Comparative test of emulsion and pentolite based explosive seismic sources

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Abstract

In land acquisition, explosive sources that release a great amount of energy at a minimum charge and environmental impact are preferred. In order to compare two explosive sources, namely emulsion and pentolite based sources, we performed a series of thirty-two isolated test shots and two surveys of two-hundred shots in parallel seismic lines. For the isolated shots we measured the top and volume of cavities to estimate its environmental impact. We also measured the three-component signals and peak particle velocities with a portable seismograph. These quantities allowed to obtaining a rough estimation of the energy equivalence for a pentolite/emulsion charge ratio of 2kg/3kg per shot. In order to obtaining a statistically meaningful comparison we performed a two-hundred shot pentolite survey, to be compared with an already done emulsion survey, with the pentolite charge determined from the isolated shot charge ratio. The pentolite and emulsion seismic lines were then processed with same parameters. The amplitude spectrum, the ratio between geological response and noise, the visual inspection of seismic resolution and lateral continuity of reflectors showed that the source energy of pentolite is relatively smaller than that of emulsion for the chosen pentolite/emulsion charge ratio.

Introduction

The ideal impulsive seismic source is the one that concentrates its energy in one point in space and releases it instantaneously. Such source would produce a seismic signal with a very narrow wavelet that could be processed to better resolve subtle stratigraphic and structural features of the subsurface. What is observed in practice is that real seismic sources have finite spatial dimensions and release their energy in a finite period of time, and hence, they generate seismic signals with relative wide wavelets that reduce the resolution of the subsurface imaging.

Explosives are considered the most effective seismic sources in land exploration because they have high power and short duration, generating seismic signals with narrow wavelets that have a wide frequency band. Concerning these characteristics of an explosive, the higher the power and the faster the energy is released, the narrower the wavelet and the wider the frequency band will be, and, thus, the corresponding seismic data will have better quality and resolution (Yilmaz, 1991; Rosa, 2010).

Regarding the search for a more efficient seismic source, a test was proposed in order to compare two different explosive sources: emulsion-based explosive, currently used in our seismic crew, and pentolite-based explosive. The technical specifications of the sources are in Table 1.

Table 1.Technical specification of the explosive sources.

Name	*emulsion*	*pentolite*
Class	1.1.D	1.1.D
Velocity of Detonation	5200 m/s	7340 m/s
Gas generation	1100 l/kg	658 l/kg
Density	1.15 g/cc	1.6 g/cc
Packing	Plastic film	High Density Polyethylene

The source type determines the energy, shape, and duration of the signal. The explosive sources are mainly characterized by the velocity of detonation, i.e., the velocity at which the shock wave travels through the material (Cordsen et al., 2000). The pentolite has a velocity of detonation of 7340 m/s (Table1) which tends to produce a very sharp, short-duration impulse rich in high frequencies. On the other hand, the emulsion has a velocity of detonation of 5200 m/s which tends to produce a slightly broader impulse less rich in high frequencies. The performance of each explosive depends on amount of charge, hole depth, soil, water saturation, source array, etc. In this work the goal is to estimate the charge relation between emulsion and pentolite that corresponds to the same energy, keeping the other variables at same conditions.

Test proposition and methodology

We planned a three step experimental test in order to compare the performance of two explosive based seismic sources. In the first step, the same hole depth and amount of explosives were kept constant for the shotpoints 1-6 of Fig. 1 and Table 2. This was made in order to compare, at same conditions, the peak particle velocity, the total energy, and depth of the generated cavities. In the second step, different amount of explosives were used for same shot pairs (see Fig.1 and Table 2, shotpoints 7-18) in order to estimate the equivalent amount of energy between the emulsion and pentolite sources. Furthermore, another series of shots were detonated in order to estimate the cavity volume through the time spent to plugging the cavities and holes with sand (shots 19-32), and measure the volume of sand (shots 19-20). All shot pairs of the first and second tests were close each other in order to resemble same soil conditions.

