Processing seismic reflection data from high fold, crooked line surveys in crystalline geological terrain

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Summary

Most reflection surveys in crystalline terrains are high fold 2D crooked line profiles. In this paper we demonstrate two techniques that can aid in extracting maximum structural information. The first is a method for determining the optimum cross-dip for stacking each individual small part of the seismic time section. Because the geometry of the reflectors usually is complicated it can improve the quality of the final section and also provide additional geometrical information about the reflectors. The second (which we call the amplitude processing method) is a way of combining trace signals in a CMP stack or a migration that is more robust to residual time anomalies than the conventional summing method which requires phase coherency. It reduces the selectivity of the final stack and reduces the loss of signal due to uncorrected time anomalies. However, the amplitude method is used essentially as a measure of last resort. Every effort is made to determine and correct as many causes of time anomaly as possible, and phase coherent processing is applied to all data over at least a limited offset range.

Introduction

Strong, continuous, reflecting interfaces like those found in many sedimentary basins are rare in crystalline (igneous/metamorphic) terrains. Nevertheless, reflected P waves obtained in seismic reflection surveys of crystalline crust are often strong enough to be clearly visible on individual shot gathers. Generally, reflecting interfaces are likely to have very complicated geometry, indicating that 3D survey methods ought to be employed in order to image structures correctly (e.g. Milkereit et. al., 1996). But, because of terrain access and cost limitations, most surveys are high fold 2D profiling on crooked lines, and very useful results have often been obtained in this manner. Furthermore, because Q_P usually is much greater in crystalline than in porous sedimentary rocks, the seismic records often contain more high frequency energy than usual (e.g.,up to 150 Hz on crustal scale reflection records and up to 500 Hz on surveys on paths of several kilometers).

The main problem in processing such data is that reflector geometry is highly complex, to the point that reflections sometimes might better be called scattering. Most importantly, strong reflections recorded by a 2D survey profile will come from any point around the survey line where the cross-dip of reflecting feature can direct energy back towards the survey line. Also, the complicated shapes and layering of reflecting interfaces can produce erratically high amplitude reflections where the (complex) amplitude of reflected (scattered) events is strongly dependent on scattering angle. As a result, observed reflections may exhibit excellent phase coherence over a limited aperture range, but coherence disappears and events drastically shift in phase over wider ranges.

Neither cross-dip nor amplitude processing are novel ideas. However, they are only rarely a part of standard processing practice. It is interesting to note that in sonar and radar imaging, where the ratio of signal pathlength to wavelength usually is very much larger than in seismology, all the early imaging methodology was based on signal power or amplitude. Only more recently has it been possible, to exploit signal phase information fruitfully. As we begin in seismology to obtain data with higher pathlength to wavelength ratios, we can learn from these other fields that there can be good geological information in reflected signals that have lost their phase coherence.

The examples in this paper involve two seismic data sets, one a Project Lithoprobe crustal seismic reflection profile from the Abitibi region of the Archean Precambrian Shield of Ontario which was "shot" on a very crooked line using a 12 km spread with 200 m VP and 50 m RP spacings. The resulting fold of CMP bin gathers was irregular but usually well over 100. The recording frequency band was 10 to 56 Hz. Useful data were obtained to about 16 seconds, a ratio of travel time to shortest period (= wavelength to pathlength) of about 800.

The second survey was on a smaller scale and from the Sturgeon Lake area of the Archean PC shield in Ontario, where a fixed spread of 393 traces at 20 m spacing recorded dynamite shots at 40 m intervals on a crooked 8 km line. Recording time was 3 seconds. Although the frequency cutoff for our tests was set at 150 Hz (giving a pathlength to wavelength ratio of ≈ 400), strong reflected energy was present at much higher frequencies.

