Analysis of S-waves generated by explosive sources in boreholes: modeling and the Priddis experiment

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ABSTRACT

The Priddis field experiment, carried out this year by CREWES, included explosive sources in boreholes. This report presents analysis of this source of S-waves using synthetic data generated by a finite difference method, and also shows some results at Priddis. The resulting synthetic data in the horizontal component, corresponding to the same source location and velocity model, are compared, and the effect of the vertical and tilted boreholes are clearly identified. A real case of 10 m depth vertical and tilted sources in Priddis, show variation in the energy distribution, but the S-wave pattern was not clearly identified. Further analyses will study this issue. The uphole experiment allowed to obtain a velocity model for S-waves in the near surface by events identified in the horizontal component. Additional analysis of other events of the wave field detected by the sensors deployment of these explosive source experiments will be considered,

INTRODUCTION

Shear wave generation have been an issue for the multicomponent data method (e.g. Garotta, 2000). Besides that a near-surface velocity model of the S-wave will contribute to better near-surface correction, since it would take advantage of more physical properties. It can also contribute to other applications where near-surface S-waves are used, such as engineering (e. g. related to the earthquake response) and environmental purposes.

An explosive charge in a borehole is a common energy source in seismic exploration. Usually it is assumed to be a pure dilatational source, generating only compressive waves. However, some authors (e. g. Heelan, 1953, and Lee and Balch, 1982) have shown theoretically that an explosive source inside a borehole can generate S-waves. Besides that they have been observed by some authors, e. g. White and Sengbush, 1963. A previous work in CREWES has also shown a case history that presents that kind of events. Then, in principle, the S-wave near-surface velocity model can be obtained from shallow boreholes, and perhaps some other applications can be identified. Consequently a closer study of this source of S-wave energy appears appropriate.

The Priddis Experiment carried out by CREWES in 2013 (see Hall et al., 2013, and Bertram et al. 2013, this issue) included explosive sources in boreholes with the purpose to investigate on this energy source. Two analysis are presented in the following: a numerical experiment about the effect of the borehole on the seismic events generation and a preliminary analysis of the data generated by explosive sources of the Priddis experiment.

FIELD LAYOUT

The experimental data were acquired at the Priddis Observatory of the University of Calgary. Details about that can be found in Hall et al., 2013, and Bertram et al. 2013, (this issue). A number of energy source and receiver configurations, including the instrumented wells, were included in this experiment. This report will be only concerned with surface multicomponent receivers and explosive sources inside of boreholes.

Figure 1 shows the relevant field layout. Figure 1a shows the four receiver lines, identified as L1, L3, L5 and L7. Lines L1 and L3 are about 300 m length. Lines L5 and L7 about 60 m length. The interception point corresponds to the instrumented well (Hall et al., 2013). The receivers are separated by 6 m to each other.

Figure 1b is a close-up of the central part, which includes the explosive sources, identified by red dots. There are six 10 m depth shots to the East and West of the instrumented well and an uphole survey to the North. The six 10 m depth shots are identified with the letter S and a number. Arrows in Figure 1b indicate the tilted boreholes and their tilt direction. The uphole is identified by a circle to the North and had nine sources spread over 20 m deep.

