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Vibroseis Deconvolution with Maximum Likelihood Approach

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Summary

The most commonly used deconvolution (Decon) method is based on minimum-phase assumption for the wavelet which is often not valid. Explosive energy source is close to minimum-phase which makes seismic data with explosive somewhat amenable to predictive Decon though the result is imperfect in phase. Decon of Vibroseis data is more problematic because the wavelet in a correlated Vibroseis trace is mixed-phase in nature. In the commonly used method for Vibroseis Decon, the Klauder wavelet is replaced with its minimum-phase equivalent which is a difficult proposition for band limited Vibroseis sweep. As an alternative, we have used Maximum Likelihood Deconvolution (MLD) for Vibroseis data because it has no restrictive assumption for the phase of the wavelet.

Use of MLD for Vibroseis data of Vindhyan basin in the north central part of India where delineation of locales with fault activity which may lead to fracture induced secondary porosity is an important exploration objective. A number of faults including subtle ones are well resolved in MLD data of Jabera dome area in the southeastern part of the basin where a deep seated fault system forming flower structure is seen. It is likely that this fault system has contributed to secondary porosity in Jabera dome area where gas was found.

Introduction

Spatial distribution of earth's reflectivity depends on the distribution of lithofacies which in turn is governed by sea level changes during sedimentary cycles (Mushin etal, 2000). Thus, linking the acoustic impedance boundaries to layer interfaces is one important aspect of seismic interpretation. Correlation of stratal boundaries to seismic events is primarily based on the assumption that a seismic section mimics the distribution of normal incidence reflectivity of the earth. Since a seismic trace is the product of convolution of earths reflectivity and the source wavelet, extraction of the reflectivity from the seismic trace by removing the wavelet, i.e., deconvolution is an important problem of seismic data processing. Several deconvolution of this, predictive deconvolution is effective to some extent for seismic data acquired with explosive energy source procedures with varied degree of applicability and efficacy are available for achieving this goal of which the least square inverse filtering (Robinson, 1957) is the most commonly used in the industry. A common difficulty with most of the deconvolution methods including the least square inverse filtering is the assumption of minimum-phase for the wavelet which is often not met.

A seismic wavelet is the result of convolution of various time varying factors like earth's attenuation, different types of multiples, and time independent effects such as response of the recording system. These effects are known to be minimum-phase in nature (Futterman, 1962; Robinson and Trietel, 1977; Robinson and Saggaf, 2001). Thus, if the seismic energy source is minimum-phase, the effective wavelet in a seismic trace too, is minimum-phase. Because which is close to minimum-phase though the result is somewhat imperfect in phase.

The problem of deconvolution of Vibroseis data is even more formidable because Vibroseis, unlike explosive is not an impulsive source and the embedded wavelet in correlated Vibroseis trace is not minimum-phase (Robinson and Saggaf, 2001; Ristow and Jurczyk 1975). Despite of this, deconvolution of Vibroseis data is often done just in the same manner of deconvolution of explosive data. Proper deconvolution of Vibroseis data is important not only for stratigraphic and structural interpretation, it is crucial for seamless integration of Vibroseis data with data acquired with other energy sources. The problems associated with various methods of deconvolution of Vibroseis data have been pointed out by various authors, e.g., Yilmaz (1987) and Cambiosis (2000).

Deconvolution of Vibroseis data

A seismic trace z(t) can be represented by the convolution model, $z(t)= r(t)* w(t) + n(t)$, where r(t) is earth's reflectivity, w(t) is the source wavelet and n(t) is the additive noise. For Vibroseis this becomes,

$v(t)= r(t)*e(t)*s(t) + n(t)$, where v(t) is the recorded Vibroseis trace, e(t) is earth's transmission filter and s(t) is the Vibrator sweep. The raw Vibrosesis data is crosscorrelated with the sweep to obtain data that can be interpreted. A crosscorrelated Vibroseis trace is given by,

$v_c(t)= r(t)* e(t)*s(t)*s(-t) + n(t)*s(-t) = r(t)* e(t)*k(t) + n(t)*s(-t)$, where $k(t) = s(t)*s(-t)$ is the Klauder wavelet which is zero-phase. The effective wavelet e(t)*k(t) in a correlated Vibroseis trace is thus a mixed-phase wavelet. Evidently, deconvolution of Vibroseis data with minimum-phase assumption, the mainstay of standard deconvolution processing will not give correct result.

