

## **Seismic source comparison for compressional and converted-wave generation at Spring Coulee, Alberta. Part I: Heavy vibroseis-dynamite comparison**

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### **ABSTRACT**

A seismic line was shot in such a way that characteristics from two different seismic sources could be compared. Two 54-shot seismic datasets were created that were identical in all respects except that one used a dynamite source, while the other used two 48,000 lb vibrators. After identical processing, the final stacked sections of the dynamite and vibroseis datasets are very similar in character and temporal resolution. Examination of the P-wave raw shot records show that in terms of frequency content and signal strength, the explosive data appears superior to the vibroseis; however, the quality of the dynamite records is variable. F-x spectral analyses of the raw data and stacked sections reveal that both datasets show similar characteristics for areas corresponding to noise, data and first breaks for the raw shot gathers, and power and coherence from 10 to 40 Hz for the P-wave stacked section, and from 10 to 25 Hz for the converted-wave stacked section. From our results, we could say that in terms of data quality any of the sources could be used; however, these criteria must be judged with respect to the total cost of the project and the most appropriate source for the project budget.

### **INTRODUCTION**

In seismic reflection surveys, acquiring good quality data is more likely assured by choosing optimum parameters with respect to the target zone (Scheffers et al., 1997). One of the key parameters is the selection of the appropriate seismic source and its characteristics. This selection should be done using several criteria which are related to the type of the problem under consideration. Some of the important criteria to consider are: the source energy content, which should be large enough so that adequate information is recorded from the desired maximum depth of the survey; the produced reflection pulse, which should have high and broad frequency content to obtain the required resolution for the exploration of the particular problem. Other selection criteria are related to the signal-to-noise ratio, the convenience, safety requirements, and the repeatability. Finally, all previous criteria are judged with respect to the total cost of the project, and the most appropriate source for the project budget would be selected (Karastathis et al., 1995).

A number of comprehensive source tests have been carried out (Davis and Lawton, 1985; Pullan and MacAulay, 1987; Miller et al., 1986; *ibid*, 1992; Parker et al., 1993, Tilander and Lattimore, 1994, Karastathis et al., 1995, Steer et al., 1996, Scheffers et al., 1997, Bühnemann and Holliger, 1998, Staples et al., 1999, Bremner et al., 2002, Quigley, 2004, Calvert et al., 2005). These efforts have been mostly geared toward shallow seismic reflection, refraction seismic applications and deep seismic reflection profiling.

The technological advances have improved the performance of the different source types; however, the results of previous studies showed clear differences in the performances of the various sources as a consequence of the site condition: the performance of a source is proved, in practice, to be different in different study areas (Miller et al., 1986; Millet et al., 1992; Pullan and MacAllay, 1987; Bühnemann and Holliger, 1998).

From this premise, we want to find the best source under specific conditions and locations. It is therefore useful to conduct a quantitative comparative study of various sources in a particular environment to study in detail the characteristics of each (Karastathis et al, 1995).

Following the initiatives of previous experiments, the CREWES Project acquired three 2D 3-C lines with different seismic sources (IVI-mini vibroseis, 52,000 lb vibroseis and explosives), receivers, and recording systems during January, 2008 in the Spring Coulee Area, Southern Alberta (Figure 1). One of the main objectives was to study three seismic sources to investigate their characteristics at the Spring Coulee site. This paper describes the analyses done in these three seismic lines acquired with different sources and discusses the results of the comparison between all of them.

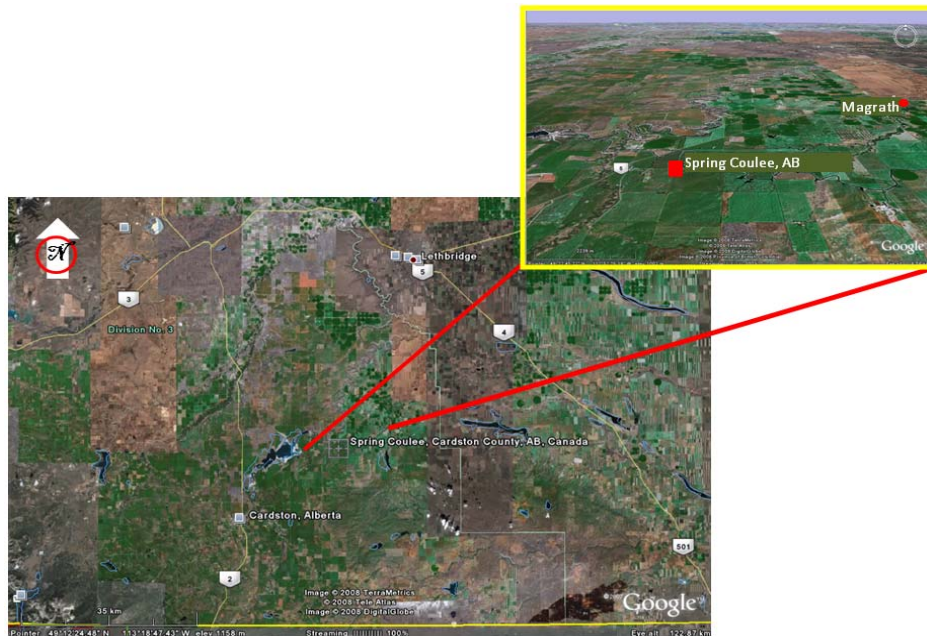


FIG. 1. Satellite photograph showing the location of the study area. Photograph from Google Earth.

### The Spring Coulee survey

The Spring Coulee datasets were recorded in a 3D manner because of the simultaneous recording of the multiple shot and receiver lines (Figure 2). Two different recording systems, three types of receivers and three types of sources were employed on the survey. The data acquired by the geophones (SM7 10 Hz 3-C and SM24 10 Hz 3-C)

were recorded by an ARAM Aries system and the accelerometers (DSU3 MEMS) by a Sercel 428XL system. Both receivers and recording systems acquired the data produced by dynamite, heavy vibroseis and an IVI-minivibroseis as seismic sources. The data used in the source comparison were recorded with the ARAM system and SM7 10 Hz 3-C geophones.

The sources were 52 dynamite shot points (2 kg at 15 m depth), 657 vibrated points with two 48,000 lbs and 134 vibrated points with one IVI Envirovibe (18000 lb). The 48,000 lb vibroseis had a 4 times vertical stack, sweeping from 4 to 130 Hz with an 12 s listening time; for the Envirovibe, a 4 times vertical sweep was also used but sweeping from 10 to 200 Hz with an 11 s listening time. The receivers were located every 10 m and the sources every 30 m, and the lines were separated approximately one meter between them.