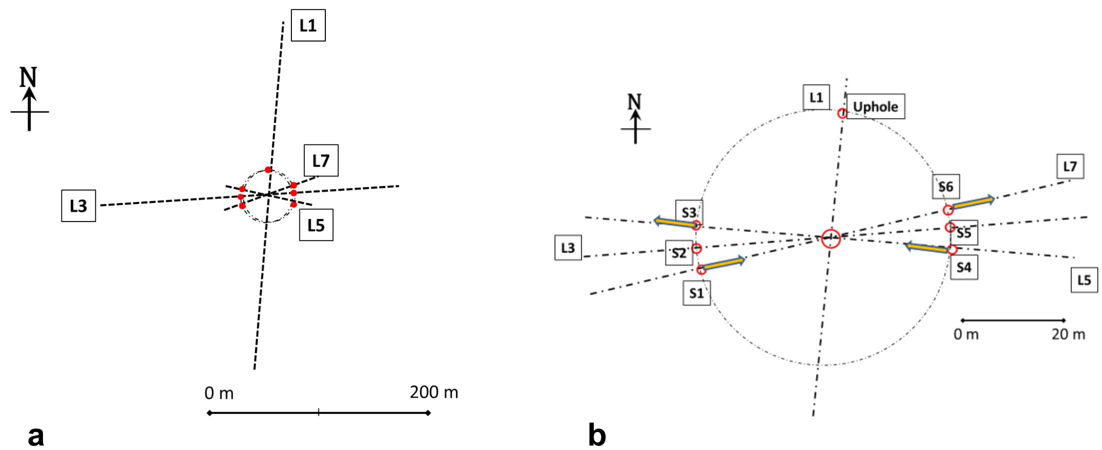


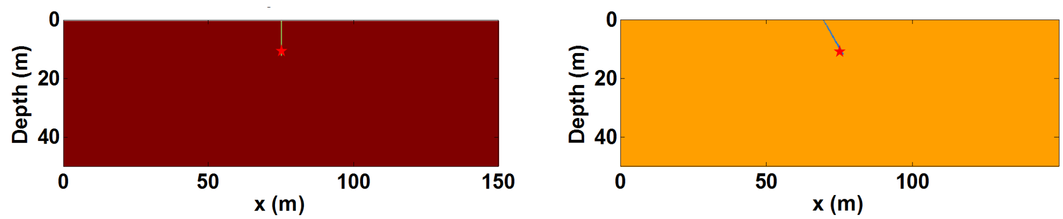
FIG. 1. Spread for the Priddis experiment data referred in this work: (a) Surface multicomponent receiver lines, identified by corresponding labels, and explosive source locations, identified by red dots. (b) Zoom of the source locations with their identification.

NUMERICAL EXPERIMENT

A numerical experiment was carried out to shows the effect of the source in the resulting seismic events. It was used a 80 Hz Ricker wavelet as a source. A finite difference 2-D elastic code was used. A fine space grid (0.2 m in x and z directions) allowed to model 0.2 diameter wells. The same velocity models was used with three different source configurations: without borehole, with a vertical borehole and with a borehole tilted 30°. Figure 2 illustrates the two borehole configurations for P- and S-wave velocities. The properties are in Table 1.The properties inside the borehole correspond to a quasi-fluid, such as can be the mud that is used for drilling.

Figure 3 shows the resulting data gathers from modeling, for the horizontal component, Figure 3a correspond to no borehole, 3b to a vertical borehole and 3c to a tilted borehole. Notice the additional event in Fig. 3b, whose velocity correspond s to the S-wave velocity.

Figure 3c, corresponding to the tilted borehole, shows an additional event, which agree with the relation between the axis of the borehole (tilted 30°) and the source radiation pattern, as shown by theoretical models (see Figure A1b in Appendix A).

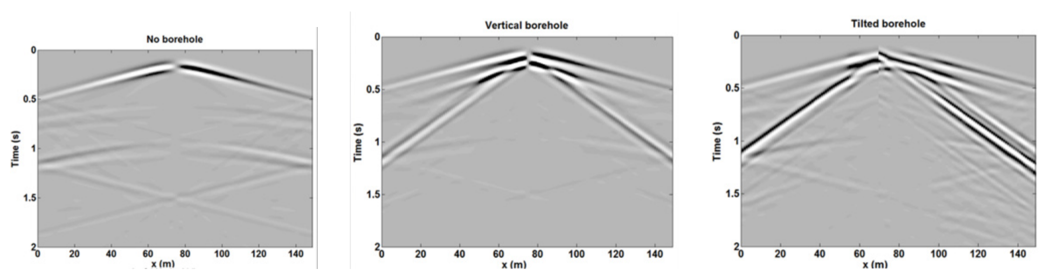


a b

FIG. 2. Model for the source configuration. (a) vertical Model, and (b) Tilted model

	Vp (m/s)	Vs (m/s)	Density (kg/m3)
Geological Medium	2000	800	2400
Inside the borehole	1500	150	1000

TABLE 1. Parameters of the model.



a b c

Fig. 3. Modeling of the borehole effect: (a) without borehole, (b) with a vertical borehole and (c) with a tilted borehole.