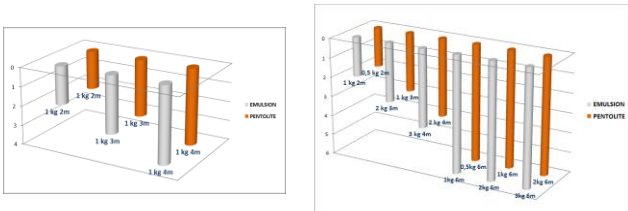

Fig.1. Explosive charge and hole depth for the 18 shotpoints of first (left) and second (right) steps. Grey is for emulsion and orange for pentolite.

Table 2. Source parameters for the 18 isolated experimental shotpoints of Fig.1.

Shotpoint	*Explosive amount (Kg)*	*Explosive*	*Depth (m)*
1	1.0	Emulsion	2.0
2	1.0	Pentolite	2.0
3	1.0	Emulsion	3.0
4	1.0	Pentolite	3.0
5	1.0	Emulsion	4.0
6	1.0	Pentolite	4.0
7	1.0	Emulsion	2.0
8	0.5	Pentolite	2.0
9	2.0	Emulsion	3.0
10	1.0	Pentolite	3.0
11	3.0	Emulsion	4.0
12	2.0	Pentolite	4.0
13	1.0	Emulsion	6.0
14	0.5	Pentolite	6.0
15	2.0	Emulsion	6.0
16	1.0	Pentolite	6.0
17	3.0	Emulsion	6.0
18	2.0	Pentolite	6.0

In the third step, 200 shotpoints were loaded with pentolite in a line parallel and 10 meters apart from the original emulsion line. The purpose was to resemble the same conditions of the emulsion based production line. The source array was the same for the emulsion and pentolite (one hole for shotpoint), but the explosive amount of pentolite per hole was estimated by the results of first and second steps. Both data acquired in the emulsion and pentolite lines were processed with the same processing flow.

In steps one and two, to record the detonations, portable seismograph SSU 3000 EZ Plus (Geosonics) was used in the trigger mode and the lowest triggering level available (0.13mm/s) was selected. It was applied an electric detonator. The record length was 5 seconds with a sampling rate of 1 ms and frequency range from 2 – 500Hz. It was measured the three-component signals. The device was placed 30 meters from the shotpoint. Two softwares were used to process the data acquired in first and second steps: GeoSonics Inc. Seismic Analysis 8.1.54 and GeoSonics Inc. Seismic Analysis v6.3.37 Basic. In the third step, the recordings were acquired by an Aram Aries seismograph. The same parameters applied in the production line were applied for the experimental one (8s recording length and 2ms sampling interval). The data was processed using SeisSpace (Landmark). In this step, the pentolite and emulsion explosives were made up with electronic and electric detonators, respectively. This test was held in the seismic project 2D SD Parecis Teles Pires at the Parecis basin in Mato Grosso State in 2014.

Results and discussion

In Table 3 it is shown the measured peak particle velocity PPV in the vertical direction, and its total velocity, for the emulsion and pentolite cases. It is also shown the calculated ratio between the pentolite and emulsion velocities, and the ratio between the pentolite and emulsion total energy. The energy is obtained from integration of the corresponding power spectra of the signals. All shot pairs present different mass and depth conditions, so we perform the following qualititave analysis. The quantities of shots 1-6 does not discriminate unambiguously what explosive results in more energy. However analysis of shots 7-10 and 13-18 indicates a tendency, sometimes substantial, that the emulsion has higher PPVs and more energy than pentolite. This may be expected since the pentolite/emulsion proportion is of either 1:2 or 2:3. The shots 11-12 present quantities close to 100% for a 2:3 pentolite/emulsion proportion. However, this analysis is not sufficiently accurate, so we gathered the data in three sets of constant charge ratio, namely 1:1, 2:3, and 0.5:1, and performed a statistical analysis. It must be point out that each set has data from two or three depths. We calculate the average and standard deviation (error bar) of the pentolite/emulsion ratio of vertical and resultant velocities and energies as is shown in Fig.2.