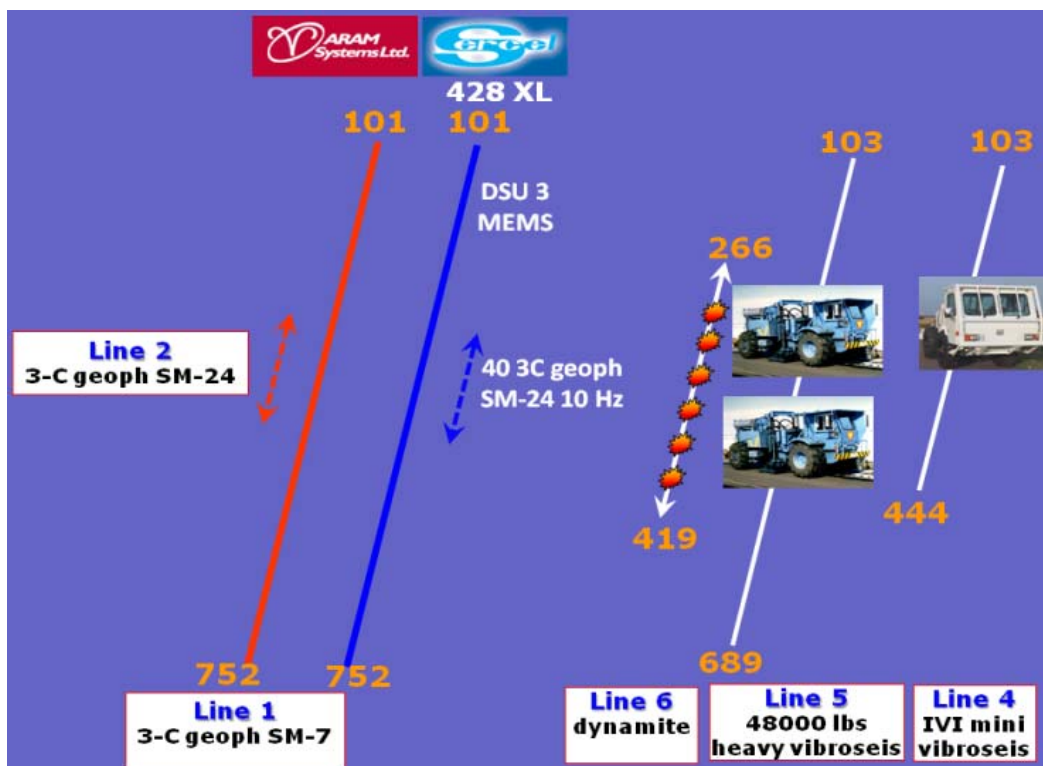


FIG. 2. Schematic diagram of the Spring Coulee experiment. Details of the ARAM layout are shown as well.

#### *Coincident source points of the ARAM Aries spread for the three source types*

From all three source lines only 54 coincident source locations existed. These points were located approximately in the center of the full length six kilometre line. The comparison datasets were separated in two groups, based on the number of traces per shot and dead traces.

The first group consists of the comparison of the heavy vibroseis versus dynamite sources with 652 maximum number of traces and good quality data. The second group will be presented on the second part of this paper, and consists of the heavy vibroseis, dynamite, and mini vibroseis sources with a maximum of 470 traces, and with the same dead traces to make an exact comparison of the datasets. The data of the mini vibroseis does not have the same quality as the other two sources but still can be used for comparison in the shallow region.

## **PART 1: HEAVY VIBROSEIS-DYNAMITE COMPARISON**

### **1. Raw data: Characteristics of different types of signal and noise**

For a better understanding of the difference between the different sources, the most significant signal and noise waves shall be described as they were observed in the raw data. Consistency from shot to shot along the line is another characteristic that should be considered as it reflects how variable the source is and how dependent it is from the near surface conditions. This is also an important point to take into account for future 4D methods and because it can benefit data processing, especially with the treatment of common-receiver or cross-spread gathers.

Vertical channel: Qualitative analysis of the raw shots indicates an improved bandwidth and S/N with the dynamite source, but also shows an increase in the level of ground-roll amplitude and in the low-frequency noise (Figure 3a and 3b). The vibroseis data shows less prominent groundroll and low-frequency noise but stronger airwaves and high-frequency noise especially at short offsets and deeper times.

The vibroseis data shows better shallower data than the dynamite (from 0-0.6 s). However, the dynamite signals appear to have a much deeper energy penetration leading to a better imaging of the deeper subsurface. At first look, it appears there may be more reflection energy from the dynamite shots.

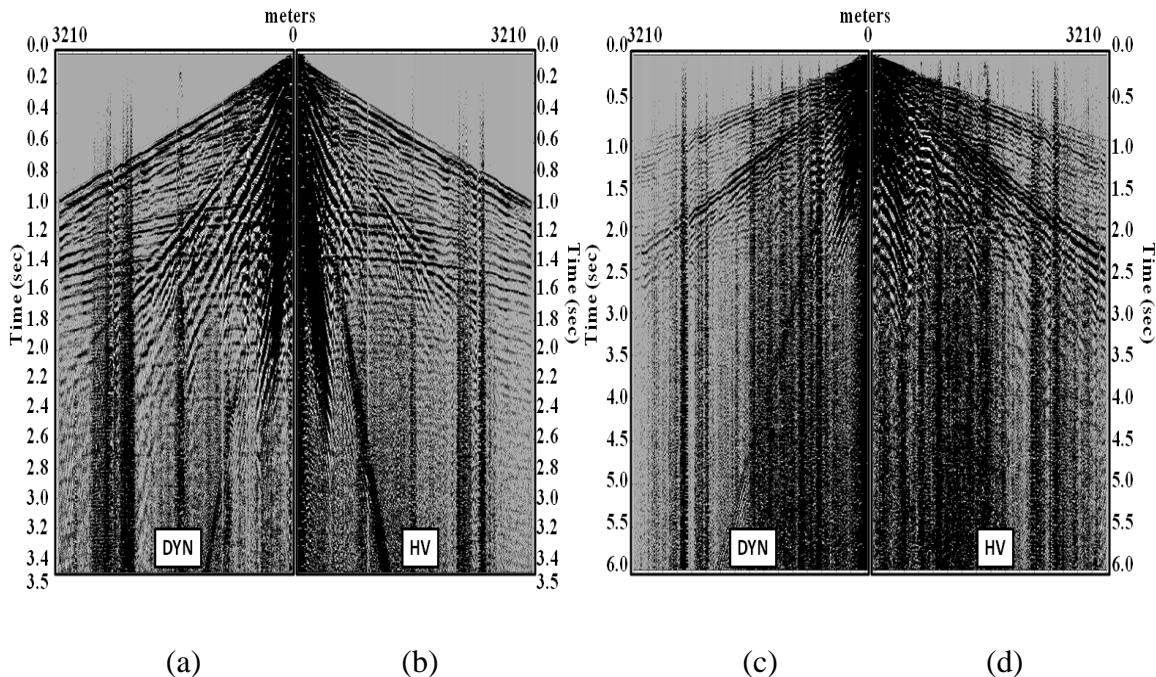


FIG. 3. Comparison of two raw shot gathers. In (a), half of a split spread record from the vertical-component dynamite line. The same shotpoint from the vertical-component heavy vibroseis line is shown on (b) with the lateral coordinate reversed to ease the comparison. The same comparison is shown for the same record for the radial-component of the dynamite on (c) and of the heavy vibroseis line on (d).

Although deep reflections are dramatically clearer on certain explosive source records, the quality of such records varies considerably. These differences occur because shots could be placed in different media (clay, sand, shale, or sandstone), into different hole sizes and water saturation. The shot-to-shot variability could be evaluated comparing shots from different locations along the line; another way is analyzing amplitude spectra from first breaks to see how their character varies. For the vibroseis, the records appear slightly consistent in terms of the data character and in the level and nature of the ground roll. The amplitude levels from shot to shot are more consistent for the vibroseis than for the dynamite data, where we see a big amplitude difference between the center shot in respect with the other ones. The first dynamite shot appears to have more reflected energy, which is not the case for the vibroseis shots where the events appear consistently across all shots.

