Imaging the earth using seismic diffractions by means of Radon transform

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Introduction

Diffractions in seismic data indicate discontinuities of the subsurface, although they are often obscured by and difficult to separate from the more prominent reflection events. A seismic section containing only diffractions could therefore be of great significance for the interpretation of seismic data. Here, some techniques such as dip filtering and Radon transform are adapted and used to extract diffractions from prestack seismic data. Final diffraction stack sections will be shown and possible applications are discussed. I show that not only can the identification of the discontinuities in structure be enhanced, but, also, the resolution may be dramatically improved in contrast to the traditional definition of resolution in seismology.

By high-resolution, I actually mean super-resolution, when compared to the traditional definition of resolution. Typically, the vertical resolution of seismic exploration is defined as a quarter of the dominant wavelength

$$\lambda = v/f$$

where λ is the velocity and f is the dominant frequency, which varies with both the medium and the source properties. Practically, we assume half wave length as a reasonable value for resolution.

As I will show later, diffractions can provide higher resolution than that of the above convention. This is a striking but not surprising fact: if the size of an object is close to the wavelength, the dominant energy will be the diffracted rather than reflected. Reflections can, in fact, totally disappear. This phenomenon is well known in physics but is not fully utilized in exploration seismology.

Separation of diffractions and reflections

Diffractions and reflections have different characteristics, such as amplitude and travel time, which facilitates their separation. Complete separation is only possible in very rare cases, but, from a practical point of view, it is not necessary to completely eliminate the reflections. My aim is to reveal the potential of diffractions so some part of reflections may remain as long as the diffractions are not masked.

It is known that the reflection events of both the flat and the dipping reflectors in CMP domain are hyperbolae with apex located at zero offset. After NMO correction, the responses of flat reflectors will be flattened if the correct RMS velocity v_0 is used, but events of the dipping reflectors are not flattened using the same velocity. However, if the velocity is adjusted by the dip angle α, that is

$$v = v_0/\cos(\alpha)$$

then those events corresponding to dipping reflections can also be flattened. This is also true for diffraction events and consequently this approach is not suitable to differentiate them. However, I found that dipping reflection responses in the common shot gather domain will become dipping linear events if they are NMO corrected using RMS velocity without angle adjustment.

For a dipping reflector, the travel time equation can be deduced

$$t = \frac{1}{v}\sqrt{x^2 + 4hx \cdot \sin(\partial) + 4h^2}$$

or

$$t = \frac{1}{v}\sqrt{(x + 2h \cdot \sin(\partial))^2 + 4h^2\cos^2(\partial)}$$

where h is the vertical distance between the source and the dipping reflector, α is the dip angle. It is a hyperbola with a shifted apex in $-2h\sin(\alpha)$.

The travel time equation after NMO correction (using a two term approximation) of a flat reflector and dipping reflector are

$$t_{NMO} = \frac{2h}{v} - \frac{1}{64}\frac{1}{h^3 v}x^4 - O(x^6)$$

and

$$t_{NMO} = \frac{h(1+\cos^2(\partial))}{\cos(\partial)v} + \frac{\sin(\partial)x}{\cos(\partial)v} + \frac{(1-\cos(\partial))x^2}{4h\cos(\partial)v} + O(x^4)$$

respectively. It is clear that if x is not too large, the travel time for the flat reflector becomes a horizontal line as expected $t_{NMO} = 2h/v$, but when $\alpha \neq 0$, i.e. the dipping reflector, the linear term in equation can't be ignored but higher order terms can be, so we have

$$t_{NMO} \approx \frac{h(1+\cos(\partial))}{\cos(\partial)v} + \frac{\sin(\partial)x}{\cos(\partial)v}$$

which is a dipping straight line. It is easy to see that if $\alpha=0$ the result for dipping reflector is identical to that for a flat reflector. A linear Radon transform is now used to filter out those reflections after NMO correction. To achieve this, I developed a special strategy to do this process. In case accurate velocities are known, PSDM can always give better results. Here, PSDM can be applied to the extracted diffractions to obtain a superior image.