As a solution to this problem, replacing the Klauder wavelet by its minimum phase equivalent has been tried (Ristow and Jurczyk 1975). However, there is no unique minimum phase equivalent of the Klauder wavelet. Construction of this minimum phase equivalent requires amplitude spectra outside the swept frequency which is generally met by adding white noise to the data. It has been shown by Bickel (1982) that different levels of white noise lead to markedly different equivalent wavelets. Secondly, the effect is Q dependent; it increases with increasing level of earth's attenuation (Gibson and Learner 1984). To tackle this problem, Cambiosis (2000) has proposed a spectral replacement technique in which instead of adding white noise, the low frequency part of the amplitude spectra is replaced by decay estimated from the amplitude spectra of the sweep.

In another approach, instead of replacing the Klauder wavelet with its minimum-phase equivalent, Robinson and Saggaf (2001) proposed a method based on polynomial factorization in which the Klauder wavelet is removed, i.e., the resultant trace emulates data acquired with explosive source.

In the present study, we have used Maximum Likelihood Deconvolution (MLD) based on state-phase formulation

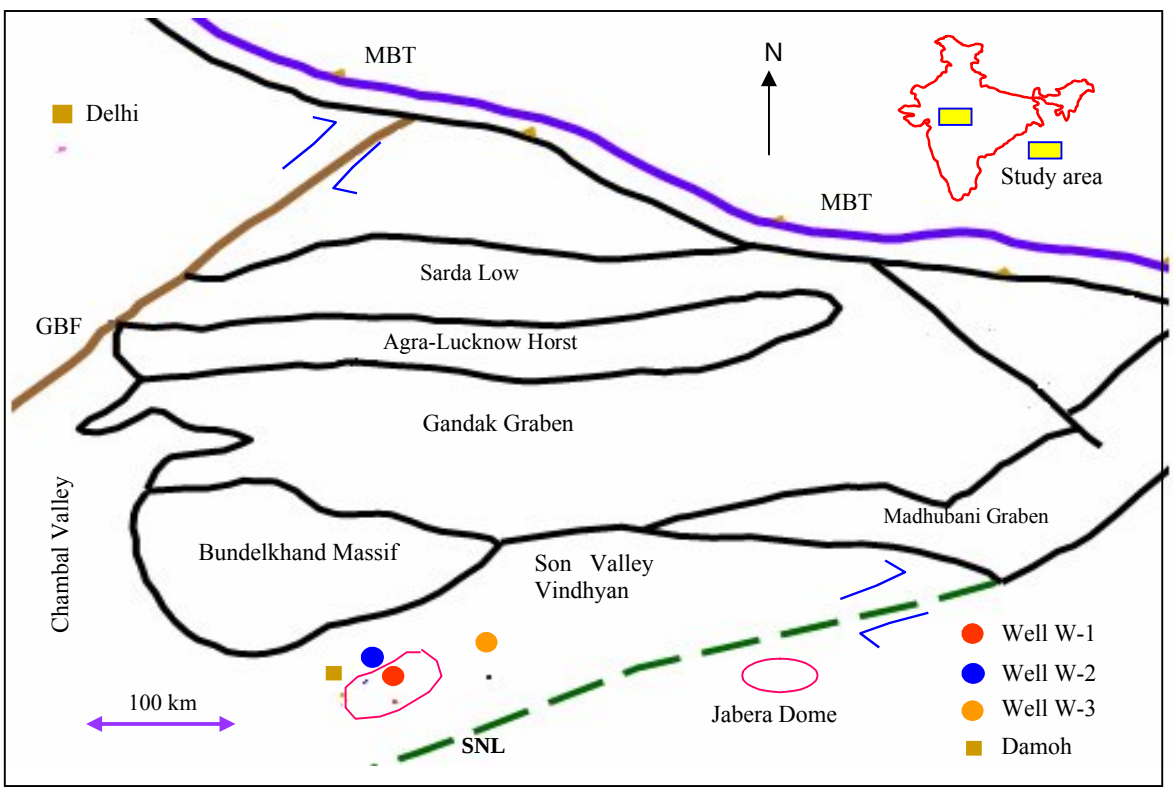

Figure 1. Major tectonic elements of Vindhyan basin. MBT: Main Boundary Thrust. GBF: Great Boundary Fault. SNL: Son-Narmada Lineament.