The amplitude and cross-dip methods

The paper has three main elements. The first section shows that with conventional stacking little of what clearly appears to be signal in the shot gathers and in the partially stacked data survives to the final section. The second shows how a locally optimized cross-dip can be determined for the each part of the 2D section. The third shows how amplitude processing can be applied to obviate signal loss in the final stages of stacking and mi-

CLEANED UP PRESTACK DATA	
PARTIAL STACK (WITH AMPLITUDE BALANCING)	
DMO	
CROSS-DIP ANALYSIS	AMPLITUDE STACK
MIGRATED CROSS-DIP STACK	MIGRATED AMPLITUDE STACK
INTERPRETATION SECTIONS	

Table 1. Basic phase and amplitude processing sequence.

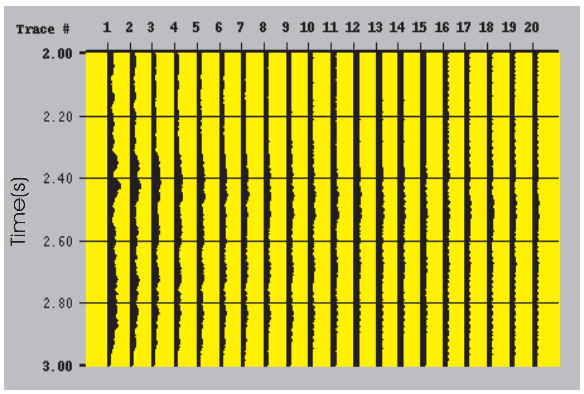

Fig. 1. Amplitude of the cumulative stacked traces from CMP bin 3015 of the Sturgeon Lake Line 1 data set. The first trace in the figure represents a stack of data with offsets from 2400 to 2600 meters. For each of the succeeding traces the the offset range was increased by 200 meters (2200-2600m, 2200-2800m, etc.). To show the progressive decline in amplitude and loss of events, the stacked traces were converted for plotting to absolute amplitudes and convolved with a short running average filter. For the Sturgeon Lake data set, the maximum offset range for little or no signal loss is about 200m.

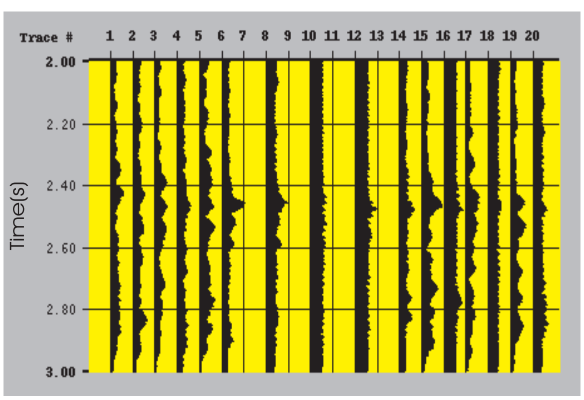

Fig. 2. Stacked traces from the offset ranges (2400-2600m, 2200-2400m,2600-2800m, etc.) used to form the cumulative stack in Figure 1. Most of these partially stacked traces contain strong events, and there is considerable trace to trace similarity. However, the visible shifts in time explain why signal to noise ratio of the cumulative stacks weakens progressively as wider range of offsets are included.

gration and provide an alternative to standard phase coherent processing.

The basic processing steps are illustrated in Table 1. A fairly normal sequence is followed, but it is eventually broken into two streams:- one trying to make as accurate time corrections as possible, the other using amplitude methods to bypass the problems. The initial data cleanup phase consist of editing, refraction statics estimation, surface consistent spectral and amplitude balancing and a local slant stack filtering of provisionally NMO corrected shot gathers to accept only events with a multi - trace coherency in horizontal slowness range consistent with their being reflected P waves.

The main processing begins with velocity estimation (that may be refined at later processing stages) and a stage of partial stacking into a set of narrow offset windows. This reduces the data volume, improves the fold uniformity in constant offset gathers, and makes DMO processing feasible. The other steps follow. Because of the irregular geometry of the surveys, large variations of the CMP bin fold often remains in the partial stack, and it can be difficult to preserve amplitude balance.

