Seismic diffraction imaging for improved coal structure detection in complex geological environments

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SUMMARY

To provide a "no major surprises" guarantee of coal seam conditions, reflection seismic surveying is often used for delineation of faults and dykes that have the potential to disrupt underground coal mining operations. Although reflection seismic methods are usually effective for locating faults with throws greater than 5-10 m for 2D and 2-5 m for 3D seismic data, detection of faults with smaller throws, shears and dykes with widths of a few metres remains a challenge to seismic methods.

Instead of ignoring or suppressing diffractions by conventional seismic data processing, it has been demonstrated that diffractions contain valuable information, which can be used for identification of subtle coal seam structures. In this paper, we describe a moving average error filter (MAEF) applied in the neighbouring traces to extract diffractions from post-stack reflection seismic data. The filter estimates the reflections with the average values of the neighbouring traces along the reflection direction or dip, which can be computed by the gradients of seismic data. The difference (or error) between the original data and the estimated reflections, yields the diffractions. By identifying diffractions, small faults and other minor features that are difficult to detect using conventional seismic reflection processing can be detected. Numerical and real data examples are used to illustrate the effectiveness of the proposed method in coal seam structure detection by extracting diffractions from reflection seismic data in a relatively complex geological environment.

Key words: reflections, diffractions, fault detection.

INTRODUCTION

Due to its superior performance, seismic reflection surveying, especially 3D seismic, has been a major technique in the Australian coal mining industry for coal seam structure detection, to provide a "no surprises" guarantee of seam conditions before mining. For seismic data from coal formations, it is generally accepted that seismic reflection methods have the ability to locate faults with throws greater than 5-10 m for 2D and 2-5 m for 3D seismic data (Zhou and Hatherly, 2000 a & b; Zhao and Wu, 2005). However, the detection of more subtle faults, thin dykes and other minor geological features is still a challenging task for reflection seismic methods. An alternative way to address this challenge is through diffraction imaging.

According to seismic wave theory, in addition to reflections commonly used in seismic surveying for structural delineation, there are diffractions generated when a seismic wave encounters subsurface horizon discontinuities such as faults, dykes and fractures. Diffractions can be generated by any objects that are less than a seismic wavelength in size and therefore they can be used for high resolution imaging of small faults and other small features. In fact, this is not a new concept. In the early days of seismic surveying, diffraction patterns were sought by seismic interpreters as an indication of faulting, especially for small faults where the discontinuities of the seismic reflections are less evident (Krey, 1952; Hagedoorn, 1954; Kunz, 1960; and Trorey, 1970). Most modern seismic processing procedures, such as stacking and migration, are aimed at suppressing these diffractions (Khaidukov et al., 2004; Bansal and Imhof, 2005; Moser and Howard, 2008). However, in recent years, techniques for diffraction imaging developed for petroleum seismic data processing, makes small fault detection possible by separating the diffraction events from the reflection seismic events (Shtivelman and Keydar, 2004; Fomel et al., 2007; and Landa, 2010). Various applications of diffraction imaging have been reported: fault and other discontinuity detection (Neidell, 1997; Landa, 2010; Zhu and Wu, 2010; Sturzu et al., 2014); seismic velocity analysis (Harlan et al., 1984; Landa and Fomel, 2008; Reshef and Landa, 2009); tunnel digging monitoring (Landa and Keydar, 1998); CO_2 sequestration monitoring (Alonaizi et al., 2014); unconventional reservoir characterisation (Rauch-Davies et al., 2014; Sun et al., 2014); and complex geological imaging in hard rock environments (Tertyshnikov et al., 2014).

Recently, we developed a moving average error filter (MAEF) technique in conjunction with a seismic event flattening process, to extract diffractions from conventional reflection coal seismic data (Zhou et al., 2017). The extracted diffractions can be used as an aid to detect potential structures such as faults and dykes of a few meters. This MAEF filter requires that the coal seam strata are relatively flat or sub-parallel. Although this is true in many coal mining situations, coal seams are not always parallel and may dip at different angles. To accommodate more complex geological settings, in this paper we first estimate the local dip and then apply the MAEF filter in the corresponding reflection direction to extract diffractions from reflection seismic data. We use numerical and actual coal seismic examples to illustrate the feasibility of this extended MAEF filter, in diffraction imaging for coal seismic fault structure detection.