Amplitude spectra of a window located on the first breaks from all three shots of every source indicates that there is some variability from shot to shot in the dynamite, however is not what is expected when we have different near surface media, they might be small changes in the conditions but it does not cause a substantial difference. The first breaks on the vibroseis present similar characteristics from shot to shot with small variations.

Radial channel: Compared with the vertical-component, the converted-wave data looks noisier, with less bandwidth and the reflection energy is not as strong and evident (Figure 3c and 3d). The overall noise content looks less in the dynamite than in the vibroseis data, with a strong random noise masking most of the reflections. In the dynamite data, the near offsets are more contaminated with noise and its amplitude level



is lower. Overall, the frequency content looks higher in the dynamite data than in the vibroseis data.

The consistency from shot to shots looks similar for both datasets); there is not as much difference in amplitude levels between the dynamite shots as in the vertical-component.

Not many observations could be done about the energy penetration for the converted-waves because of the difference in amplitude and the noise that is masking most of the reflections. The apparent reflections go up to 2.5 s and they are more evident on the vibroseis data, but once again this observation could be driven for the amplitude differences.

## 2. Unmigrated stacked sections

Vertical channel. The dynamite data appear generally superior to vibroseis data at the shot-gather level. This is perhaps to be expected, because the vibroseis method was developed as a “low impact” source that takes advantage of common depth point (CDP) redundancy to achieve useful S/N levels at depth (Schrodt, 1987). The comparison of the stacked seismic sections indicates that the vibroseis is slightly superior in the shallow section (0–0.6 s) (Figure 4) and the dynamite in the deeper section (0.6–2 s) (Figure 4).

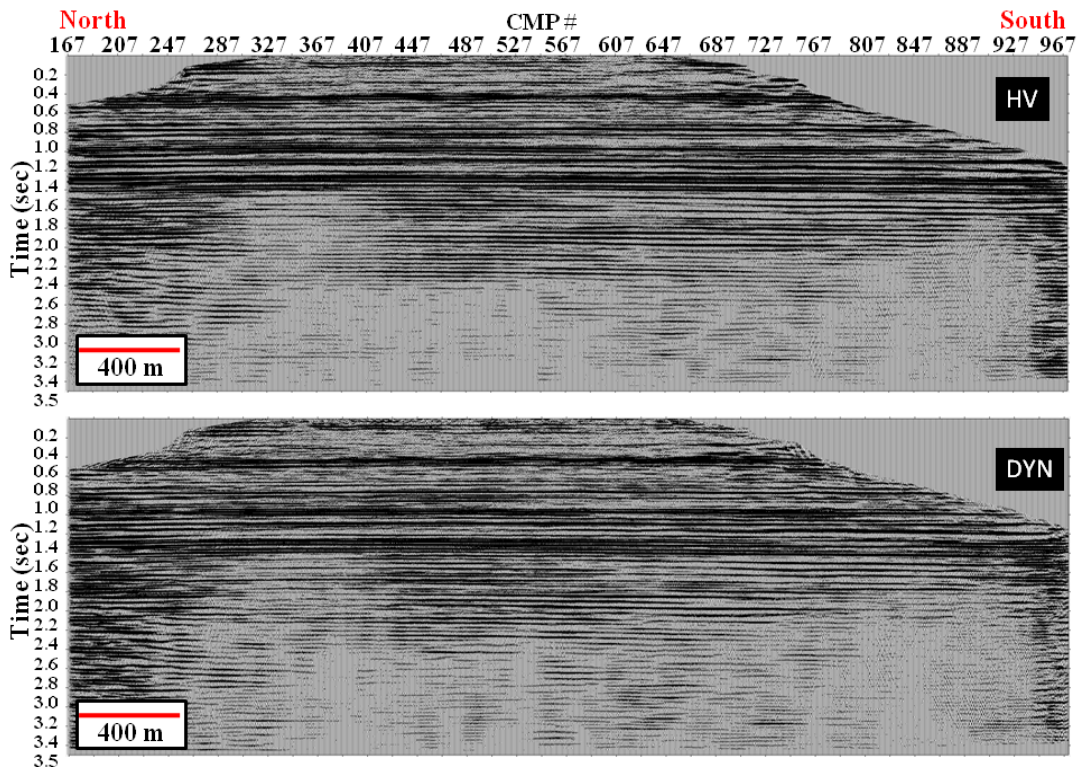


FIG. 4. Comparison of the vertical-component heavy vibroseis (top) and dynamite (bottom) stacked sections. The sections were generated with coincident data, with phase and amplitude match of the dynamite to the vibroseis, best mute and velocities.

The target zone for this area is located between 0.5 and 1.5 s two way time (Figure 5). Analysis of this area indicated improved bandwidth and signal-to-noise ratio could be achieved with a dynamite source but the possible improvement in P-wave image quality might not be considered sufficient to select this as the source of preference; survey costs related factors would have to be evaluated to make this decision.

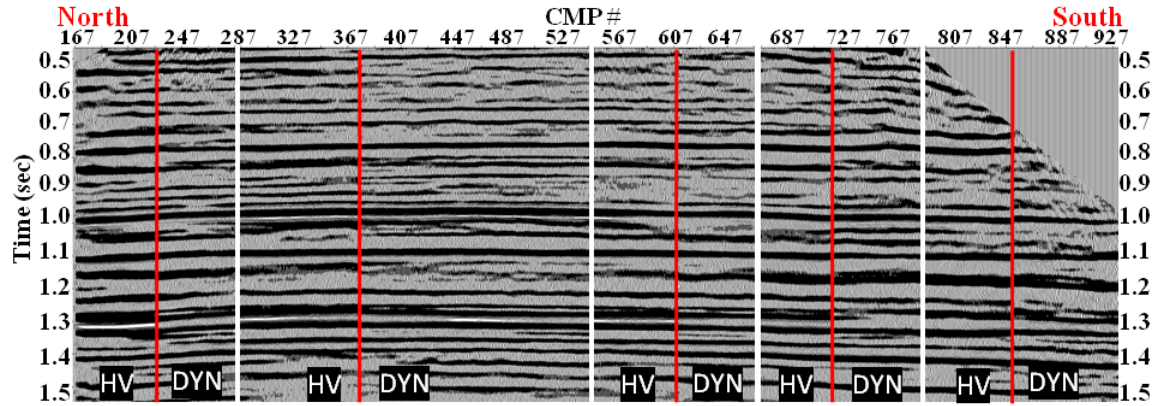


FIG. 5. Side-by-side comparison of different portions along the vertical-component stacked sections for the dynamite and heavy vibroseis.

**Radial channel:** The same observations made for the vertical channel stacks applied to the radial channel stacks (Figure 6 and 7). However, the difference on the shallow reflectors is not as noticeable as for the vertical; in the deeper part the dynamite shows better resolution that might be a reflect of a higher frequency content.

Between CMP's 287 and 447, there is an area of lower amplitude in comparison with the rest of the section. This difference cannot be observed in the vertical channel and might be caused due to a higher attenuation of the converted-wave by scattering and absorption that did not allow obtaining usable high frequencies. Another reason could be that the receiver statics were not completely resolved. In this portion, the dynamite data appears to have more continuous reflections between 1.5 and 1.9 s.

