Near-surface S-wave velocity from an uphole survey using explosive sources

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Summary

A near-surface S-wave velocity model was obtained from an uphole survey using seismic events identified as S-waves generated by explosive sources. The model was obtained by picking zero offset events analogously to the method used for P-waves. These events appear frequently mixed with other wave modes, which makes this procedure challenging and somewhat uncertain. The complexity of the wave field increases the closer the energy source is to the surface. However a lithological profile with depth generated from rock samples (from drilling) shows a good correlation with the resulting velocity model. Probable velocity inversions were also observed in this model. The uphole data were compared to data from a surface 2D seismic line acquired at the same place. These surface data show events with characteristics of S-wave refractions, besides Rayleigh waves and probably other wave modes. These events show a lower frequency content than the uphole data, and some complex variations noticed in the uphole can be masked by the low-frequency high-energy ground-roll in the surface data. Refractions on the horizontal component data from the 2D line can also be correlated to some extent with the velocities obtained from the uphole.

Introduction

The land near the surface is typically heterogeneous, which affects S-wave propagation, distorting seismic events from deeper layers. Techniques to obtain a better S-wave velocity (Vs) model of the near surface can improve the seismic image of deeper targets. In addition, they can provide useful information about the near surface.

A near-surface Vs model can be obtained from surface (indirect) methods or from borehole (direct) data. The surface seismic methods include analysis of Rayleigh (surface) waves and refractions, which can provide wide spatial coverage. However these methods, are somewhat restricted by the assumptions of the corresponding mathematical model, and can have limitations such as poor horizontal resolution (Socco et al., 2010) and troublesome event picking (e. g.. Al Dulaijan, 2008).,

Borehole data surveys allow relating Vs to depth and to lithological properties for an specific location. There are two kinds of borehole surveys: downhole, with sources at the surface and receivers inside the borehole, and uphole, the other way around (see Cox, 2000). Downhole surveys have had engineering applications (e. g. Kim et al., 2004). Uphole surveys, on the other hand, appear less commonly used, and the difficulty to get appropriate S-wave sources in this case has been mentioned in the literature (Bang and Kim, 2007).

This work explores uphole data obtained from a field experiment carried out by Ecopetrol SA, at a Valley in the Andes mountains of Colombia. Characteristics of the vertical and horizontal components are analyzed and a method to obtain a Vs model to 60 m depth is applied. The relevance of this method to obtain a near-surface Vs model, and the relation of this data to a land surface 3C seismic survey are investigated. Finally the velocity model and the potential and shortcomings of the method are discussed.

Field Data

The data analyzed here come from a multicomponent experiment, which included two shallow boreholes approximately 3 km apart, acquired simultaneously with a 3C seismic surface survey, in the Magdalena Valley of Colombia. The two boreholes are identified by 1 and 2 in Figure 1(a). Borehole 1 was located in a flat area on a Quaternary Formation, about 400 m away from a river on its flood plain, and Borehole 2 was located on moderately rough terrain, on Tertiary rocks.

The seismic energy was provided by two energy source types: dynamite charges (150 g) and 2 to 4 caps, located intermingled inside the borehole, and separated 2.5 m from each other, as illustrated in (Figure 1(b)). The maximum depth was 60 m. The receivers were 3C accelerometers deployed on the surface with a maximum offset of 200 m, and separated by 5 m in Borehole 1 and by 2.5 m in Borehole 2.

This work is focused on Uphole 1. The chosen data correspond to a receiver line with a maximum offset of 100 m. Figure 2 shows a lithological profile at this location, obtained by analyzing the drilling cuttings. Most of the profile corresponds to clays interbedded with sands, however there is a layer of conglomerates and other hard materials between 23 and 42 m depth.

Figure 3 shows examples of the data obtained in borehole 1, for source depths of 55, 45, 30, 20 and 10 m. Figure 3a corresponds to the Vertical component and Figure 3b to the Horizontal one. Noticeable events are the strong first breaks (FB) on the vertical component and a later hyperbolic, high energy event on the horizontal component. In Borehole 2 a more complex seismogram could be observed, with many more irregular, non-hyperbolic events, as shown in previous work (Guevara et al., 2011).

