Cross-equalization for Time-lapse Study in Balol Field, India

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Summary

A successful 4D imaging requires that the non-repeatable noise due to acquisition or processing between successive seismic surveys should be minimized to bring out 4D signal unambiguously. However, even well-designed, dedicated ime-lapse studies are contaminated by several sources of non-repeatable noise such as differences in source waveform, varying near-surface conditions, changes in geometry/offsets due to logistics and differences in source/receiver positioning, processing algorithms/flows, data dependent operators, velocity models and statics. The accurate matching of different datasets is a key issue in a time-lapse study to extract useful 4D signal.

In this paper, we present a case study to match two 3D datasets acquired at an interval of 12 months to monitor a thermal EOR process in the northern part of Balol Field of Cambay basin, India. The first 3D survey was conducted prior to the commencement of in-situ combustion process in the already identified set of injector wells and therefore was meant to serve as base 3D survey. The second 3D survey spaced 12 months thereafter was to become 1st monitor survey for studying the changes in the reservoir due to this thermal process. The matching procedure begins with identically processed PSTM gathers of the two datasets as inputs that undergo a step-by-step processing flow for gain correction, frequency balance, differential statics, phase adjustment and finally designing moving window match filter. The matched datasets are then differenced to derive 4D signal. Appropriate QC at each stage of the 4D workflow ensures that the desired 4D effect is preserved as the two datasets become increasingly comparable and look-alike in the non-reservoir zones where ideally no changes are expected. The final difference volume clearly shows high amplitude 4D anomalies around injector wells due to combustion/air injection. The possible fairways of flue gases and/or propagation of combustion can also be brought out through horizon/time slices and vertical sections.

Introduction

Monitoring of fire-flood or steam flood effects in a hydrocarbon reservoir is one of the most promising areas in which 4D seismic or time-lapse surveys have been successfully used in the past (Greaves & Fulp, 1987; Eastwood el al, 1994; Lumley 1995; Eastwood, 1997; Jenkins, Waite & Bee, 1997; Heaton et al, 2002). As the need for integrating 4D technology in a reservoir management workflow grows, more and more dedicated time-lapse surveys are being planned worldwide to achieve higher degree of seismic repeatability between successive surveys and derive a meaningful 4D signal. However, a simple differencing of identically processed seismic volumes even in case of dedicated surveys done for the purpose does not bring out the desired time-lapse effect in the reservoir due to non-repeatable noise and acquisition/ processing footprints. The accurate matching of different datasets is, therefore, a key issue in a time-lapse study to extract useful 4D signal. It involves a careful processing and calibration procedures that remove the different acquisition footprints, reduce the noise and retrieve the required time-lapse signature (Stucchi, Mazzotti & Ciuffi, 2005). As the individual case studies vary significantly, the industry is yet to develop a standard matching and calibration procedure, generically termed as 'cross-equalization,' that removes systematic differences between surveys attributable to non-repeatable seismic acquisition or processing (Lumley, 2001).

The time-lapse data for this study pertains to northern part of Balol Field, situated in the heavy oil belt of Mehasana block, Cambay basin, India (Fig.-1). The reservoir sands are within Kalol Formation which is overlain by Tarapur Shale. The major sand is KS-1 unit of Middle Eocene age at a depth of about 1000m, mostly unconsolidated with porosity in the range of 25-30 % and permeability varying between 1-5 darcies. The primary recovery of viscous oil from Balol Field is 10-12%. In-situ combustion process is being carried out in the field on commercial scale for improving the recovery of oil from the reservoir. Despite success of the process, the movement of thermal front and estimation of aerial sweep have remained unpredictable giving rise to uncertainties in the placement of future injector and producer wells. To address the issue, a timelapse study was planned in a small area of