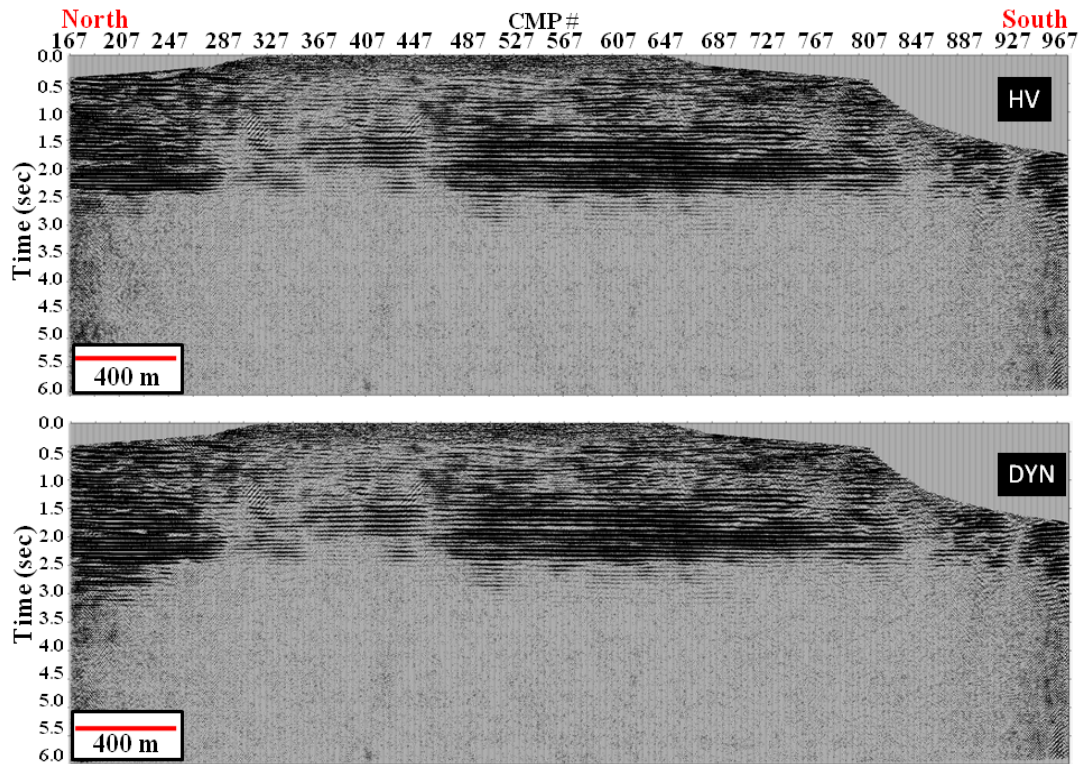


FIG. 6. Comparison of the radial-component heavy vibroseis (top) and dynamite (bottom) CCP stacked sections. The sections were generated with coincident data, with phase and amplitude match of the dynamite to the vibroseis, best mute and velocities.



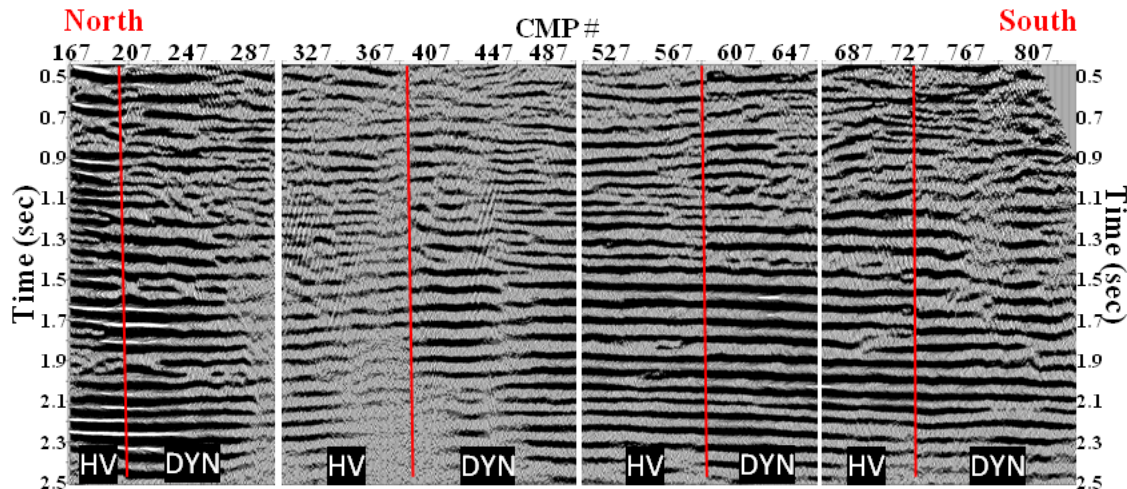


FIG. 7. Side-by-side comparison of different portions along the radial-component stacked sections for the dynamite and heavy vibroseis.

### 3. Seismic signal band estimation using f-x spectra

An f-x analysis of raw shot gathers and unmigrated stacked sections is done in the different source datasets to estimate the potential signal band and the realized signal band (Margrave, 1999), respectively.

#### 3.1. F-x analysis of the raw shot gathers

Vertical channel: An average Fourier amplitude spectrum was calculated on a raw shot gather for a window corresponding to what is hoped are subsurface reflections (Figure 8a). From 0-10-Hz the dynamite shows slightly higher power, then to about to 40 Hz the curves are similar with a dominant frequency of 25 Hz. After 40 Hz, the dynamite shows higher power up to 65 Hz, and then the amplitudes of the vibroseis keep higher until it reaches the maximum sweep frequency (130 Hz).

Using the same amplitude spectrum plot of Figure 8(a) and based on the potential band estimation method presented in Margrave (1999), we identified the “corner frequency” for both datasets. For both datasets, the apparent corner frequency seems to be located around 70-75 Hz. The corner frequency was approximately identified where the signal attenuated spectrum drops below the constant background noise level (Figure 8a).

The same analysis was done in windows that cover a portion of the first breaks and noise (Figure 8c and 8e). In the first break window (Figure 8c), is intended to characterize refracted energy from shallow interfaces. The dynamite shows slightly more power between 0-5 Hz and in the range 25-160 Hz. In the range 5-25 Hz the curves are very close.

For the window located in the noise area (Figure 8e), the vibroseis shows a much stronger Rayleigh wave on the high-frequency side (25-250 Hz). From 0-25 Hz the curves are very similar.

Radial channel: The same Fourier analyses were done in the radial channel, for signal, refracted wave and noise windows (Figure 8b, 8d and 8f). In the data window (Figure 8b), the dynamite shows slightly higher amplitudes to about 10 Hz, but from 10-25 Hz the curves are similar with a dominant frequency of 20 Hz; in the 30-40 Hz the dynamite shows higher amplitudes. After the 40Hz the amplitude levels of the vibroseis are 5 dB different than the dynamite. For the radial channel datasets, the apparent corner frequency is around 40-45 Hz for the vibroseis, and 50 Hz for the dynamite.

For the refracted arrival window, the event selected could be a P-S-P refraction that appears strongly in both datasets (Figure 8d). This event shows almost the same power for both sources to about 30 Hz. After 30 Hz, the vibroseis power is different by 4 dB until it reaches the maximum sweep frequency.

In the noise window (Figure 8f), the dynamite shows slightly stronger Rayleigh waves up to 20 Hz, then the vibroseis shows a much stronger waves with dominant frequency of 15 Hz until it reaches the maximum sweep frequency.