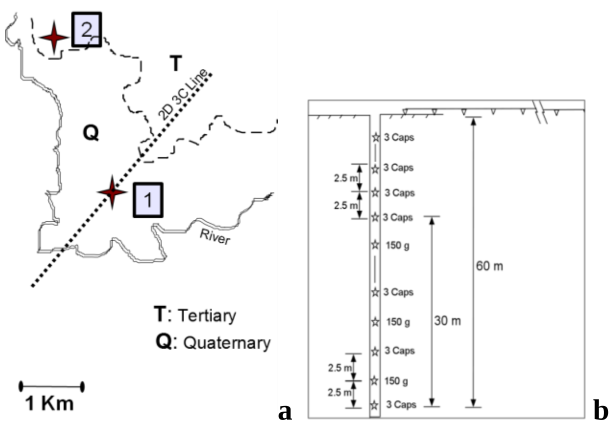

Figure 1: Upholes field layout: (a) Location. The boreholes are identified by numbers. (b) Profile of the borehole, showing the typical source distribution.

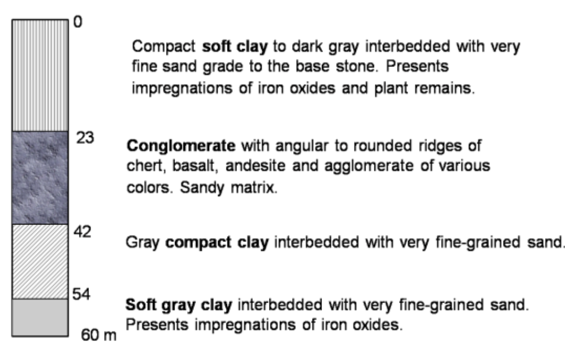

Figure 2: Stratigraphic profile (Borehole 1) from drilling cuttings.

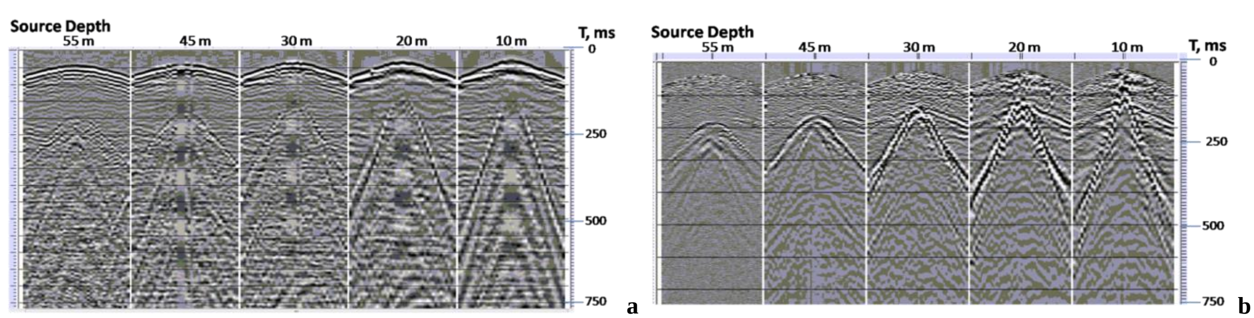

Figure 3: Example records from Uphole 1 for different source depths.(a) Vertical Component (b) Horizontal component.

The Vs velocity model

The S-wave velocity model was generated assuming that S-waves were generated by explosive sources inside the borehole. As the strong event on the vertical component or First Breaks (FB) corresponds to direct P-waves generated by the source, the strong event on the horizontal component can correspond analogously to direct S-waves. Similar results on real data have been provided in the literature, (e. g. White and Sengbush, 1963; Lash, 1985), and have also been derived theoretically for waves generated in a borehole (e. g. Heelan, 1953; Lee and Balch, 1982).

Additionally, a test for this hypothesis using the Dix NMO equation with the resulting velocity model is shown below. The horizontal polarization of the event also corresponds to S-waves. The S-wave detected on the horizontal component at the surface could also be generated from P to S-wave conversion to S upon its transmission through an interface. However, this does not agree with the high energy of this event, as shown in the literature (e.g. Muskat and Meres, 1940).

According to this working hypothesis, the events for zero offset were picked (Figure 4a) and velocity models with depth were obtained for P and S-waves (Figure 4b). Picking the S-wave event was less obvious than the P-wave FB, and even harder for some depths, such as shallower than 20 m, and again about 30 m depth, because some other events interfere (see Fig. 3b for illustration). The resulting model of Figure 4b shows a number of layers, the Vs layering can be related to the lithological profile shown in Figure 2. Also, there is a strong velocity increase for P-waves at about 5 m depth, whereas S-wave velocity increases slowly with increasing depth. These characteristics match the expected near surface behavior due to the different response between P and S-waves due to the water table (Stümpel et al., 1984 Molotova and Vassiliev 1960).