EXPERIMENTAL DATA

As shown in Figure 1, six single explosive sources in 10 m depth holes were shot. and an uphole, which had nine charges along about 20 m. A preliminary review of the surface data is presented in the following.

Figure 4 shows an uphole shot gather corresponding to the shot depth of 19.6 m, as recorded by the NS receivers line (L1 in Fig. 1a). It is the radial horizontal component, and the event identified as S-wave generated by the explosive source is shown by a red line, which is an arrival time picking. Notice the polarity reversal depending on the side relative to the shot location (offset). The amplitude for this event was calculated using the Hilbert Envelope method, and is shown in Figure 4b. Notice the higher amplitudes for shorter offsets and smaller for farther offsets, which agrees with the theoretical model for S-waves generated by explosive sources (Appendix A). Figure 5 shows a tomography carried out from the data picked for the 9 shots in the borehole. Figure 5a corresponds to S-wave and Figure 5b to the P-wave taken from the first breaks, for completeness. Additional data would allow to test the reliability of this velocity model.

Records of the shots identified as S1, S2 and S3 in Figure 1 are shown in Figure 6. Figure 6a correspond to the southern one (S1), tilted to the East, Figure 6b to the middle one (S2), corresponding to the vertical borehole, and Figure 6c to the northern one (S3), tilted to the West. There are some differences specially in the short time events with small offset, however is not possible to identify clearly the asymmetry or symmetry of the events as in the synthetic case of Figures 3b and 3c. It can be attributed to interfering events, difference energy or coupling of the energy sources or geological complexity. Tuning of the horizontal components orientation can also contribute. Future work will be related to these issues.

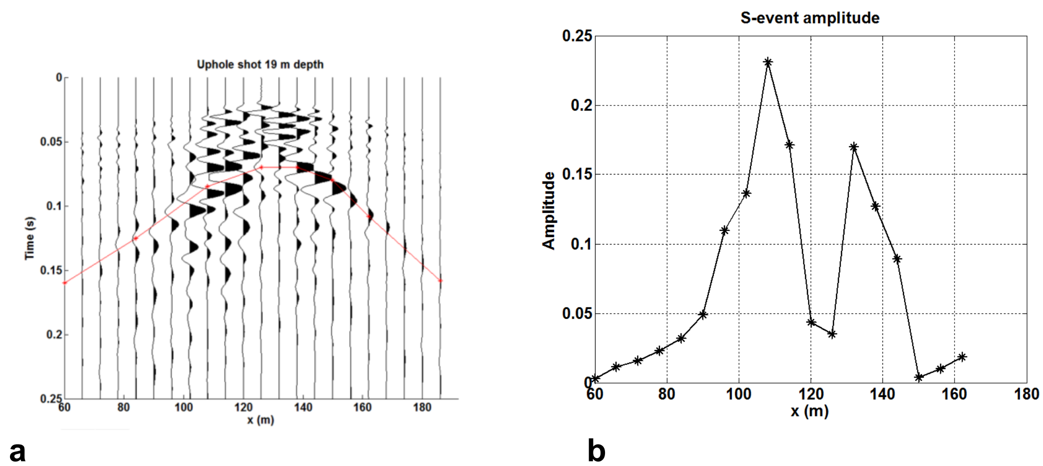


FIG. 4. (a) The 19 m depth source horizontal component. Picking of the S-wave event is identified by the red line. (b) Amplitude with offset for the same event.

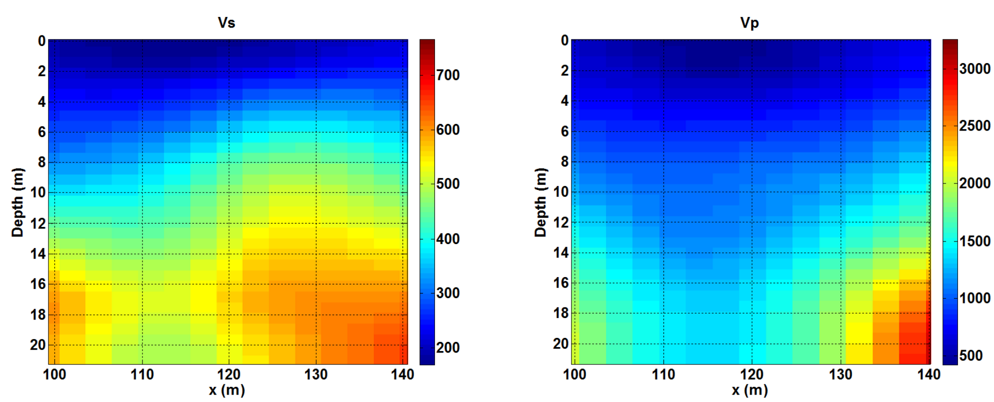


FIG. 5. (a) S-wave velocity from the uphole tomography. (b) P-wave velocity from the first breaks tomography.