1. Stacking problems. A common observation in velocity analysis of our data is that, despite the presence of strong reflection events and the use of long spreads, semblance does not peak sharply in the narrow ranges that theory predicts. This is still true even when special techniques are applied to correct for the effect of in-line dip. Use of constant velocity panels lead to the same conclusion. Usually, results are more sharply focussed when CMP records with low fold are analyzed.

Figures 1 and 2 give a clearer view of this problem. Traces from one CMP bin of the Sturgeon Lake survey (on which strong events occur) have been stacked progressively and their amplitudes plotted. The stack begins at the 2500 m offset range where reflections tend to be clearest. More traces with successively higher and lower offsets are added in 200 m intervals until an offset range of 4 km is reached. Fig 1 shows the amplitude of the cumulatively stacked trace while Fig 2 shows the individual 200 m contributions (a few intervals have zero fold due to irregular survey geometry). The stacked traces are normalized by the trace count, so amplitude of coherent signal should remain constant and that of incoherent noise should fall in proportion to the square root of the trace count. What we see is that all amplitudes fall with increasing fold, despite the fact that many amplitude features of the individual traces are similar at all offsets. But even on the amplitude plots, minor trace-to-trace time shifts can be seen and these are altogether too much for phase coherent stacking to accommodate. Additional tests on this data show that significant signal amplitude is lost even with the 200 m aperture used in

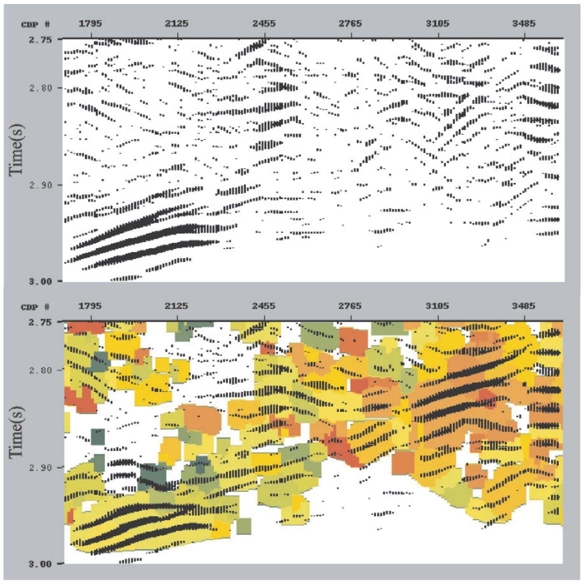

Fig. 3. Upper section is a part of the non-migrated Sturgeon Lake Line 1 phase stack. The lower section is a combined image of the optimum cross-dip stack and the color dip map of the same data. The length of the both sections is about 3 km. The optimized stack shows a higher stack power and some events not present on the phase stack emerge (particularly in the upper right part of the combined image). Colors depict the dip of the events. Shades of yellow represent zero and near zero dip. As the color changes to red and green reflector dip to the right and left of the profile. No color (white) is assigned to parts of the section where no dip was reliably determined.

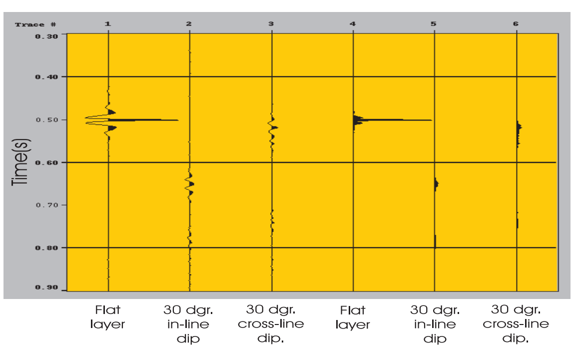

Fig. 4. Testing of phase and amplitude stacking using data generated by a 3D Born scattering code and the real geometry of the Sturgeon Lake Line. Traces 1 - 3 are obtained by phase coherent stacking of all the modeled traces in CMP bin 2915. Traces 4 to 6 are the amplitude stacked traces (power = 2) and are amplitude balanced so that the level of random noise is equal. See text for more details. Although the amplitude method does not always yield the larger maximum amplitude for every event it does focus the signal much better. Phase stacking even in this simplified model exhibits a ringing effect; there are several cycles for each event.