(Mendel, 1983; Chi et al, 1984; Goutsias and Mendel, 1986) to remove the embedded wavelet in a Vibroseis trace. This has the advantage that the additional task of conditioning the data to data acquired with explosive prior to deconvolution can be avoided because MLD involves no restrictive assumption for the phase of the wavelet. We have used this method for Vibroseis data in Vindhyan basin (figure 1) in the north central part of India.

The exploration problem

Vindhyan basin is a Proterozoic peri-Cratonic rift basin (Jokhan Ram et al, 1996) with several kilometers thick clastic and carbonate sediments. It is bound by the Great Boundary Fault (GBF) in the northwest and Son-Narmada Lineament (SNL) in the southeast. The roughly N-S trending Bundelkhand massif divides the basin in two parts, the eastern part is known as Son-valley Vindhyan and the western one as Chambal valley. The basin has drawn considerable attention because of its similarity with many other Proterozoic basins of the world with established hydrocarbons, eg, McArthur basin, Australia. Vindhyan sediments form two major sequences, namely, the lower Vindhyans and the upper Vindhyans. There are three wells in the basin of which gas was found in a siltstone layer near top of Deonar formation of the Semri group of lower Vindhyan sequence in the well W-1 in Jabera dome area, a prominent folded structure in the southern part of Son valley area. The other two wells, W-2 on Damoh structure and W-3 to the northeast of Jabera structure are dry.

The main problem in the area is lack of good reservoir facies as the Vindhyan sediments have low primary porosity and permeability because of digenetic effects. Nonetheless, considerable fractured induced secondary porosity is expected in the basin. Secondly, some reservoir facies are expected to be preserved in stratigraphic and subtle traps (Pratap et al, 1999). Identification of entrapment locales with good build up of secondary porosity and or with remnant reservoir facies is important exploration targets in the basin. Mapping of such features requires seismic data with well resolved events.

Maximum Likelihood Deconvolution (MLD)

In MLD, the convolution model of seismic trace is replaced by a state variable model and deconvolution is formulated as an L2 norm optimization problem of an objective function. In this sense, MLD is a deterministic inversion scheme. The main difference of MLD with other deconvolution methods are that it involves no a priori assumption for the phase of the wavelet. MLD is an iterative process between two steps, the first being estimation of reflectivity with an initial estimate of the wavelet and then estimation of the wavelet by maximum likelihood method.

It is known that the output of deterministic inversion of band limited seismic data is a sparse reflectivity series

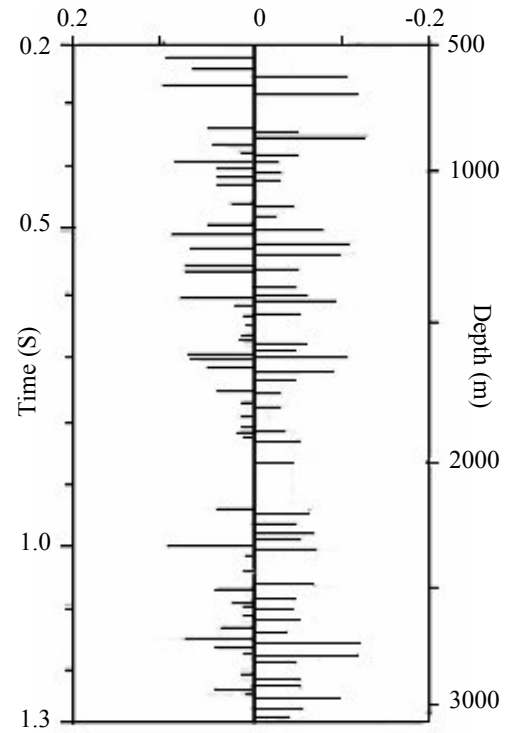

Figure 2. Reflectivity series at the well W-1 from sonic data.

(Francis, 2006). In MLD, the reflectivity is explicitly formulated as sparse and modelled as an assemblage of relatively small number of large spikes for reflection from the stratal boundaries in a background of small spikes representing smaller features. The reflectivity series is represented as a zero mean Bernoulli-Gaussian process. Estimation of reflectivity series too, is a two step process- estimation of locations of the spikes and their reflection strengths. Subsurface reflectivity computed from sonic data of the well W-1 (figure 2) supports sparse reflectivity series in the study area. There are only a few widely spaced spikes of magnitude of ~ 0.1 in figure 2 while most of the spikes have magnitude of less than 0.05.