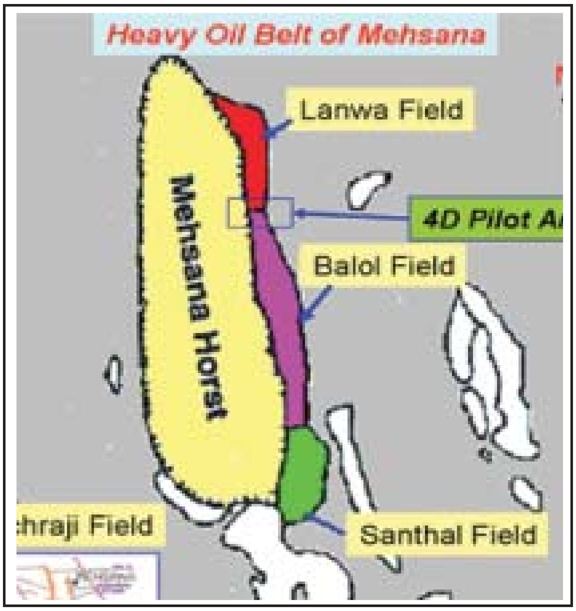

Fig. 1: Location map of Balol Field, Cambay Basin, India. The area of time-lapse study is marked by the blue rectangle in the northern part of the field.

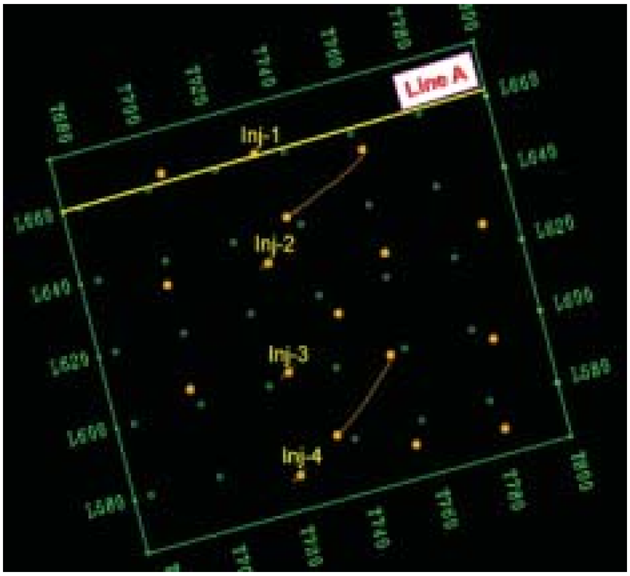

Fig. 2: Area of study with injector wells.

0.96x1.36 sq. km. in the northern part of Balol Field. A feasibility study based on rock physics and forward modeling indicated that in-situ combustion process can give rise to an observable change in seismic response due to substantial decrease in impedance in the combustion zone/ gas zone and thus it would be possible to monitor the thermal EOR in successive repeat surveys (Asit Kumar & Shyam Mohan, 2004). Accordingly, base 3D data, representing precombustion stage, was acquired during Oct-Nov, 2003 with a bin size of 10mx10m. After the acquisition of base 3D data was over, four wells in the area (Fig.-2) were put on in-situ combustion successively from north to south. First monitor 3D survey was carried out 12 months later under similar climatic conditions with same survey geometry and instrumentation to attain greater repeatability at the acquisition stage. Shot and receiver positioning accuracy between successive surveys was ensured by using Differential Global positioning System (DGPS).

Method

The basic processing of both the datasets was carried out in the identical manner. Table-1 shows the most significant steps of the processing applied to the data. Both the datasets were subjected to pre-stack time migration and the resulting PSTM gathers were utilized as the inputs for 4D processing workflow. The basic processing was aimed at true amplitude preservation, random noise elimination and to enhance repeatability through surface-consistent amplitude balancing by compensating for variation in source/receiver variation and other near surface effects. Base dataset was taken as the control input to which monitor dataset was matched during the cross-equalization process. The choice of control dataset was mainly guided by the bandwidth of base dataset which is somewhat lower than the monitor dataset. Attempting to increase the bandwidth of a survey can increase noise levels and make time-lapse interpretation more difficult (Rickett and Lumley, 2001).

Table-2 illustrates the important steps in a 4D processing workflow with PSTM gathers of base and monitor dataset as the input. The workflow starts with a basic preprocessing stage that establishes live sample range of input traces through spatial and temporal cross-equalization and sets a common geometry from both input volumes. In the present case, base as well as monitor data

Table 1 : Basic Processing Flow for base and monitor 3D datasets.

➢	Preprocessing and binning(10mX10m)
➢	TAR
➢	Surface Noise Attenuation to handle ground roll
➢	Surface Consistent Amplitude Balancing
➢	Surface Consistent Deconvolution
➢	Velocity picking
➢	Residual Statics
➢	Velocity model building and Updating
➢	Pre-stack Time Migration (PSTM)

Table2: 4D Processing Flow for base and monitor 3D datasets.