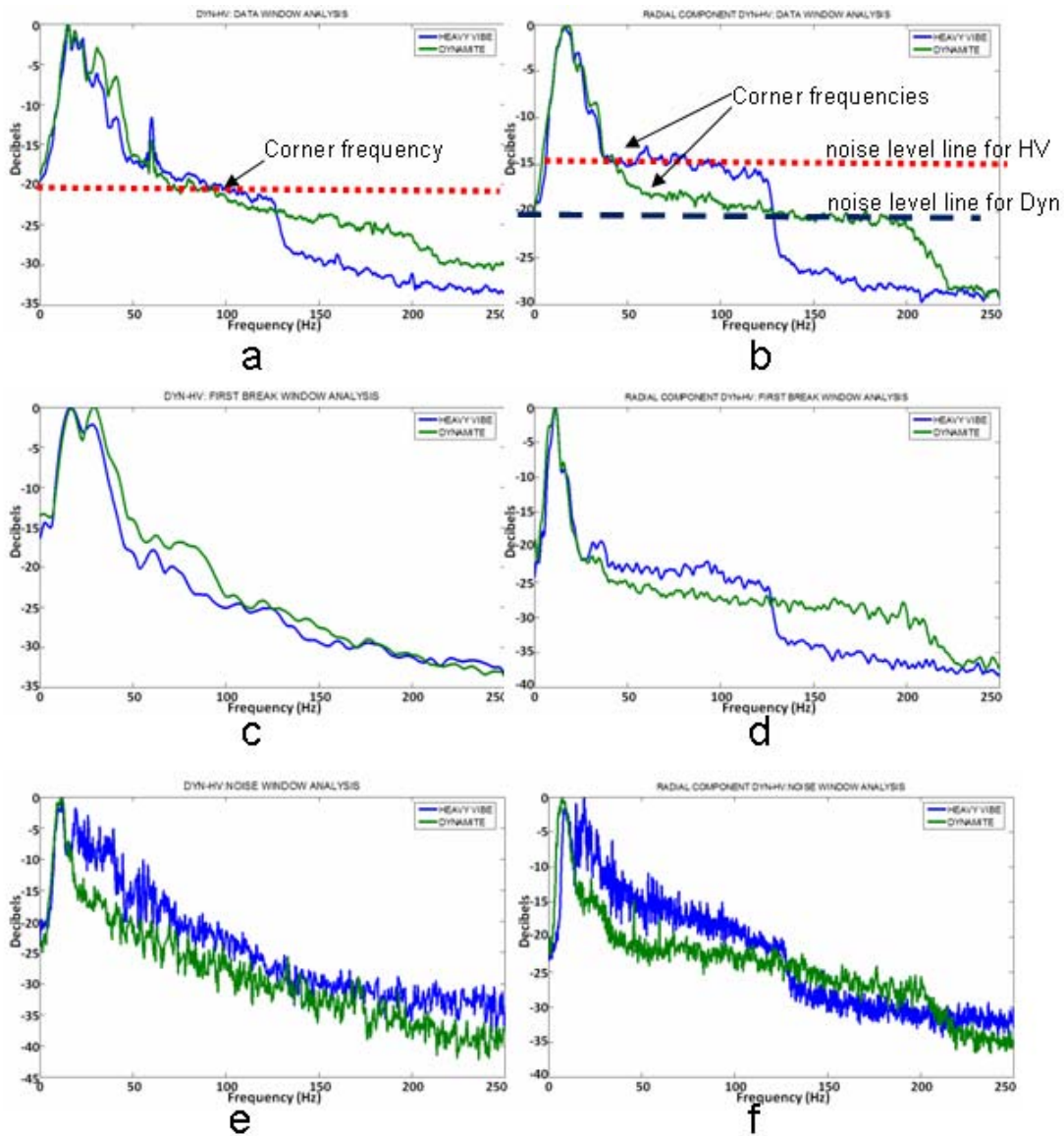


FIG. 8. Average Fourier amplitude spectrum of a raw shot gather for the vertical channel (in the left column) and radial channel (in the right column) of the heavy vibroseis and dynamite data, with windows corresponding to: (a) and (b) signal only area, (c) and (d) first break area (vertical-component)/refraction event (radial-component), and (e) and (f) noise area.

### 3.2. *F-x analysis of the unmigrated stacked sections*

Vertical channel: An *f-x* analysis of both unmigrated, unfiltered stacks is shown in Figure 9 to estimate the realized signal band.

The *f-x* amplitude spectrum for both datasets (Figure 9a and 9b) shows a drop in spectral power at 40-45 Hz. After this frequency, the dynamite shows weaker amplitudes than for the range 15-40 Hz, but they are still stronger than the vibroseis up to 55 Hz.

The phase coherence of the two datasets is contrasted in Figure 9(c) and (d). For the vibroseis, there is a reduction in phase coherence at 40-45 Hz that is coincident with the drop in spectral power in Figure 9(a). However, subtle phase coherence persists up to at

least 85 Hz. The dynamite reduces its phase coherence at about 55 Hz. These observations may be interpreted as indicating similar signal levels below 45 Hz. In the 45-60 Hz band, the signal strength of the dynamite is greater. On the other hand, from 60 to 90 Hz both datasets look weak but the vibroseis shows more coherency.

Radial channel: The same f-x analysis for both unmigrated, unfiltered CCP stacked sections is shown on Figure 10. The f-x amplitude spectra for both datasets (Figure 10a and 10b) are similar without major differences. They show a drop in spectral power at 20 Hz. After this frequency the data shows little signal.

There is a reduction in coherency for the two sections at about 25 Hz (Figure 10c and 10d). From 25 to 35 Hz there is evidence of weak signal but not very coherent. From 35 to 55 Hz the signal is coherent but weak.