The wavelet is modelled as an Auto Regressive Moving Average (ARMA) process and the z- transform w(z) of the wavelet of order n is expressed as,

$$w(z) = \sum_{i=1}^{n} b_i z^{-i+1} \quad / \sum_{i=1}^{n} a_i z^{-i}$$

Instead of minimizing the prediction error $\Sigma (z - r*w)^2$ as in Wiener algorithm, in MLD the quantity $\Sigma ((z - r*(A/B))^2$ is minimized with respect to the ARMA parameters A and B. This requires an initial guess of the wavelet. For this, we have used wavelet obtained by minimum-phase spectral factorisation of the ARMA representation of

autocorrelation (Mehta *et al*. 1991). In MLD, the wavelet may change from trace to trace and the final wavelet may not be minimum-phase. The starting wavelet and the final extracted wavelet at one location on a seismic profile are shown in figure 3. The MLD processing has been done with FORTRAN code developed by Mehta *et al*. (ONGC internal report, 1988).

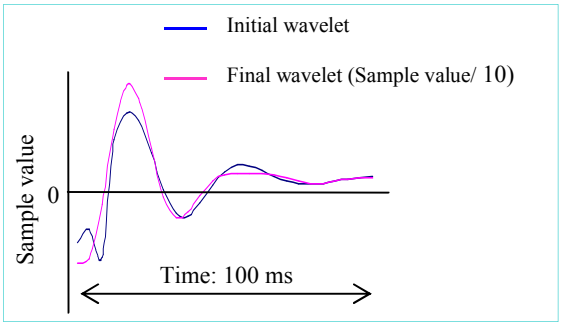

Figure 3. Staring and final wavelet at one location.

MLD of Vibroseis data

Proper treatment of the reflection phase is important for meeting the degree of detail required for value added stratigraphic and structural interpretations of modern day complex exploration problems. Prospectivity of Vindhyan basin is inexorably linked to fracture induced secondary porosity, stratigraphic entrapments and subtle traps. Properly deconvolved data is an imperative for delineation of such prospects. For this, we have used MLD because it is a high resolution method even for narrow band data (Goutsias and Mendel, 1986). We believe that MLD sans any a priori assumption for the phase of the wavelet can effectively remove the mixed-phase embedded wavelet from Vibroseis data and have been used in Jabera dome-Damoh area in the southeastern part of Vindhyan basin.

The data were acquired with 30 fold split-spread configuration with both receiver and shot interval of 50 meters. The Vibrators were used in linear up-sweep mode. Layout of the seismic lines is given in figure 4. f-k filter was applied on final post-stack migrated data for improvement of data quality prior to MLD. Many structural and stratigraphic features not clear in migrated data are well resolved after MLD. Correlated MLD section for line L-02 is shown in figure 5. Recently, Chatterjee and Dutta (2007) have identified from MLD data sixteen seismic sequences in the area correlatable with well data.

In addition to the stratigraphic features, reliable fault mapping is an important objective here because of their likely bearing on development of secondary porosity. Gibson and Learner (1984) have shown the importance of proper choice of wavelet for deconvolution for delineation of faults. MLD has greatly facilitated identification and interpretation of faults including subtle faults because the breaks in seismic events are clear after removal of the wavelet.

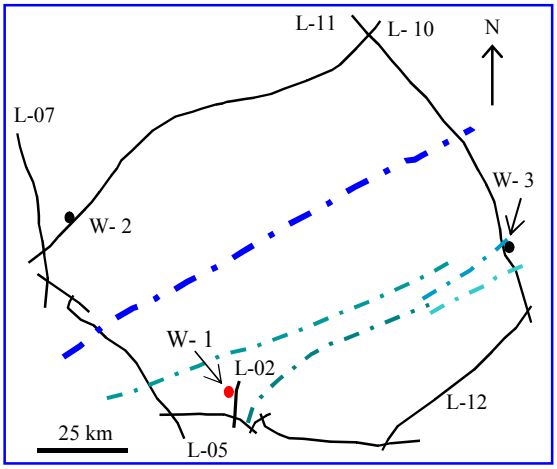

Figure 4. Seismic location map. Effective lines after crooked profile adjustment shown. Great Vindhyan Syncline.