Table 3. Measured and calculated quantities for 18 experimental shotpoints. *PPV* stands for peak particle velocity, *Pen* for pentolite, *Em* for emulsion, and *En* for energy.

Shots:1,2	*PPV Em 1kg 2m*	*PPV Pen 1kg 2m*	*Vel Pen/ Vel Em*	*En Pen/ En Em*
Vertical	387 mm/s	356 mm/s	92.0%	80.0%
Result.	768 mm/s	1010 mm/s	131.5%	106.0%
3,4	*PPV Em 1kg 3m*	*PPV Pen 1kg 3m*	*Vel Pen/ Vel Em*	*En Pen/ En Em*
Vertical	356 mm/s	489 mm/s	137.4%	168.3%
Result.	857 mm/s	914 mm/s	106.7%	140.0%
5,6	*PPV Em 1kg 4m*	*PPV Pen 1kg 4m*	*Vel Pen/ Vel Em*	*En Pen/ En Em*
Vertical	483 mm/s	394 mm/s	81.6%	55.9%
Result.	762 mm/s	768 mm/s	100.8%	71.6%
7,8	*PPV Em 1kg 2m*	*PPV Pen 0.5kg 2m*	*Vel Pen/ Vel Em*	*En Pen/ En Em*
Vertical	387 mm/s	279 mm/s	72.1%	62.0%
Result.	699 mm/s	667 mm/s	95.4%	71.9%
9,10	*PPV Em 2kg 3m*	*PPV Pen 1kg 3m*	*Vel Pen/ Vel Em*	*En Pen/ En Em*
Vertical	483 mm/s	311 mm/s	64.4%	45.3%
Result.	813 mm/s	673 mm/s	82.8%	60.2%
11,12	*PPV Em 3kg 4m*	*PPV Pen 2kg 4m*	*Vel Pen/ Vel Em*	*En Pen/ En Em*
Vertical	572 mm/s	584 mm/s	102.1%	88.9%
Result.	946 mm/s	997 mm/s	105.4%	109.0%
13,14	*PPV Em 1kg 6m*	*PPV Pen 0.5kg 6m*	*Vel Pen/ Vel Em*	*En Pen/ En Em*
Vertical	527 mm/s	464 mm/s	88.0%	43.9%
Result.	1003 mm/s	610 mm/s	60.8%	33.7%
15,16	*PPV Em 2kg 6m*	*PPV Pen 1kg 6m*	*Vel Pen/ Vel Em*	*En Pen/ En Em*
Vertical	705 mm/s	457 mm/s	64.8%	35.8%
Result.	1022 mm/s	711 mm/s	69.6%	35.9%
17,18	*PPV Em 3kg 6m*	*PPV Pen 2kg 6m*	*Vel Pen/ Vel Em*	*En Pen/ En Em*
Vertical	959 mm/s	686 mm/s	71.5%	56.0%
Result.	1467 mm/s	953 mm/s	65.0%	53.0%

Percentage of 100% means PPV velocity or energy equivalence. The figure shows that 1:1 ratio is closer to 100%; the 2:3 ratio is close to 80% with error bars that overcome or almost reach 100%, and 0.5:1 is around 60%. Although the charge ratio of 1:1 has percentages closer to 100% than 2:3, the error bars are large. Taking this into account and the cost of pentolite (which is currently relatively high) we chose 2:3 as a suitable charge proportion to be tested in a 200 shot comparative survey.

Now let us consider the cavity issue. Due to the unavailability of, e.g., a Ground Penetrating Radar survey to estimate the depth and volume of the cavity accurately, a simple procedure was used to measure the top of cavities using hand auger and a measuring tape. As the hand auger of 4m was the longest available, the 6m depth shotpoints were not evaluated. The top of cavity depth measurements were performed for shots 1-12 in a dry clayey soil and are shown in Table 4.