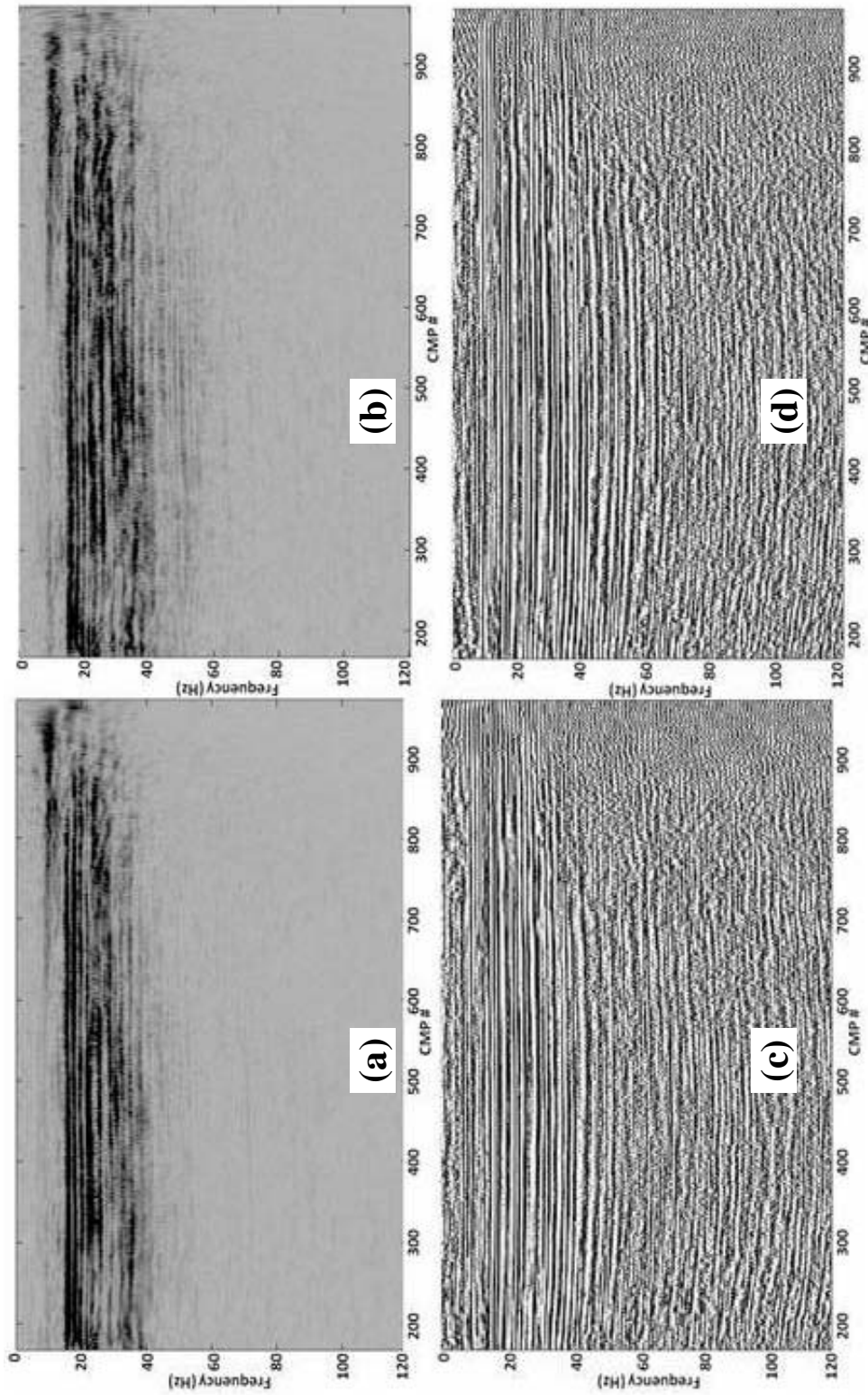


FIG. 9. F-x spectral analysis for the final unmigrated, unfiltered P-wave stack for the comparison heavy vibroseis and dynamite data computed over the time zone 432-1467 ms. The f-x amplitude spectrum for the heavy vibroseis is shown in (a); (b) shows a similar spectrum for dynamite data. In (c) and (d) are shown the f-x phase spectra corresponding to (a) and (b), respectively.



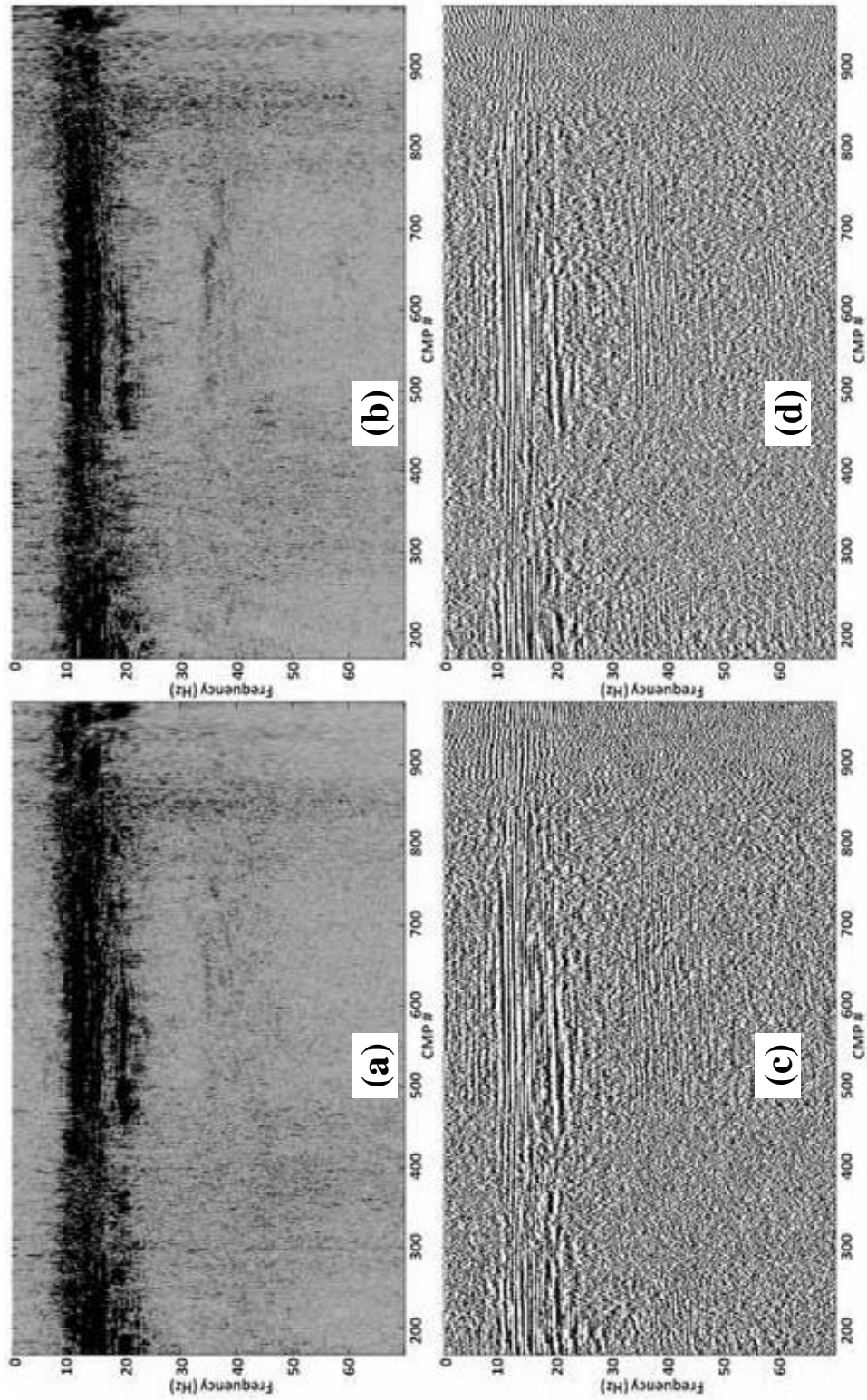


FIG. 10. F-x spectral analysis for the final unmigrated, unfiltered PS-wave stack for the comparison heavy vibroseis and dynamite data computed over the time zone 700-2500 ms. The f-x amplitude spectrum for the heavy vibroseis is shown in (a); (b) shows a similar spectrum for dynamite data. In (c) and (d) are shown the f-x phase spectra corresponding to (a) and (b), respectively.

#### 4. Quantified attribute measurements for the source comparison

Seismic resolution is one of the most important parameters in seismic exploration. Defining resolving power or vertical resolution is a difficult task because it is not a quantity that depends on a single factor, instead it is a system that depends on the seismic system and in the type of distribution of the reflections. It has been proposed (Berkhout, 1984; Widess, 1982) that the resolving power of seismic data be defined by quantitative properties. These properties are calculated using the assumption that the distribution of reflections and of noise be treated as a random (Gaussian) distribution (Widess, 1982).