DIFFRACTION IMAGING BY MAEF

Diffraction Extraction by MAEF

One of the most important steps in seismic diffraction imaging is to extract or separate diffractions from reflections. However, care is required as the diffraction events, which are very much weaker in amplitude than the specular reflections, are generally obscured and often beneath recognition thresholds, especially on post-stack data and in the presence of noise (Klem-Musatov, 1994; Reshef and Landa, 2009). Yet they carry very diagnostic information about small seam disruptions, such as faults and dykes, which may be hard to see as vertical offsets on conventional reflection sections. Many approaches have been proposed to extract diffractions from reflection seismic data, including: the local slant stack (plane wave decomposition, τ-p transform) (Harlan et al., 1984 and Fomel et al., 2007); plane-wave destruction filter (predictive error filter) (Fomel, 2002 and Taner et al., 2006); focusing and defocusing approach (Khaidukov et al., 2004; Berkovitch et al., 2009; Landa et al., 2010); dip angle domain common imaging gathers (Sava and Fomel, 2003; Klokov and Fomel, 2012; Zhang and Zhang, 2014), and common reflection surface (CRS) stack approach (Dell and Gajewski, 2011; Asgedom et al., 2013; Faccipieri et al, 2013).

In searching a simple and yet effective approach for extracting diffractions from seismic data, in recognition of the fact that coal seam reflectors are sub-horizontal and sub-parallel in many mining situations, Zhou et al. (2017) used a moving average error filter (MAEF), after aligning or flattening the dominant reflector of interest (eg coal seam being mined), which enables the separation of the diffracted energy from the reflected energy as it exploits the hyperbolic moveout of the diffractions. The filter estimates the reflections with the average values of the neighbouring traces. The difference (or error) between the original data and the estimated reflections, yields the diffractions. This approach is essentially very similar to the plane-wave destruction filter (predictive error filter) of Fomel (2002) and Taner et al. (2006). Once separated and enhanced, the diffraction events (after compensation for the earlier reflection flattening operation) can then be added back into the original stacked section where they are much more prominent and their apices time-aligned with the horizon of interest, as demonstrated by the authors. This filtering process has the advantages of its simplicity, fast computation and effectiveness.

Non-iterative Local Dip Estimation

The key requirement for the application of a MAEF is that the reflections are horizontal. If they are not, a flattening process through static time-shifting of the target horizon is required before applying the filtering process to extract diffractions so that dipping and undulating horizons can be accommodated. Although this is true in most coal mining situations, coal seams are not always parallel and may dip at different angles. To accommodate these more complex geological settings, the MAEF filter can be applied to the location direction or dip of the reflection, providing the local dip can be reliably estimated.

To enable application of the MAEF filter in the dip direction, we first need to estimate the local dip of the seismic event on the seismic section. To do this, we assume that the observed seismic waves can be considered as plane waves at observation points. The local plane wave can be expressed as (Claerbout, 1994; Bednar, 1997; Fomel, 2002)

$$\frac{\partial P(x,t)}{\partial x} + \sigma(x,t)\frac{\partial P(x,t)}{\partial t} = 0 \ , \tag{1}$$

where $P(x,t)$ is the seismic wavefield and $\sigma(x,t)$ is the local seismic dip or the apparent slowness unit on seismic section as a function of distance x and time t. The dip is in time unit per distance unit. From equation (1), the local seismic dip $\sigma(x,t)$ can be estimated by the gradients or the derivatives $\frac{\partial P}{\partial x}$ and $\frac{\partial P}{\partial t}$ of the seismic wavefield,

$$\sigma(x,t) = -\frac{\partial P(x,t)}{\partial x} / \frac{\partial P(x,t)}{\partial t} \ , \tag{2}$$

or

$$\sigma(x,t) = -\left(\frac{\partial P(x,t)}{\partial x} * \frac{\partial P(x,t)}{\partial t}\right) / \left(\frac{\partial P(x,t)}{\partial t} * \frac{\partial P(x,t)}{\partial t} + \varepsilon\right) \ , \tag{3}$$

where ε is a very small value for stabilising the computation of the dip when the wavefield or its time derivative $\frac{\partial P}{\partial t}$ is ignorable. Based on equation (3), one can easily estimate the seismic local dips by computing the first derivatives of the wavefield, which can be computed by any numerical methods such as the standard finite difference (FD) approach or the Fast Fourier transform (FFT) method. Unlike Fomel's plane wave destruction approach (Fomel, 2002), this approach is non-iterative, making the dip estimation easy to implement and fast in computation. To improve the dip estimation for noisy data, one may implement the computation of equation (3) using the average wavefield or gradients of the wavefield in a specified window.