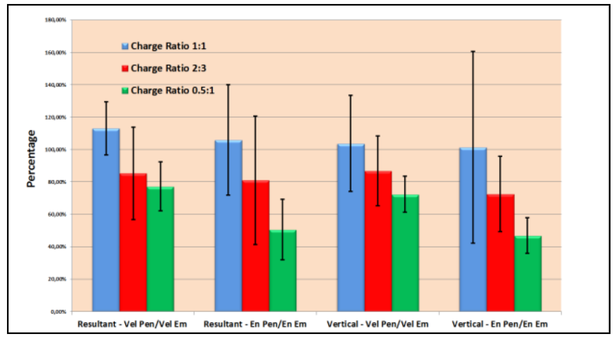

Fig.2. Percentage of pentolite/emulsion ratio of both resultant and vertical velocities and energies for charge ratio of 1:1 (blue); 2:3 (red); and 0.5:1 (green). On top of each bar is the center of the error bar.

The pairs of shots from 1 to 6 of Table 4 show that, at same charge and depth conditions, the pentolite cavity tops tend to be found at greater depths than the emulsion ones. The pairs 7-12, which present less pentolite than emulsion charge at same depths, do not contradict this tendency. In summary, the 12 shot samples of Table 4 shows that the pentolite tends to produce cavity tops deeper than emulsion ones.

In order to measure the cavity volume we conducted an additional 14 shotpoints (19-32) experimental test in a dry sandy soil as is shown in Table 5. After the detonation, the shotpoints were drilled until the top of the cavities. The volumes of the cavity and the hole were estimated by the time required for three men to plug it completely. This is a rough estimation of the volume. For two shotpoints the amount of soil to plug the hole was measured. The 4m and 2kg three shotpoint pairs show that for these shots the pentolite time is less. However for the 2m and 1kg the pentolite time is higher than emulsion. In order to be more conclusive it would be necessary perform tests on several types of soils, use a better technology to measure the cavity, and have more statistics. However, based on this results, we conclude that for the pentolite, the top of cavity has a tendency to be deeper than emulsion and, for 4m hole depth, the

Table 4. Measured depths of top of cavities.

Shot point	*Explosive*	*Explosive (Kg)*	Depth (m)	*Cavity top (m)*
1	Emulsion	1	2	0.67
2	Pentolite	1	2	1.00
3	Emulsion	1	3	1.45
4	Pentolite	1	3	1.45
5	Emulsion	1	4	2.20
6	Pentolite	1	4	2.65
7	Emulsion	1	2	0.66
8	Pentolite	0.5	2	0.90
9	Emulsion	2	3	1.20
10	Pentolite	1	3	1.25
11	Emulsion	3	4	1.40
12	Pentolite	2	4	2.50

Table 5. Comparison of the volume of cavities. P and E stand for pentolite and emulsion. The odd and even shotpoints are close each other.

Shot point	*Explo sive*	*Explo sive (kg)*	*Depth (m)*	*Plugging time (min:sec)*	*Obs.*
19	P	1	2	12:40	23 buckets of 18 lit. of sand
21	P	1	2	04:10	-
23	P	1	2	03:20	-
25	P	1	2	03:09	-
27	P	2	4	02:42	-
29	P	2	4	11:20	-
31	P	2	4	02:37	-
				39:58	
20	E	1	2	06:40	11 buckets of 18 lit. of sand
22	E	1	2	03:20	-
24	E	1	2	02:00	Opened up to the surface
26	E	1	2	02:00	-
28	E	2	4	03:00	Cavity not reached
30	E	2	4	11:00	estimated time
32	E	2	4	04:00	-
				32:00	

volume of cavity tends to be less than the emulsion. In contrast, for the 2m hole depth, the volume of cavity tends to be larger than emulsion one. This last result may be a problem for community safety issues and, for the field operation, it implies extra effort as it takes either more time to plugging or more manpower to be added.