Resolution implies separating into constituent parts, that for seismic is separating constituent reflections. A reflection includes a time variable and a waveform variable, so any attributes that will help us characterize them will allow us to determine distinctness and therefore resolution (process of making constituent reflections distinct).

##### *4.1. Analysis of the deterministic trace attributes for the Spring Coulee source comparison heavy vibroseis-dynamite:*

Additionally to all the analysis that has been done to compare both datasets, a deterministic method is used to obtain statistical information about the data quality. The statistical trace attributes have been determined in a selected time window of 500-2500 ms TWT over the whole stacked section to cover the most relevant targets.

This analysis is based on quantified attribute measurements on seismic data. The statistical attributes used for the deterministic analysis are: resolving factor, time length, frequency length, first zero-crossing, and bandwidth related attributes (Figures 11 and 12). All these plots are similar with respect to the information they provide. They reflect vertical and lateral resolution, quantifying wavelet attributes.

Vertical channel: From these attributes, we are looking for the smallest signal length, a higher frequency length, smaller values for the first zero crossing, the higher frequency content and broader signal bandwidth. The wavelet that meets all these requirements holds better resolution.

The time length and temporal resolution graph (Figure 11b) indicates that the dynamite have smaller values than the vibroseis, with differences between 2 and 4 ms. The frequency length values (Figure 11c) for the dynamite in the CMP range 150 to 800 are higher, with average values of 10 Hz and 8 Hz for the vibroseis. CMP range 800-950 shows anomalous values that might correspond to noise or low fold areas.

First zero crossings values (Figure 11d) are smaller for the dynamite in the CMP range 150-550, with average values of 8.5 ms and 9 ms for the vibroseis. After CMP 550 the values continue increasing. This indicates that there are some areas in the section that might have better imaging and resolution.

The bandwidth attributes (Figure 11e) corroborate some previous observation, such as the mid-frequency and peak-frequency values. The dynamite shows slightly higher

frequencies if compare with vibroseis (about 5 HZ higher) but on the low-frequency side the curves are almost indistinguishable.

The total effective bandwidth (Figure 11f) is not a very indicative factor because for its determination is not always easy to identify accurately the peak- and low-frequency bandwidth. However, looking at the plot we could say that dynamite data have a higher effective bandwidth.

From these attributes we keep supporting what has been consistently observed from previous analyses: the dynamite performs better than the heavy vibroseis.

Radial channel: A general conclusion from all these attributes is that the vibroseis and the dynamite produce similar results (Figure 12). The differences are not very evident; maybe in the frequency length plot the vibroseis have a slightly higher value, but this observation is not constant for all the CMP range.

If the values of the attributes for the radial channel are compared with the vertical channel, we see how the data is of less quality with less resolution and more contaminated with high-frequency noise. This is indicated by longer wavelets, with smaller frequency length and shorter bandwidth.

A positive observation from these analyses is that the apparent lower frequency content is much better for the radial channel, which is an important factor for converted-waves. Another observation from these attributes is that the heavy vibroseis shows a slight advantage over the dynamite.

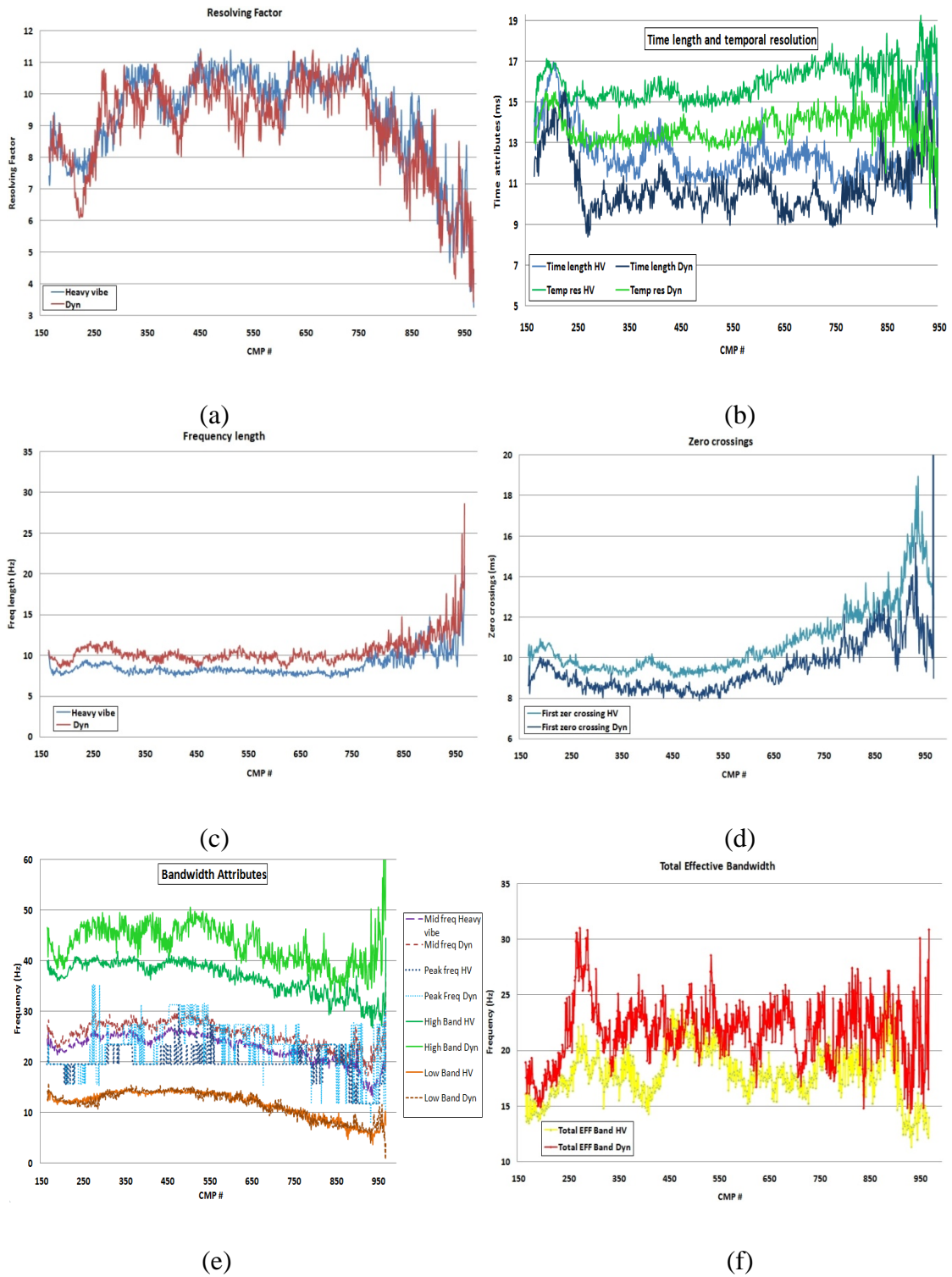


FIG. 11. Deterministic trace attributes calculated for all CMP locations in the vertical component stacked sections: (a) Resolving factor, (b) time length and temporal resolution, (c) frequency length, (d) first zero crossing, (e) bandwidth attributes and (f) total effective bandwidth. For every plot there is a curve corresponding to the vibroseis (HV) and to the dynamite (Dyn) data.