One conspicuous feature in MLD data of line L-02 (figure 5) in Jabera dome area is a deep seated fault system forming flower structure. This fault system has affected all the stratigraphic levels of Vindhyan sedimentary column. On the other hand, no significant fault activity is seen around the well W-2 in the western part of line L-10 (figure 6) and in the southern part of line L-07 (figure 7) over western flank of Damoh structure.

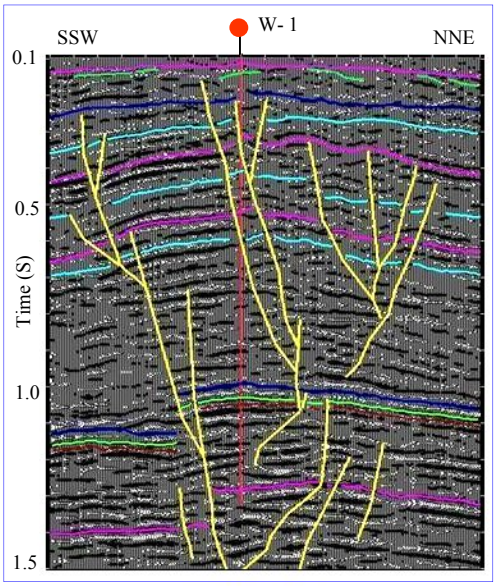

Figure 5. MLD section along L-2. A reverse fault system forming flower structure is well resolved

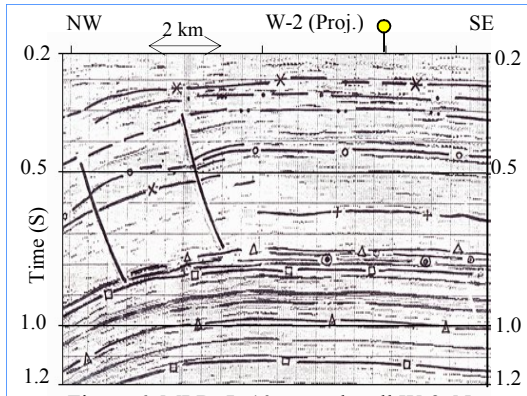

Figure 6. MLD: L-10 around well W-2. No significant faulting near the well.

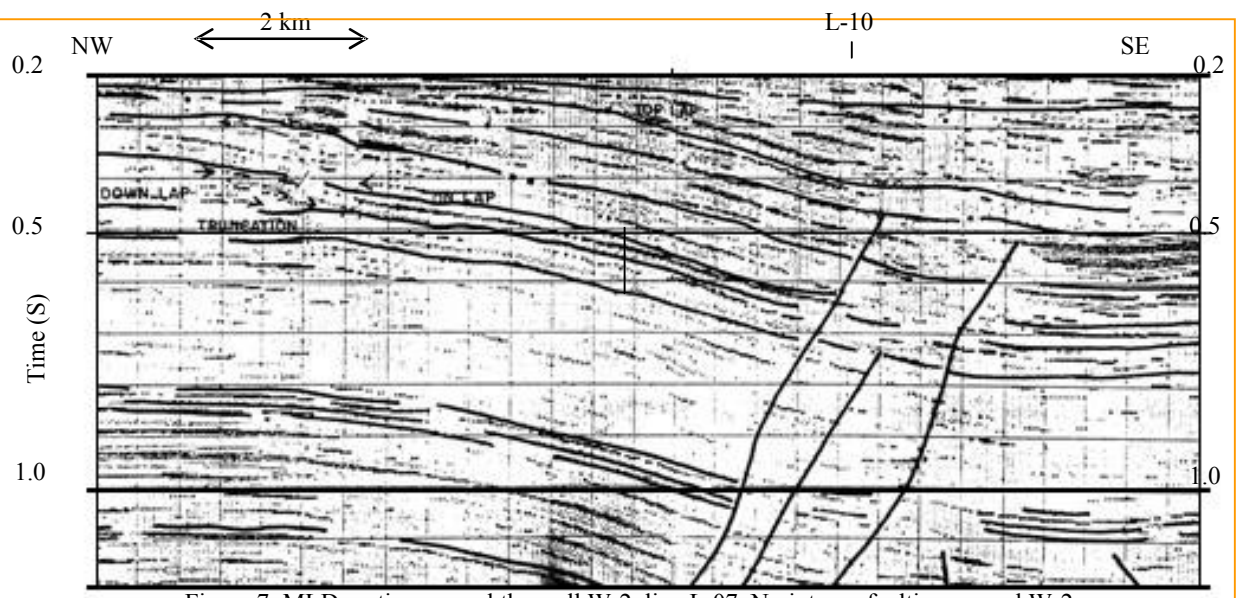

Figure 7. MLD section around the well W-2, line L-07. No intense faulting around W-2.