- ❖ **4D Processing Flow**
  - Preprocessing
    - o 4D Post Stack Geometry & Preprocessing
    - o CDP Intersect
    - o Pad after CDP/Time intersect and Stacked
    - o Time Intersection
- ❖ ***4D processing***
  - o ***Amplitude Envelope XEQ***
  - o ***Frequency Balance***
  - o ***Compute/Apply Global Shift***
  - o ***Statics/Time Variant Stretch***
  - o ***Differential Phase Adjustment***
  - o ***Scalar Gain/Variable Gain***
  - o ***Moving Window Match Filter***
- ❖ Differencing

were acquired with the same survey parameters and geometry and subsequently processed in identical way to minimize acquisition/processing footprints, thus obviating the need of any grid alignment or re-binning. However, only a subset of the entire volume covering the zone of interest adequately was considered to eliminate noisy/unwanted data near the extremes.

Preprocessing stage was followed by the actual 4D processing/cross-equalization stage involving a number of steps shown in italics in Table-2. The general idea here was to minimize the differences in amplitude, frequency, phase and time between two data volumes. Amplitude envelope XEQ was applied trace-by-trace to make the smoothed amplitude envelope of the input (monitor) data set similar to the control (base) dataset. Frequency balance was used to correct the seismic data for difference in spectral content between datasets. Global shift and phase shift were aimed to find the best global spatial, temporal and phase corrections and adjust the monitor dataset to match with the base dataset. Differential statics was applied to adjust the monitor dataset on a constrained space-variant basis to best match the base dataset. Differential phase was meant to adjust the waveform phase of the monitor dataset with the base dataset. Moving window match filter was used to compute and apply a set of match filters that remain constant in time but vary in space. All 4D processing operators were derived from time gates from non-reservoir part of the seismic volumes. The requirement of QC is vital for any 4D processing and hardly needs to be overstressed (Magesan et al, 2005). Therefore, the Differencing stage, although the final stage, was utilized through all the processing stages to QC and to assess the results of processing.

Results and Analysis

A time-laspe data typically contains the combined effect of geology, noise and time-lapse(4D) signal. The ultimate goal is to be able to see/extract the production/ injection effects by suitably removing geology and noise through the use of baseline data which presumably contains the former two effects only. Subtraction of monitor data from base data should ideally result in very little residual energy everywhere in the data volume except at the place where air injection/combustion has given rise to visible changes in the seismic response. However, without cross-equalization this is generally not the case (Ross et al, 1996). Fig.-3 depicts a simple difference section of base and monitor volumes along a line (Line A) passing through the injector well Inj-1 after basic processing of the two datasets. A high residual energy in the difference section indicates large difference in the energy levels of base and monitor data and only partial cancellation of the effects of geology and noise.

The purpose of amplitude envelope cross-equalization is to apply time and space variant corrections to make the smoothed amplitude envelope of the monitor dataset similar to that of control dataset. The scaling of amplitude was based on the RMS energy in the two surveys. Fig.-4 and Fig.-5 depict this equalization process. Amplitudes were balanced in the non-reservoir part of the

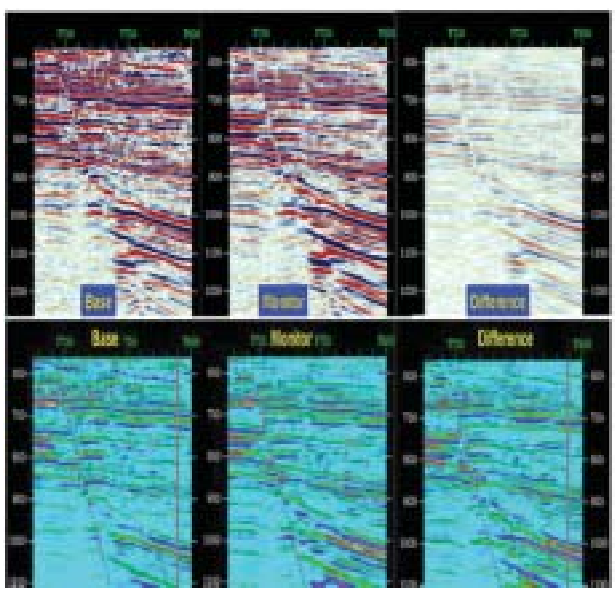

Fig. 3: Simple difference section of base and monitor datasets in different color scale (top and bottom) along Line A after basic processing.