In the third step, 200 shot points with 2kg of pentolite at 6m depth were loaded in a line parallel 10 meters apart from the corresponding emulsion line (of 200 shots with 3kg at 6m depth). We have applied the same processing sequence and parameterization to the emulsion and pentolite data. The applied processing sequence was: geometry, deconvolution of instrument, resampling, static correction, F-K filtering, velocity analysis, spherical divergence correction, surface consistent deconvolution, automatic gain control, stacking, and band-pass filter. The parameterization was chosen from the processing of the emulsion data.

In Fig. 3 it is shown a zoom of the seismic section of the emulsion and pentolite lines. Comparing the lower right corner of each section, it can be noticed a significantly better resolution in reflectors of the emulsion section. In general, the visual comparison between the two sections shows that emulsion presents better reflectors than pentolite, with more lateral continuity and resolution. In the upper part of each section a plot shows two curves (black and red) related to noise. The black curve shows the median of the root mean square *rms* amplitude of noise per *cdp*. This noise is calculated as follows. A window above the first break was made in the shot domain. The *rms* amplitude was calculated inside the created window for each trace. For each *cdp*, the median of the *rms* amplitudes was calculated. The plot scale label (shown in the left side of the plot) of the pentolite is twice the emulsion scale. The plot shows that in the vast majority of the *cdps* the noise is larger in the pentolite section. The red curve shows the number of traces per *cdp*, i.e., the *cdp* fold. Obviously the fold is the same for both seismic sections. The larger the fold, the larger the noise attenuation towards the center of the section.

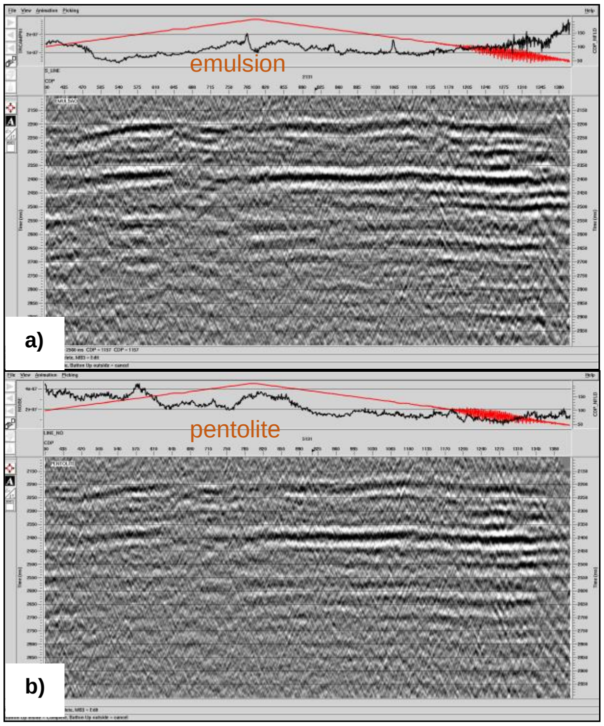

Fig. 3. Zoom of the seismic sections for the emulsion (a) and pentolite (b) lines. The pentolite/emulsion charge is 2kg/3kg per shot. Vertical axis: time (2100ms to 3000ms). The Red curve stands for the *cdp* fold (scale from 50 to 200). The black curve stands for noise *rms* amplitude. In (a) the scale is from 0.5×10^{-7} to 3×10^{-7} V. In (b) it is from 0.5×10^{-7} to 6×10^{-7} V.

Although stacking attenuates random noise, one can argue that the resolution and lateral continuity loss of the reflectors in the pentolite section of Fig.3 are caused by noise, and not from the smaller source energy. In order to address this issue we calculated the amplitude spectra after applying the following processing sequence: geometry, deconvolution of instrument, resampling, static correction, and stacking (with no FK filtering, AGC, or spherical divergence).

The amplitude spectra were calculated in windows of 500ms at a central time t_c of 250, 750, 1250, 1750, 2250, and 2750ms of the stacked section, as is shown in Fig.4.