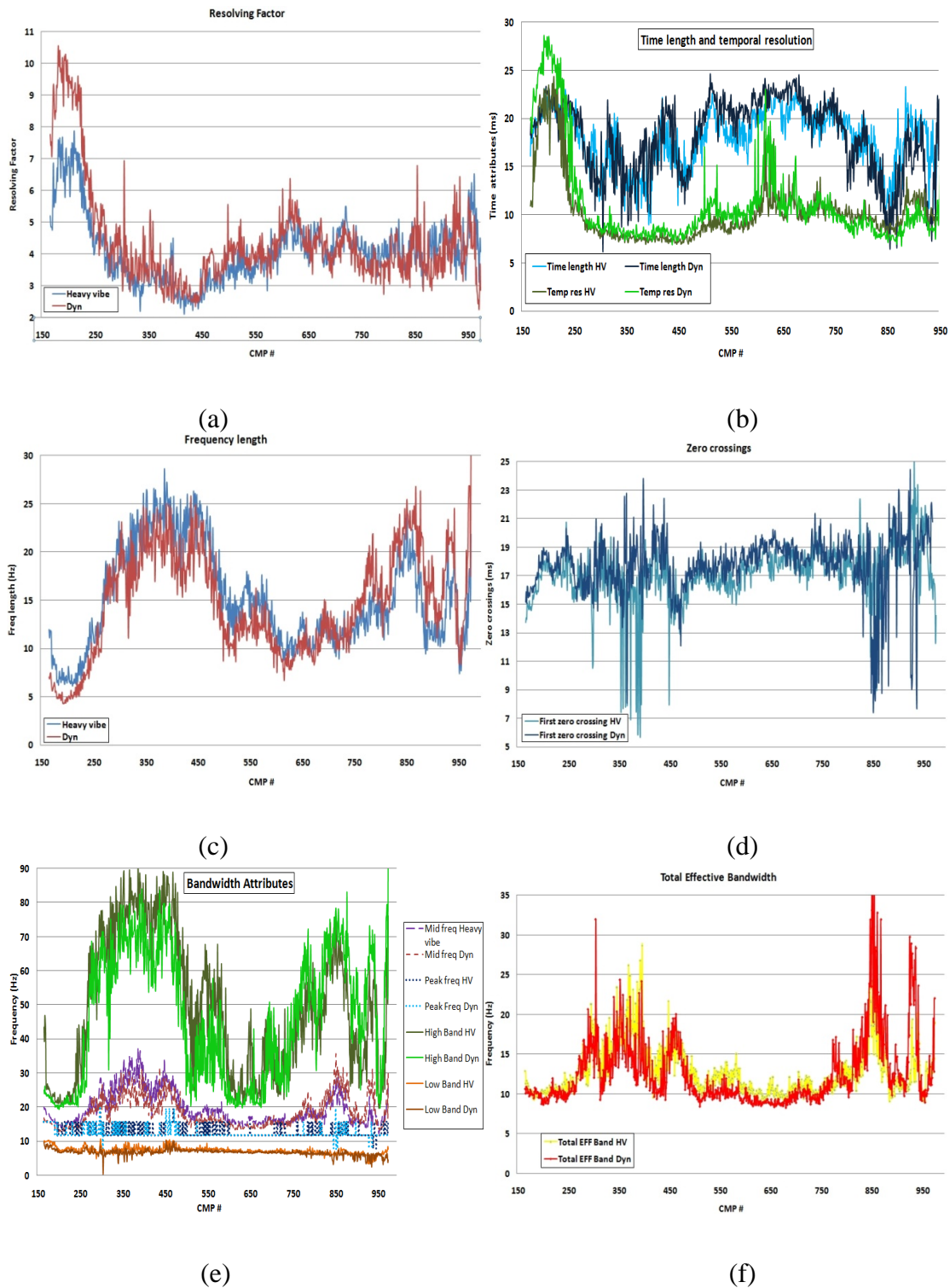


FIG. 12. Deterministic trace attributes calculated for all CMP locations in the radial component stacked sections: (a) Resolving factor, (b) time length and temporal resolution, (c) frequency length, (d) first zero crossing, (e) bandwidth attributes and (f) total effective bandwidth. For every plot there is a curve corresponding to the vibroseis (HV) and to the dynamite (Dyn) data.



## CONCLUSIONS

Analyses of these seismic sources (heavy vibroseis, dynamite and mini vibroseis) were undertaken to conduct a comparative study in the Spring Coulee area in Alberta. The objective was to study in detail the characteristics of each source, and its capability on generating converted-waves. The qualitative analyses included visual inspections of raw shot gathers, and fully processes unmigrated stacked sections. The quantitative analyses included f-x analysis of raw shot gathers and unmigrated stacked sections, and quantified attribute measurements to define which source performs better in terms of seismic resolution. Based on visual inspections made at the shot gather level to determine signal strength, shot-to-shot variation, frequency content, and any variations in noise; the explosive data appear generally superior to vibroseis data. However, the quality of the dynamite records is variable, which could be a consequence of the different near-surface media where the shots are located. This last observation is not the case for the radial channel data, where the consistency from shot to shot looks similar.

The vertical and radial channel unmigrated stacked sections indicate an apparent improvement on resolution for the heavy vibroseis in the shallow portion of the section (0 s-0.5 s), and for the dynamite in the deeper part of the section (0.5s -2 s). For the target zone (0.5 s-1.5 s), improved bandwidth and S/N was achieved with the dynamite source.

Average amplitude spectra were calculated for the raw shot gathers on three windows corresponding to data, noise and first breaks (for the vertical channel) and refraction event (for the radial channel). The data window seems to show slightly higher power for the dynamite in the very low and very high frequencies, while both sources (dynamite and heavy vibroseis) have a similar amplitude values in the 10-40 Hz range. In the radial channel, the amplitudes are very similar but in the range 10-25 Hz. For the noise window in the vertical and radial channels, the vibroseis shows much stronger Rayleigh waves for frequencies higher than 20-25 Hz. Similar power values for the first breaks (vertical channel) and refraction event (radial channel) are seen in the 5-25 Hz range.

An estimation of the signal bandwidth was achieved using the corner frequency concept on the average amplitude spectrum calculated on a data window for the raw shot gathers. Another methods used for this estimation included the realized signal band using f-x analysis of unmigrated stacked sections (amplitude spectrum and phase coherence), and filter panels of a raw shot gather. The results of this analysis indicated an apparent signal bandwidth of 70-75 Hz for the P-wave and 30-40 Hz for the converted wave. Similar signal levels for both sources are observed below 45 Hz for the vertical channel and below 20 Hz for the radial channel. However, the bandwidth of the dynamite is slightly higher for both components.

To summarize, our source comparison results showed how the dataset quality of the dynamite, and heavy vibroseis sources for P- and converted-wave generation are very similar, only small resolution improvements are achieved with the dynamite. Based on our observations, we could say that in terms of data quality any of the sources could be used; however, these criteria is judged with respect to the total cost of the project and the most appropriate source for the project budget. In general terms, the source cost differs if 2D or 3D seismic projects are considered. For 2D projects the vibroseis source would be

the most cost-effective option, considering the cost of shot-hole drilling and larger field crew for dynamite; however, for 3D projects the overcome of the dynamite for 2D projects is compensated by a higher and more stable production rate with dynamite (about 1.5 times higher than with vibroseis due to shorter registration times).

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