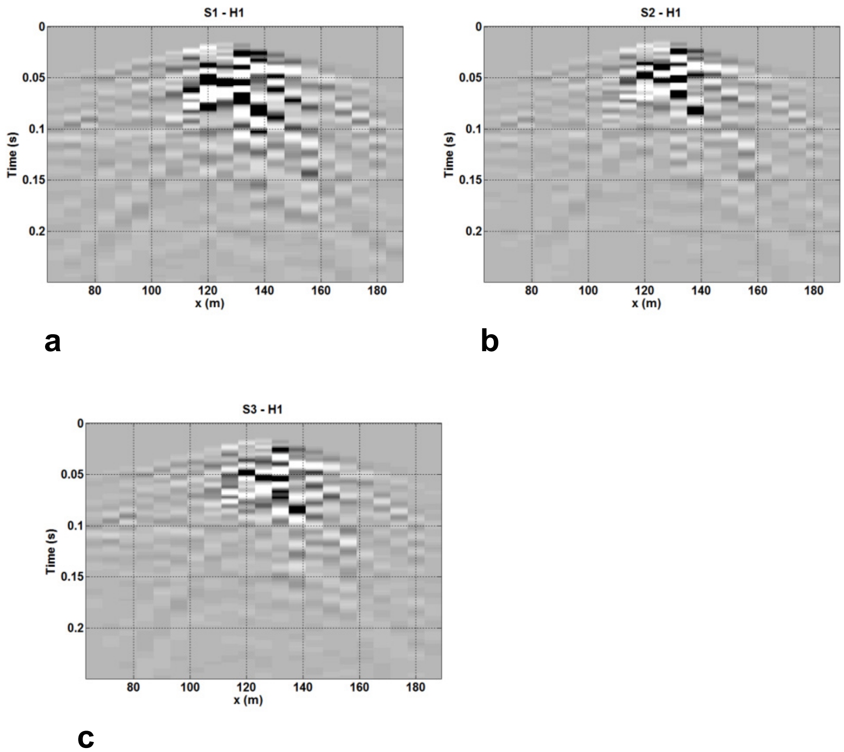


FIG. 6. Field data of three 10 m depth shots, horizontal component. (a) Shot S1, from the tilted source in direction E, (b) shot S2, vertical source, (c) shot S3, tilted source in direction W.

CONCLUSIONS

S-waves generated by explosive sources appear as a feasible source of energy, according to theoretical studies, synthetic modeling, and filed experiments. It can provide critical information about the wave field in the near surface.

However the near surface S-wave can be affected by interfering events generated by the same source, and related with layering and the free surface.

The uphole experiment show events identified as S-wave generated by the source, which allowed to create a near-surface velocity model using tomography.

The preliminary analysis of the Priddis experiment presented here provides many events whose analyses are promising about the near surface S-waves generated by explosive sources, which will be subject of future work.

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REFERENCES

Bertram, K. L., Bertram, M. B., Hall, K. W., Gallant, E. V., Lawton, D. C., Margrave, G. F., and Innanen, K. A. H., 2013, CREWES in the Field, acquisition and preliminary results. CREWES Research Report (This Issue).

Hall, K. W., Bertram, K. L., Bertram, M. B., Gallant, E. V., Margrave, G. F., and Lawton, D, C., 2013. Installation of new observation wells at the Priddis Geophysical Observatory. CREWES Research Report, (This Issue).

Garotta, R. , 1990. Shear waves from acquisition to interpretation. SEG Distinguished Instructor Short Course,

Guevara, S. E. and Margrave, G. F., 2011, CREWES Research Report.