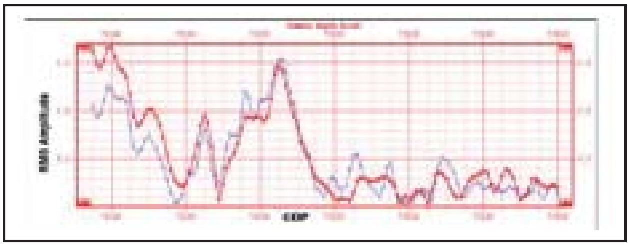

Fig. 4: RMS amplitude (unequalized) along Line A in non-reservoir part of the area. The plot shows RMS amplitude of base dataset in blue and that of monitor dataset in red.

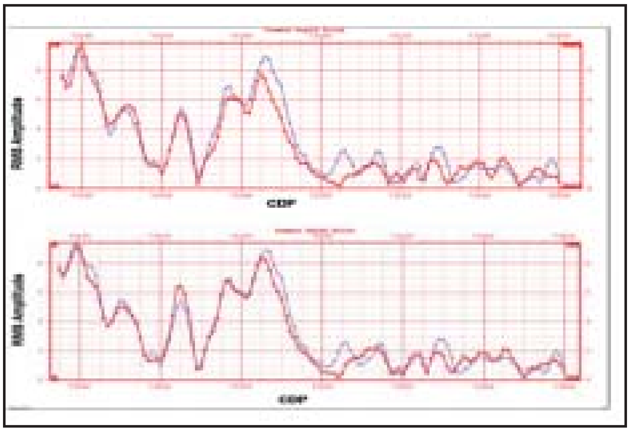

Fig. 5: Amplitude cross-equalization in non-reservoir part of the area. The plot shows RMS amplitude of base dataset (blue) and monitor dataset (red) along Line A indicated in Figure-2. The upper graph refers to RMS amplitudes after Amplitude Envelope XEQ while the lower graph indicates finally equalized RMS amplitude after match filter.

area where no changes are anticipated from one vintage to the other.

Thus, RMS amplitudes of base and monitor along Line A are clearly seen to have a very close mat ch in the non- reservoir part of the area after the equalization/ calibration. The high amplitude in monitor data (red/green) near CDP 73195 in the first (top) plot of Fig.-5 may be attributed to air injection/thermal effect due to injector well-1.

Fig.-6 shows the amplitude spectra of base and frequency content of monitor survey has somewhat higher temporal bandwidth than the base survey. However, to avoid any unwanted high frequency noise being added to base data, the monitor survey was brought to the level of the frequency content of base survey after frequency balancing of 4D workflow.

Usually, difference in phase between surve datasets. Even small phase mismatches can give rise to

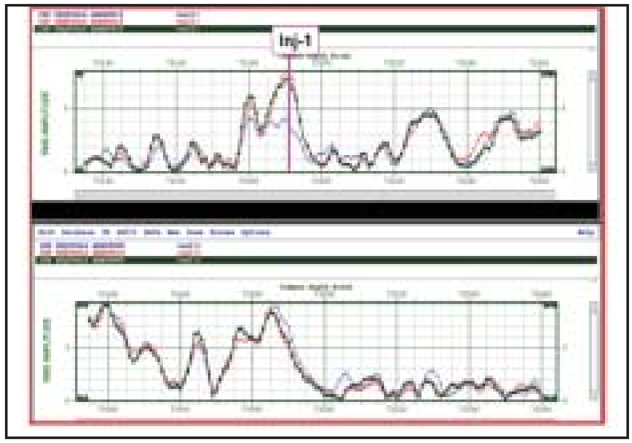

Fig. 6: Amplitude plots after cross-equalization in both reservoir (top) and non-reservoir (bottom) parts of the area along Line A. The blue curve refers to base, the red and green curves refer to monitor after amplitude

considerable error in the difference volume and therefore need to be corrected (Ross et al, 1996). Fig.-7 displays various amount of positive/negative phase correction applied to monitor data which generally varied between 10° to -10°, except near the eastern limit of the study area where it was little more than 30°.

Apart from the 4D processes describe above, other important corrections applied to the monitor database include global shift, time variant stretch (Fig.-9), differential phase adjustment and moving window match filter. A variable gain was later applied to fine-tune the matched volume.