RESULTS

Local Dip Estimation

Figure 1 shows an example of estimation of local seismic dips. Figure 1(a) is the synthetic seismic section in which there are 4 horizons labelled as H1 – H4. The 4 horizons have variable dips, which are formed by superimposing a given dip variation (of sinusoidal form) on its own background dips increasing from the top to the bottom. The dips are represented in time samples per trace. Figure 1(b) presents the estimated local dips of the 4 events in Figure 1(a). The gradient derivatives of the seismic waves were computed using a 5 point central FD algorithm and the dips estimated by equation (3) were filtered by a median filter of 5 traces by 11 time samples. Figure 2 compares the estimated dips with the corresponding true dips for these 4 events. From Figure 2, it is clear that estimated dips are, for this noise-free situation, almost identical to the true dips for all 4 events except for those dips at the start and end of the section where the derivatives of the wavefields could not be accurately calculated by the 5-points FD operator.

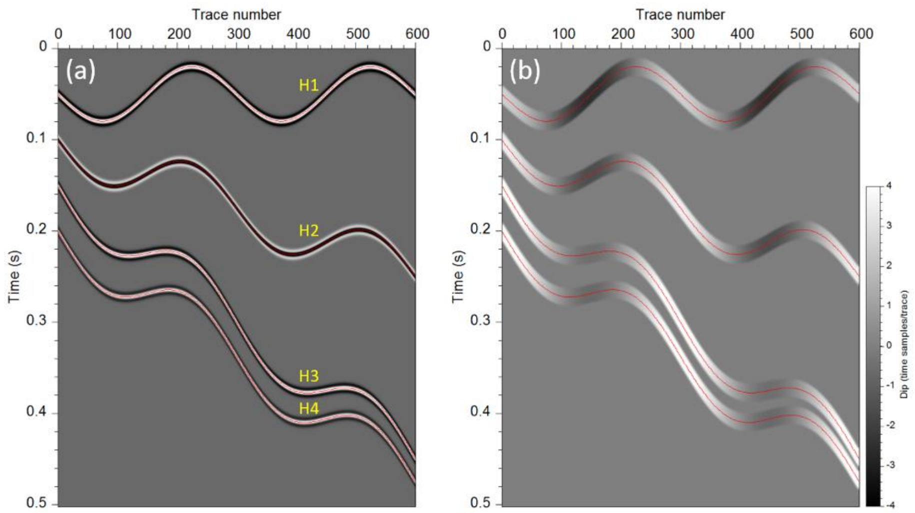

Figure 1 Local seismic dip estimation: (a) a synthetic seismic section with 4 reflection events in variable dips; (b) Estimated local dips for the seismic events in (a). The red curves are the time picks for the 4 reflections.

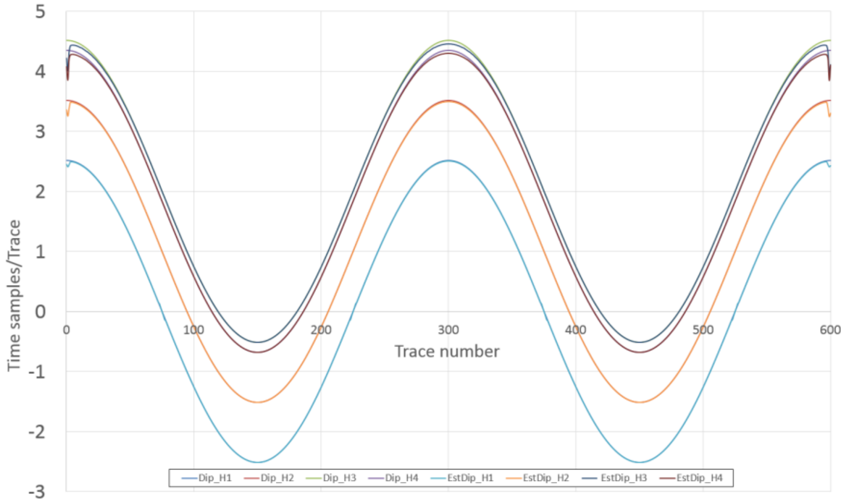

Figure 2 The comparison of the estimated local dips (EstDip_H1, EstDip_H2, EstDip_H3 & EstDip_H4) by equation (3) with the corresponding true dips (Dip_H1, Dip_H2, Dip_H3 & Dip_H4) of the 4 horizons (H1, H2, H3, & H4) in Figure 1.

