 m gas column directly underlain by water in the high permeability E4 reservoir. No gravel pack was installed when the well was completed in 1996, in view of its uncertain productive life. The well has been produced at a low rate to avoid water coning and sand production. Recently it has been shut-in. The reserves assigned to the K-4 block are $28 \times 10^9$ SCF (wellhead gas), of which $7 \times 10^9$ SCF had been produced to June 2000.

Northern blocks. K-1 and K-6 drain the same fault-bounded block in the north of the field (Fig. 3). These wells produce by volumetric depletion drive, as indicated by material balance, and the performance of each well is comparable. On the basis of material balance, $72 \times 10^9$ SCF wellhead reserves are assigned to this pool, representing a recovery factor of 85%; some $67 \times 10^9$ SCF have been produced to June 2000. The wells K-1
Fig. 6. North–south distribution of hydrocarbons, cores and tests in the C–G sands of Kadanwari (metres below mean sea-level).

Fig. 7. E sand stratigraphic correlation chart, with datum at top D sand. The main gas-producing interval in the Kadanwari Field is the E sand. The E sand is further divided into six units, E1–E6 of which E4 and E5 are the main producers. The wells with letter 'K' are Kadanwari wells, while the wells with letter 'X' are of adjacent fields.
and K-6 are on compression and are producing at a combined rate of around 20 × 10^6 SCFD.

K-3 drained a small fault-bounded closure west of the K-1/K-6 block in the north of the field. The well declined rapidly when brought on stream and there are indications of limited aquifer support. In its later life the well loaded up with water. The well was shut-in in June 1999 to tie it in for compression, but failed to flow subsequently, despite several attempts to unload it. Reserves of some 19 × 10^9 SCF of wellhead gas have been assigned to this block, of which 14 × 10^9 SCF have been produced.

K-10 and K-11 are the only wells in the northeastern block of the field. These wells are currently producing at 62 × 10^6 SCFD (wellhead gas), approximately 75% of the current field production rate. The analysis of the wellhead performance of this well to date, material balance (Fig. 11) and simulation indicate that it is draining a reasonably large pool. The GIIP of this pool is believed to be of the order of 180-220 × 10^9 SCF, out of which 18 × 10^9 SCF have been produced so far.

Initial and revised model

The initial reservoir model was based upon depth maps made by using old processed seismic data, which had some processing problems; the static correction being the main one. On the basis of these maps the reservoir was considered to be continuously spread all over the field (Fig. 12), while on the basis of the model the P50 reserves in the Core Area were estimated at 728 × 10^9 SCF.

After some production and the drilling of two unsuccessful wells – K-5 which was wet and about 100 m deeper than the prognosis and K-8 which was dry as it encountered non-reservoir quality sands – it was realized that the seismic data needed to be reprocessed. After reprocessing of the seismic data with proper static correction the new depth maps showed that the field consisted of a number of small accumulations (Fig. 3). The new P50 reserves estimate was below 200 × 10^9 SCF, assuming structural traps only and a constant GWC of 3284 mss.

Turning point

Up to the drilling of K-9, only the fault-bounded structural closures that have the E sand above 3284 mss in the Core Area were considered to be prospective. A new concept of a stratigraphic barrier in the north of the field was developed due

Fig. 8. The shot point location map of Kadanwari area. Echo Processing Center reprocessed the Core Area. After a test reprocessing, another c. 483 km were reprocessed by Mathtech.

Fig. 9. RFT data summary plot of Kadanwari wells. The FWL for most of the compartments in the field appears to be 3284 mss. Initial gas pressures in the K-10 block were 60 psia higher than the rest of the field. If a normal hydrostatic water gradient is assumed, as appears most likely, then this would imply a deeper FWL of around 3330 mss for the K-10 area.
to the finding of non-reservoir sands (zero permeability) in K-8 and two other wells just to the north of Kadanwari. In August 1998, K-10 was drilled to test this concept in the northeastern block, which has a dip closure to the east and south, is bounded by the main wrench fault in the west and is stratigraphically bounded to the north. This well was a great success, and encountered higher pressure than the other wells. This not only proved the stratigraphic trap in the north but also a deeper GWC. The estimated wellhead gas reserves on the basis of material balance and volumetrics are 150–200 $\times 10^9$ SCF. Two more wells have been drilled in this block to optimize the production from this area.