Heelan, P., 1953, Radiation from a cylindrical source of finite length: Geophysics, 18, 685-696.

Lee, M. W. and A. H. Balch, 1982. Theoretical seismic wave radiation from a fluid-filled borehole: Geophysics, 47, 1308-1314.

White, J. E., and Sengbush, R. L., 1963, Shear waves from explosive sources: Geophysics, 6, 1001-1019.

APPENDIX A

The Lee and Balch's model

Some authors have published theoretical analyses of wave generation in boreholes. Lee and Balch (1982) proposed the equations corresponding to a fluid–filled cylindrical borehole in an elastic isotropic homogeneous media. The model assumed is presented in Figure A1a (from Lee and Balch, 1992), with *z* the vertical axis of a borehole of diameter *a* and filled with a fluid of P-wave velocity α_1 and density ρ_1. The location of the displacement is a function of the distance *R* and the angle to the source ϕ. The source has a volume displacement V_0 and a variation with time *G(t)*. The elastic medium properties are P-velocity α_2, S-wave velocity β_2 and density ρ_2 .

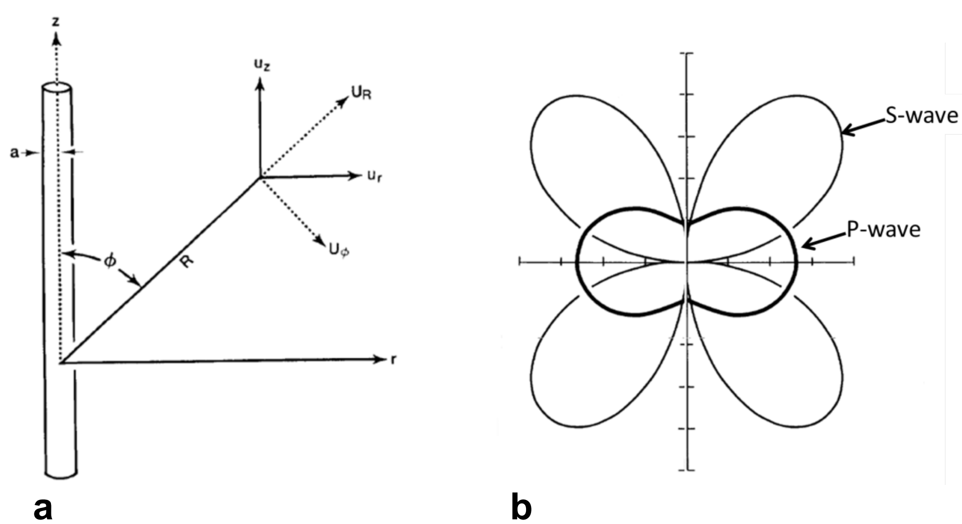

FIG. A1: Model of explosive source inside a full-filled borehole, according to Lee and Balch (1982). (a) The model geometry. (b) An example of the radiation pattern of the source.

Then when a volume displacement source is assumed, the particle displacements (radial or P and tangential or shear) in the solid are given by:

$$U_R = \frac{\rho_1 V_0 (1 - 2\beta_2^2 cos^2 \phi / \alpha_2^2) G'(t - R/\alpha_2)}{4\pi\rho_2(\rho_1/\rho_2 + \beta_2^2/\alpha_1^2 - \beta_2^2 cos^2 \phi/\alpha_2^2)\alpha_2 R}$$

and

$$U_\phi = \frac{\rho_1 V_0 \sin\phi \cos\phi \, G'(t - R/\beta_2)}{2\pi\rho_2(\rho_1/\rho_2 + \beta_2^2/\alpha_1^2 - cos^2\,\phi)\beta_2 R}$$

where:

Subscript 1: inside the borehole (fluid medium).

Subscript 2: outside the borehole (elastic medium).

V_0 : volume displacement of the source,

α : P-wave velocity.

β : S-wave velocity.

$G(t)$: Variation of the source with time.

An example of the source radiation pattern for P and S-waves for a point volume displacement source is shown in Figure A1b, taken from Lee and Balch (1982). It corresponds to a Poisson's solid with $\rho_2/\rho_1 = 2.75$ and $\alpha_2/\alpha_1 = 4.0$.