the partial stack. However, smaller windows lead to too many cases of zero fold in the partial stack, so a 200 m window was adopted as an acceptable compromise.

2. DMO and Optimum cross-dip stacking. Strong and variable in-line or cross-line dip of the reflectors could easily account for at least part of the phase incoherence in the above as is CMP gather. Dips may vary from one event to the next on the traces, and events at a single arrival time may in fact be compound. Optimally, cross-dip and in-line dip should be corrected simultaneously. However, this is very difficult to achieve in practice because crooked line surveys produce CMP bin gathers wherein in-line offset is strongly correlated with cross-line offset. Thus we have had to use separate in-line and cross-line dip correction procedures.

The DMO is carried out by a standard log stretch algorithm operating on the constant offset gathers produced by the partial stack. If many zero fold traces are present, some post-filtering may be need. The cross-dip analysis begins with sorting the DMO - corrected, constant offset traces back to CMP bin domain, ordered by their cross offset in the bin. For each value in a set of cross-dips (cross-line slownesses, actually), the data are stacked and a (slightly modified form of) semblance is calculated at close intervals along the stacked trace. Once this is done for all cross-dips, the semblance values are searched to establish the optimum cross dip in each small time interval. Then a final stack is assembled by selecting elements from the full set of cross-dip stacks.

Figure 3 shows optimum cross-dip analysis applied to the Sturgeon Lake data. A good quality cross-dip map was obtained and used to produce an optimum cross-dip stack. The two results were then combined into a single image and compared with the phase stack for zero cross-dip. Many additional events are seen in the optimum cross-dip stack, and varying cross-dips can be identified.

3. Amplitude stacking and migration. In this process, one simply converts the partially stacked and DMO corrected trace data to absolute amplitude, raises the values to a selected power between 1 and 2, and stacks the amplitude traces in the normal way over the desired aperture. Use of a higher power produces a sharper focusing of the signal, but may induce too large amplitude differences between different events. Figure 4 shows how this process and normal stacking perform on some simple model data in which time anomalies are not properly corrected. Responses (including a random noise component) have been generated using a 3D Born scattering code and the Sturgeon Lake survey geometry. Data from a 30^0 in-line dipping, a 30^0 cross-line dipping and a horizontal thin layer are studied. DMO and cross-dip corrections have not been applied in order to generate time anomalies. The results directly demonstrate how the amplitude