Example

Figure 1 shows a moderate complex synthetic model experiment. Figure (a) shows Kirchhoff PSDM result of the original data, and Figure (b) shows the Kirchhoff PSDM result of the diffraction data. This model tries to model a small salt body embedded in a sediment environment. The sediment layer structure comes with several faults. Especially there are two small faults underneath the salt body. One (right side), with 4m vertical throw, can hardly be identified in Figure (a), and another one (left side), with 2m vertical throw, is totally absent in Figure (a). They are too small to be within the conventional resolution. In Figure (b), not only do the big faults and the embedded salt body stand out, but also the two tiny faults beneath the salt body can be clearly identified. Note that there are several missing steep parts of the salt body. This is because standard Kirchhoff PSDM that I used here does not use the full wavefield. In other words, it does not take full advantage of the diffraction data.

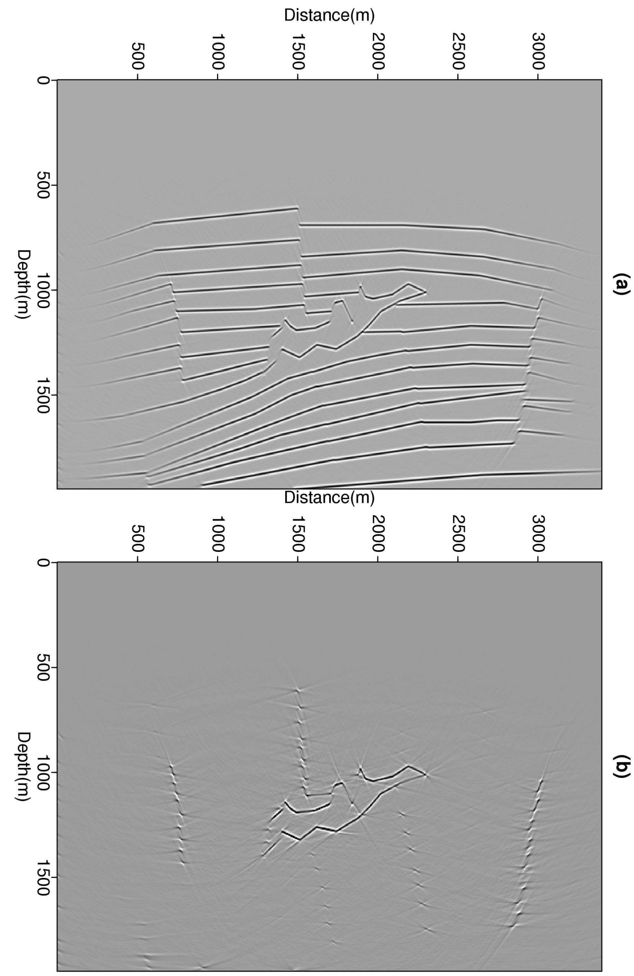

Figure 1. (a) PSDM result of the original data; (b) PSDM result of the diffraction data

Discussion and conclusions

Here I have attempted to remove all reflected energy so that the diffractions present in the section can stand out. In practice, and fortunately so, it is only required that the reflection energy is attenuated to the same level as that of the diffractions.

We have to bear in mind that the premise of diffraction imaging is the existence of discontinuities that can generate noticeable diffractions. Therefore, a smooth subsurface structure will not benefit from this technique. However imaging of discontinuities such as faults and unconformity points, especially their accurate location, is a very important task in exploration.

Diffractions are considerably more susceptible to noise than are reflections since the energy of diffractions is weaker than that of reflections. As a result, diffraction imaging is not suitable for strongly noise contaminated data. More CMP folds are always helpful. Note that the CMP folds used in our synthetic example are very low. Real data normally have larger CMP folds. In addition, it is recommended that a split-spread geometry be adopted in acquisition for better recordings of diffractions.

Diffraction imaging, if used in reflection seismology, can generate not just different but higher resolution results. It is a process suitable for discontinuity identification and imaging. It can be incorporated into conventional data processing flow, but requires special attention in data interpretation. And a directly diffrction prestack migration approach can be used if the criterion of Radon transform is not quite satisfied. I believe that diffraction imaging would facilitate the work of the interpreter, especially in the solution and clarification of problems associated with complex structure.

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