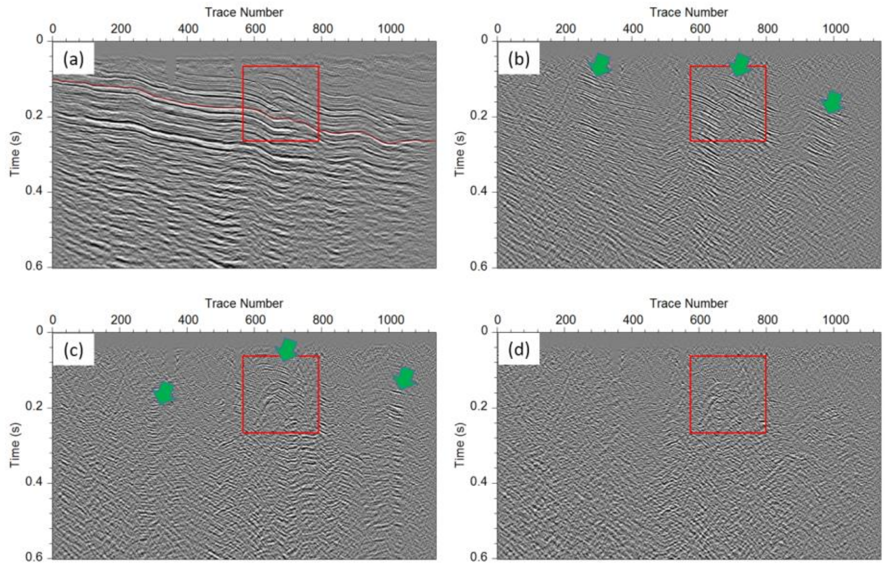

Figure 3 Diffraction extractions by with a 21-trace MAEF filter: (a) Original seismic stack section overlaid with a picked reflection in red curve; (b) extracted by a direct application of the MAEF filter to the section in (a); (c) Created by applying the MAEF filter to the flattened section of (a) with the picked reflection followed with restoring the flattening process; (a) Obtained by applying the MAEF filter in the local dip direction estimated by equation (3).

Diffraction Imaging

Figure 3(a) is an original final seismic post-stack section containing many sub-parallel dipping reflections. In particular, there is a thrust fault with relatively weak diffractions present in the red rectangular area. We applied the MAEF filter in three different ways to the seismic data in Figure 3(a) to extract diffractions: applying the filter directly to the stack section without event flattening (Figure 3 (b)); the MAEF filter is applied to the flattened stack section with the picked reflection followed with restoring the flattening process (Figure 3(c)); and the MAEF filter was applied in the local dip direction estimated by equation (3) (Figure 3(d)). Besides many residual reflections such as marked by the green arrows in Figure 3(b), the direct application of the MAEF filter to the stack section does not extract the desired diffractions effectively. If the stack section is flattened before the application of the MAEF filter, there are still some residual reflections remaining, as marked by the green arrows in Figure 3(c), the extracted diffractions are much more evident compared with the result in Figure 3(b). This illustrates the importance of the event flattening in diffraction extraction. However, if the MAEF filter is applied in the local dip direction estimated by equation (3), as shown by Figure 3(d), it produces not only more evident diffractions associated with the thrust fault, but also reduces the residual reflections significantly compared to the results in Figure 3(b) and (c). This clearly demonstrates that applying the MAEF in the seismic dipping direction is an effective way to extract diffractions from seismic reflection data without the need of flattening the target event.

CONCLUSIONS

In this paper, we have extended our previous diffraction imaging MAEF method to more complex geological environments without the assumption of relatively flat or sub-parallel coal seam strata and the need for a seismic event flattening process. This has been achieved by first estimating the local seismic dip and then applying the MAEF filter in the corresponding reflection dipping direction. The key of the extended approach is in the estimation of local seismic dips, which is realised by a non-iterative method using the gradients or the derivatives of the seismic wavefield based on the plane wave propagation. The numerically modelled example clearly illustrates the seismic event dips can be accurately estimated and the effectiveness of the extended MAEF filter in diffraction imaging for coal seam fault structure detection has been demonstrated by real coal seismic data. Our particular application of the proposed diffraction extraction method is to coal exploration and mine planning but the approach is of universal seismic interest.

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