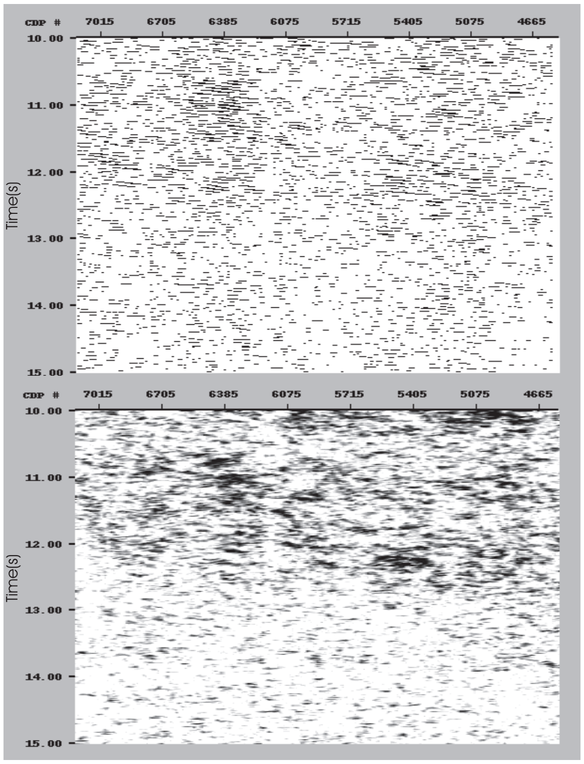

Fig. 5. The Moho discontinuity is much easier to interpret on the amplitude section (bottom) than on the normal profile (top). It represented by a sharp fall-off in reflected energy between 12 and 13 seconds of two-way travel time. The width of the section is about 10 km.

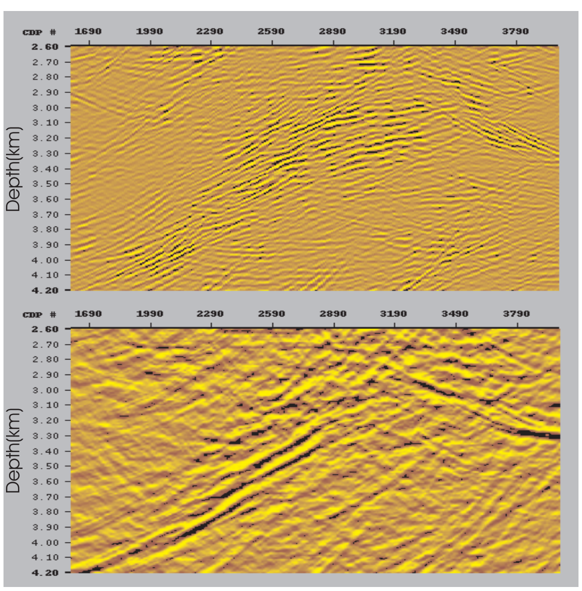

Fig. 6. The top section (migrated phase-coherent stack) and the bottom section (migrated amplitude stack) depict the same part of Sturgeon Lake Line 1.

method suffers less loss when the data are not correctly time aligned and tends to retain a distinct peak in the stacked signal.

Amplitude data can be migrated in the same fashion as phase data except that any low frequency limit in the migration algorithms need to be to be set several times lower than normal. It may also be necessary to remove the average value (zero frequency component of the amplitude trace static shift (zero frequency part) while retaining all the low frequencies that correspond to envelope variation of the original seismic trace data.

Figure 5 shows a small part of the Lithoprobe crustal reflection profile centered on the Moho discontinuity. In this data, phase coherent stacking works well within a 500 m aperture. The survey line is too short for migration, particularly for such late times, so the phase-coherent and amplitude stacks are compared. The marked reduction in reflectivity at the Moho discontinuity is much clearer in the amplitude section. Cross-dip analysis did not yield any reliable information in this part of the profile.

Figure 6 shows migrated phase and amplitude stacks of a part of the the Sturgeon Lake profile. The migrated amplitude stack gives a better rendition of the relative strength of reflectors, has better event continuity and reveals a few events that are suppressed in the phase-coherently processed data. Although resolution nominally is far superior in the phase data, the multicyclic nature of most events makes the real resolution comparable to or worse than on the amplitude section.

Conclusions

Amplitude sections and the optimum cross-dip stacks and associated color dip maps are not meant to be used in place conventional phase coherent stacks when examining high fold 2D crooked line data acquired in crystalline terrains. Rather, they represent additional tools that will hopefully provide interpreters with more information.

Acknowledgments

Many thanks to Larry Petrie and Larry Mathews of Noranda Mining and Exploration Inc. for providing us with Sturgeon Lake Line 1 seismic reflection data. Regional seismic data was acquired by the Lithoprobe project. We are also grateful to Weizhong Wang for his help during the early stages of this work.

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