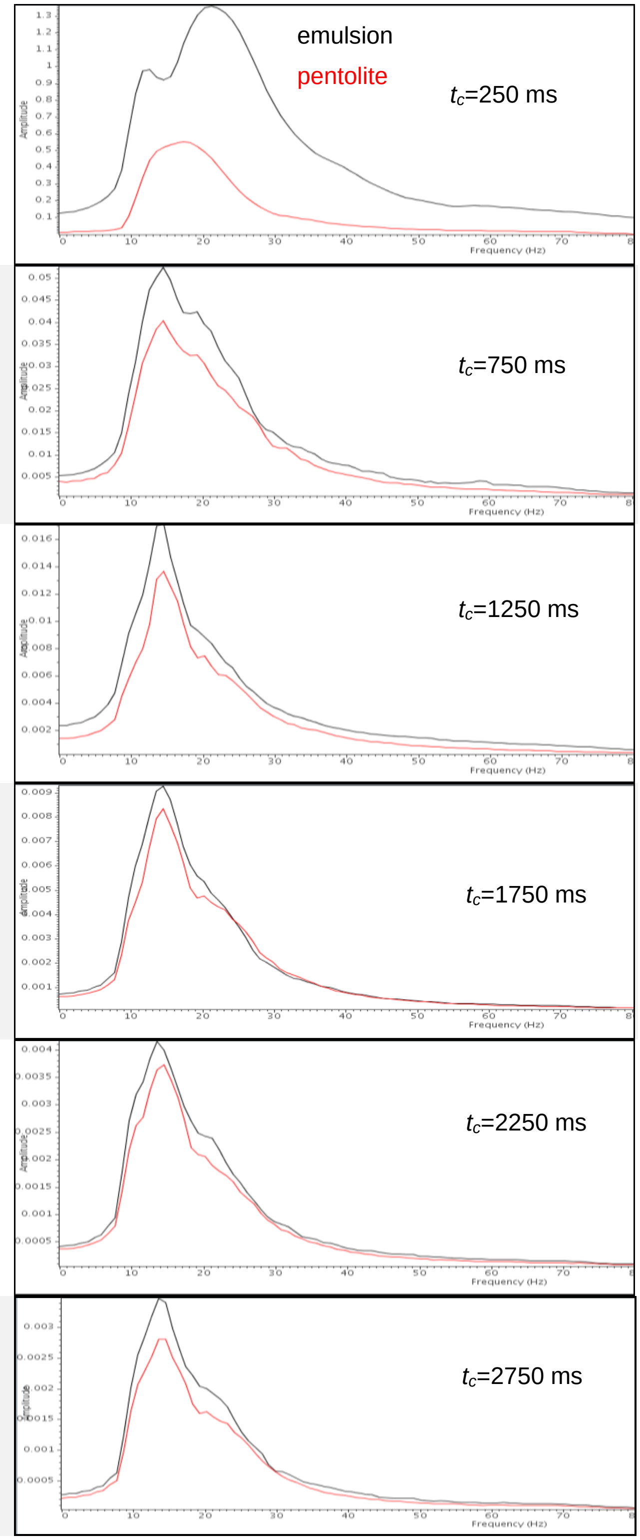

Fig. 4. Amplitude spectra from a time window of 500 ms centered at t_c along the seismic section of the emulsion (black) and pentolite (red) lines.

It can be seen that the amplitude of the emulsion is virtually always greater than the pentolite for all frequencies. However this does not necessarily mean that the energy from the emulsion source is larger than the pentolite, because there is the contribution of the noise. In order to discriminate the source contribution from the noise one, we performed an analysis to the stacked and to the pre-stacked data.