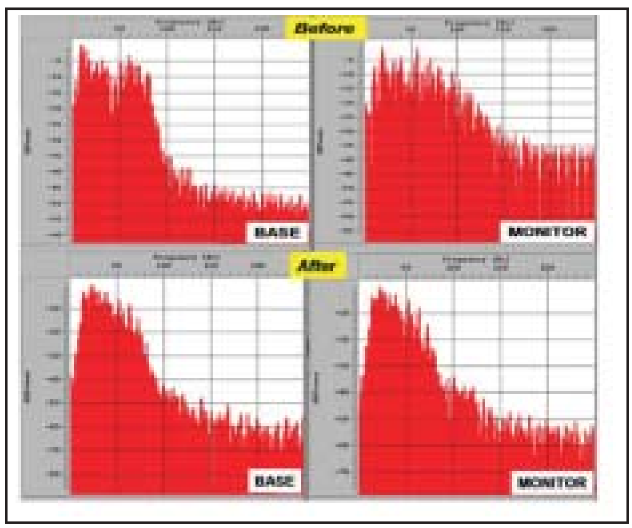

Fig. 7: Frequency balancing of monitor and base monitor data. Lower plot shows the frequency spectrum along Line A after frequency balancing.

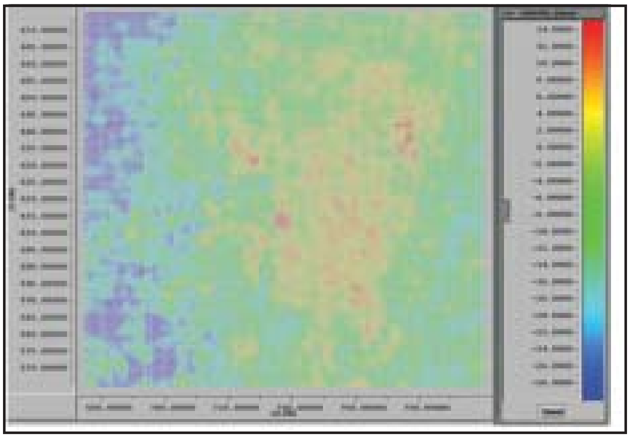

Fig.8: Phase balancing of monitor and base datasets.

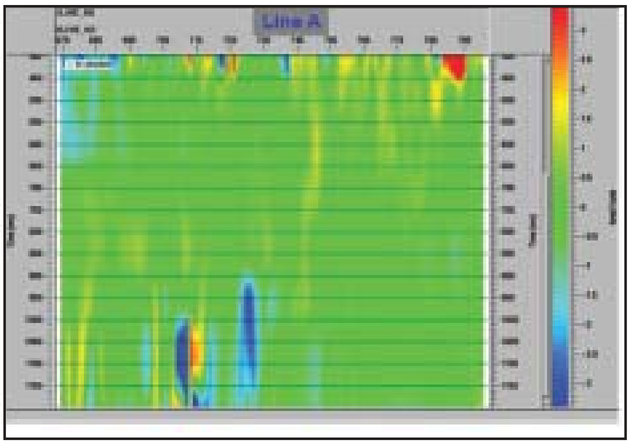

Fig. 9: Time-variant stretch applied to the monitor data. The QC panel along Line A shows the stretch to rough well Inj-1. 4D anomaly is clearly seen in the ifference section.

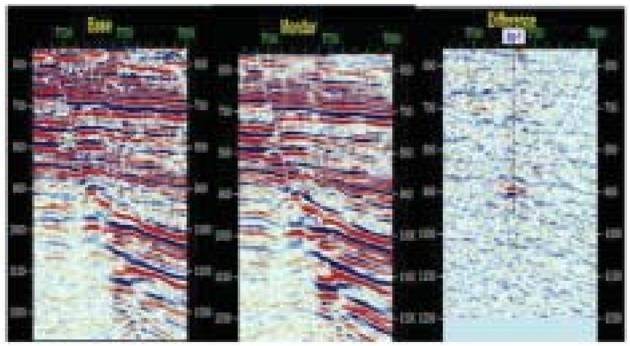

Fig. 10: Final difference section along Line A passing through well Inj-1. 4D anomaly is clearly seen in the difference section.