It is interesting to note that the gas was found in the well in area of high degree of faulting whereas the well in the moderately fault affected area is dry. The most plausible reason for this is that secondary reservoir characteristics because of faulting has not developed in Damoh structure. On the other hand, intense faulting in Jabera dome area has contributed to fracture induced porosity and enhanced reservoir property.

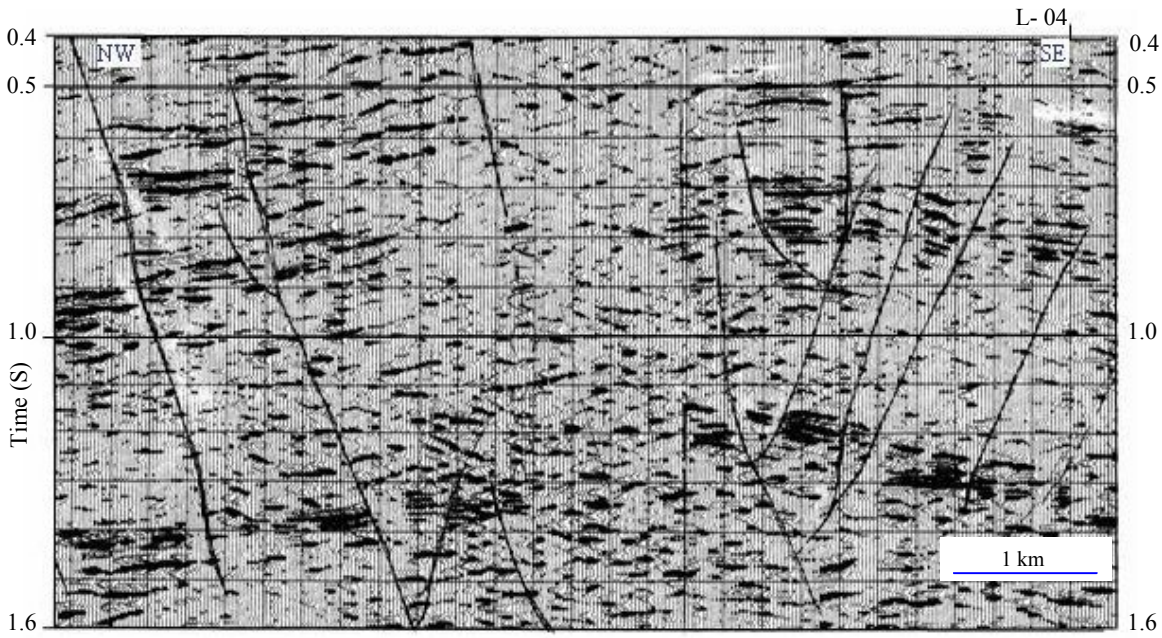

Figure 8. MLD: L-05 (southern part). Intense faulting around Jabera dome area.

Conclusion

The commonly used methods for deconvolution are not suited for Vibroseis data because of the mixed-phase nature of the effective wavelet in Vibroseis trace. MLD sans any restrictive assumption for the phase of the wavelet is an effective method for removing the mixed phase Vibroseis wavelet. With MLD, the additional task of finding equivalent minimum-phase wavelet for the seismic wavelet in Vibroseis data prior to deconvolution is avoided.

Because of effective removal of the wavelet, MLD enhances both structural and stratigraphic resolution. MLD of Vibroseis data in Jabera dome-Damoh area in the southeastern part of Vindhyan basin has resolved various stratigraphic and structural features not clear in migrated data. Various faults including subtle faults are clear in MLD data. A deep seated fault system affecting Vindhyan sediments and forming flower structure is clear in MLD data of Jabera dome area.

Intense faulting in Jabera dome area has contributed to secondary porosity improving reservoir quality. The only well in which gas was found in Vindhyan basin is located in the fault affected zone. Damoh structure is not much affected by faulting as a result of which secondary porosity has not developed and the well W-2 is dry.

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