For the stacked data, the black curves of Fig.3 show that the amount of noise present in the pentolite data before stacking is larger than that of the emulsion data. The stacking attenuates noise equally since the *cdp* fold is the same. Thus a larger quantity of noise is present in pentolite spectrum than that in the emulsion spectrum of Fig.4. Since the spectrum amplitude of the pentolite is smaller than that of emulsion, the energy of the pentolite is smaller than that of the emulsion for virtually all frequencies.

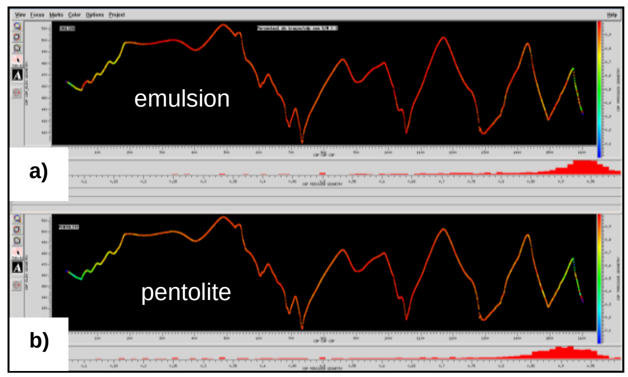

Fig. 5. Elevation vs. line distance, with color indicating the percentage of traces per shot with geological response larger than noise. In (a) the emulsion and in (b) the pentolite shot lines. Color scale: blue 0%; green 50%; red 100%. Below each plot is the histogram of the percentage (0-100%).

For the pre-stacked data, we analyze the ratio of the geological response to th e measured noise. We define the geological response GR as all seismic response of the earth (signals from reflectors, multiples, and the coherent surface noise). The noise is all that is not the GR, like the environmental and equipment noise. In order to calculate these quantities, we define a time window above and below the first break and calculate the correspondent *rms* amplitude. The *rms* amplitude above the first break is assumed to represent the noise and that below the first break is assumed to represent the sum of GR with noise. The GR is obtained subtracting the noise amplitude from the amplitude below the first break An underlying hypothesis is that the *rms* noise does not vary within the registration time (a reasonable hypothesis from the visualization of data) and that the results are not sensible to the chosen time windows. For each trace the ratio of the GR to the noise was calculated. For each shot, the percentage of traces with GR larger than noise was calculated. Figure 5 shows the elevation vs. distance along the line, with the color scale indicating the percentage of traces per shot with GR larger than noise. Red indicates high percentage, blue low percentage. It can be noticed that the emulsion shots, when compared with its correspondent shots, present equal or higher percentage of traces with GR larger than noise, for the majority of shots. This is also indicated by the histogram of the percentages, which is shown below each plot. Note that the emulsion histogram is centered around 94%, while the pentolite is around 91%, showing that the emulsion data have a larger number of shots with high percentage of traces with GR larger than noise. Taking into account that the amount of noise present in the pentolite data is larger than that in the emulsion data (the black curves of Fig.3) the analysis of Fig.5 is consistent with the result of the stacked case where the pentolite energy is less than the emulsion energy.

Conclusions

Twelve analyzed shotpoints at equal and unequal conditions showed that the pentolite has a tendency to generate deeper cavity tops than emulsion ones. Eight analyzed shotpoints at 4m depth and 2kg showed that the pentolite has a tendency to generate smaller cavity volumes. However six analyzed shotpoints at 2m depth and 1kg showed that the pentolite has a tendency to generate larger cavity volumes. Although the statistics are low, these results are relevant. For eighteen analyzed shotpoints the three component signals and peak particle velocity allowed to obtain a rough estimation of the charge ratio that resulted in energy equivalence. We applied this charge ratio to the setting of a statistically meaningful two-hundred shot survey, to be compared with an already done emulsion survey. After the seismic processing, the amplitude spectrum, the ratio between geological response and noise, the visual inspection of seismic resolution, and lateral continuity of reflectors showed that the energy of pentolite is relatively smaller than that of emulsion, for virtually all frequencies, for the chosen pentolite/emulsion charge ratio of 2kg/3kg.

Acknowledgments

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