In October 1999 the change in expectations were strengthened by the successful production of the K-7, F sand, which is 50 m shallower than the major E sand reservoir. This was the result of a reservoir study in 1998 to investigate any upside potential in the already drilled wells in the Kadanwari Field. A thorough review of the drilling data, well logs and RFT/MDT data was carried out on all the wells of the field. Although there was no significant separation on neutron-density logs of the F sand, it was observed that the recorded RFT pressure point in

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**Fig. 10.** Field production performance graph, dominated by the contributions from wells K-6, K-7, K-10 and K-11. Wells K-7 and K-9 were initially completed on the E sand and, later on, were successfully tested in the F sand also. K-1 and K-6 drain the same fault-bounded block in the northern part of the field. Wells K-10 and K-11 are located in northeastern block of the field.

**Fig. 11.** P/Z plot of K-10/K11 block indicates that it is draining a reasonably large pool. The GIIP of this pool is believed to be of the order of 180–200 $\times 10^9$ SCF.
the F sand was on the same gas gradient as that of the E sand of this well. The suppressed neutron-density log response in both K-7 and K-9 could be attributed to the presence of minerals such as micas which tend to kill gas separation on these logs. A subsequent field-wide petrophysical re-evaluation has allowed such opportunities to be firmed up. Sometimes, unfortunately, the initial completion status of the wells complicates such recompletion opportunities. Recent wells have been completed bearing in mind such later potential completions.

Cost optimization

To turn the Kadanwari Field from a disappointment into a profitable project, one of the main steps was the change in development strategy which brought down future development and operating costs (Linn 1998). Recently a number of additional steps have been taken to reduce well cost.

Loss of circulation zones and the shale instability factor primarily determine the well design in the Kadanwari Field. A typical Kadanwari well consists of three casing strings and one liner string. After improving knowledge of the area, one casing string has been dropped, resulting in a 40% cost saving in K-11.

Because of the corrosive and sour nature of Kadanwari fluids and the initially planned well lives, 22% chrome alloy was used for down-hole completion and surface equipment. Later, with better understanding of the corrosive nature of the well fluids the metallurgy has been revised and K-11 was completed with 13% chrome. This resulted in a saving of 40% in the overall completion cost.

The wells in the southern blocks, with thickly developed but poorly consolidated E4 sands, produce under aquifer drive and normally require sand control. These wells and K-3 in the northern block were gravel packed. This meant significant additional completion cost. In K-10, after a careful and detailed inspection of E sand core, the incompetent and friable sections of sand were identified which might have been prone to sand failure. These possible sand-prone sections were avoided during perforation and the well was completed without a gravel pack. The well has produced sand free at around $34 \times 10^6$ SCFD for the past 2 years. In the recently completed K-11 well the same strategy was adopted and the well is currently flowing sand free at around $30 \times 10^6$ SCFD.

**FUTURE OPPORTUNITIES**

Recognition of the stratigraphic element to the Lower Goru play and the potential for wrench faults to seal, even where reservoir sands are juxtaposed across them, has opened up a new area of potential reserves additions for the Kadanwari Field.

Some other compartments of the field have been mapped since the early days of the Tajjal Concession. However, they
were remote from the K-1 discovery well and the subsequent Core Area development and, because the closure above a 3284 mss FWL was limited, they were downgraded. The deeper GWC of the K-10 block has encouraged the concept that independent fault compartments may have independent GWCs. Possible deeper contacts could provide significant upside potential in the field. In 1999 the discovery of the F sand as reservoir in K-7 and K-9 showed that shallower sands can also be prospective. Another anticlinal body at G sand level with internal prograde geometry and associated bright amplitudes (Fig. 13) is also very prospective. Preliminary volumetric estimates indicate a potential for additional GIIP in the range of 100–500 × 10^9 SCF.

These areas are under evaluation, with particular emphasis paid to careful reprocessing of existing seismic data to provide both new time series data and to evaluate these data for indirect evidence of hydrocarbons or lithology changes by AVO and inversion processing. Furthermore, advances in work station technology now allow detailed attribute analysis to be performed which will hopefully aid the understanding of reservoir presence and distribution.

Within the existing development area of the field there are opportunities for additional updip sidetracks or new wells, and for fracture stimulation of tight sands. Many opportunities remain to fully exploit Kadanwari’s potential.

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