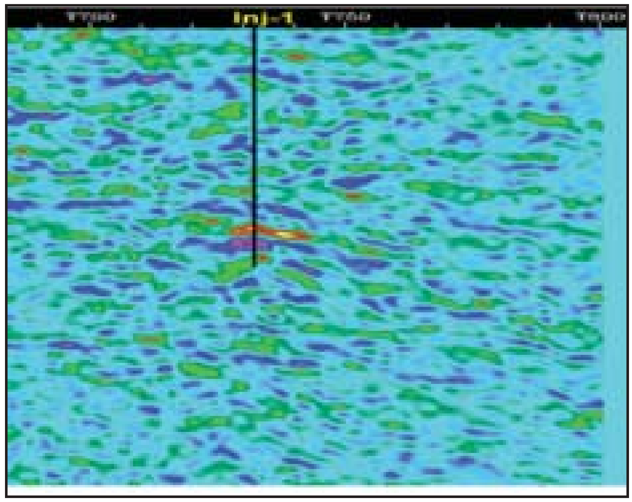

Fig. 11: Seismic difference section passing through well Inj-1

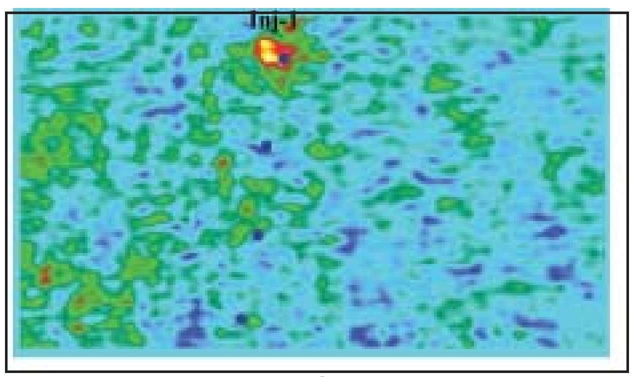

Fig. 12: Time slice at 892 ms.

Attributes and plots generated at the end of each step in the workflow were used to evaluate the efficacy of the applied process as well as to cross-equalization of both datasets. This approach of rigorous QC also ensured consistency of amplitude, phase, time and spectral content of the datasets. Following an iterative procedure, which progressively produced better matched data volumes and improved imaging of 4D anomaly in the reservoir zone, we obtained the final difference cube. Fig.-10 shows one such section from the cube passing through well Inj-1. The brightening up of amplitude near the reservoir top at the well is clearly identifiable and is indicative of the effect of combustion. Fig.-11 is a vertical difference section in different color scheme of Line A which shows the most affected zone of reservoir near the well in hot colors. Similar anomalies were also observed at other locations of injectors although with varying degree and extent. Figs.-12 and 13 represent two time slices at 892 ms and 910 ms respectively which approximately correspond to upper zone of combustion/injection at wells Inj-1 and Inj-2. At both these locations, the aerial extents of the affected zones are conspicuously visible. Thus, with careful processing and matching procedure, 4D anomaly can be clearly and unambiguously brought out in the difference volume which can subsequently be interpreted with very good confidence.

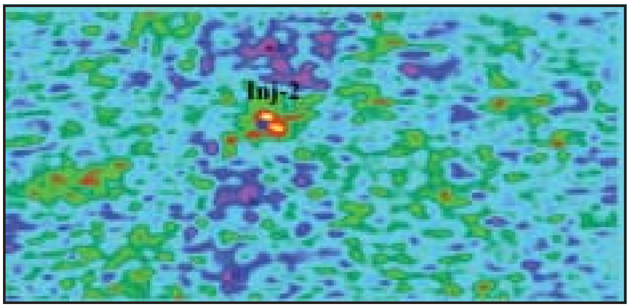

Fig. 13: Time slice at 910 ms.

Conclusions

Cross-equalization of different vintage datasets is essential even for well-designed, dedicated time-lapse surveys which are processed with the same set of parameters. The results in case of Balol Field demonstrates that careful 4D processing can significantly enhance repeatability and interpretability of time-laspe seismic data for monitoring in-situ combustion process.

Acknowledgments

The views expressed in this paper are those of authors only. The authors express gratitude to Oil and Natural Gas Corporation Limited for providing necessary infrastructure to carry out this work. The authors expre thanks to Dr. C.S. Jain, GGM-Head, Institute of Reservoir Studies, Ahmedabad for according permission to present/ publish this work in Conference at Kolkata in 2006. The encouragement and guidance given by Shri Dinesh Chandra, GM-Development Offshore, IRS is gratefully acknowledged. The many fruitful discussions with members of Balol Development Group

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