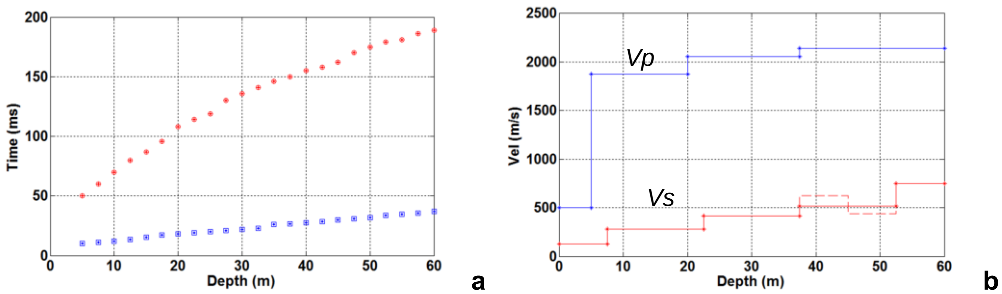

Figure. 4: Picked velocities for uphole 1. (a) Arrival times, P-wave (Blue) and S-wave (Red). (b) The velocity model. Two possibilities for *Vs* about 45 m depth, are shown.

The S-wave velocity model appears more complex than the P-wave one, with possibly two velocity inversions, at about 25 and 45 m depth (Fig. 4a). Figure 4b, besides a simpler S-wave velocity model (continuous line), illustrates a possible velocity inversion (dashed line), between 42 and 52 m depth, which could be correlated with the stratigraphic profile (Fig. 2). The complex model would be appropriate for a near surface investigation purpose, and the simpler model would be sufficient to correct the S-wave reflections from deeper interfaces.

A test for the velocity field obtained according to this hypothesis is to reproduce the time variation with offset of the real data by using this velocity model, and with the Dix NMO equation for a borehole:

$$T_r = \sqrt{\left(\frac{z_s}{V_{ave}}\right)^2 + \frac{(x_r - x_s)^2}{{V_{rms}}^2}}$$

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where z_s ≡ source depth,

x_s , x_r ≡ source and receiver surface location

V_{ave}, V_{rms} ≡ average and RMS velocities.

Figure 5 shows the resulting offset-arrival times plotted on the seismic data gathers for source depths of 45 m (Figure 5a) and 10 m (Figure 5b). A good match can be observed in Figure 7a. For the 10 m source depth the curve agrees with the high energy short offset events, while for larger offsets there are other events, including higher velocity refractions.

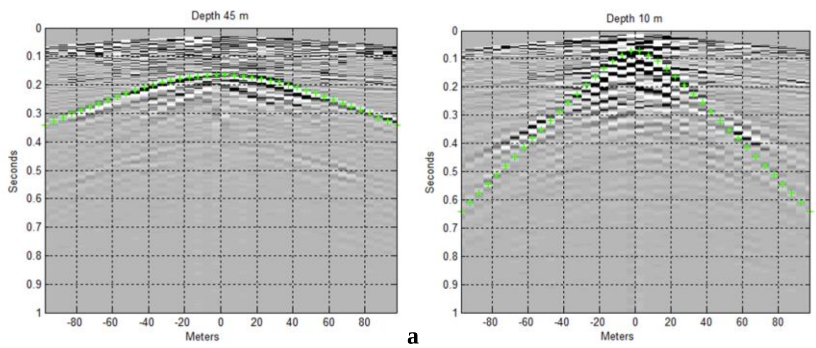

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Figure 5: Horizontal component arrivals calculated according to the NMO equation over the seismic data, for depths of (a) 45 m, (b) 10 m.

Relationship between the uphole and the surface seismic data

As mentioned earlier, a 2D 3C seismic line was acquired at the same location (see Figure 1), making an analysis of the relationship between the two datasets relevant. An explosive source of energy was used for the seismic line, with a charge size of 2700 g at a depth of 10 m. Receivers were separated by 10 m.

Figure 6 shows a shot record of this seismic line, whose source was located 20 m from the uphole 1. Data from three hundred receivers in each direction are shown, hence the farthest offset is 3000 m. Fig. 6a corresponds to the horizontal component, and Fig. 6b to the vertical one. Notice the strong low velocity event on the horizontal component (with velocity labels), probably corresponding to S-wave refractions. Their velocities can be related to the velocities found at the uphole (Fig. 2b). Figure 7 is a close-up of the same surface seismic shot gather, including only offsets lower than 100 m and arrival times less than 0.8 s. It can be compared to Fig. 8, corresponding to the shot from uphole 1 at 10 m depth. Some resemblance of the events can be noticed, especially the strongest one in both components. However the surface seismic data show lower frequency, stronger events, and reverberations, and the uphole record shows a number of higher frequency events.

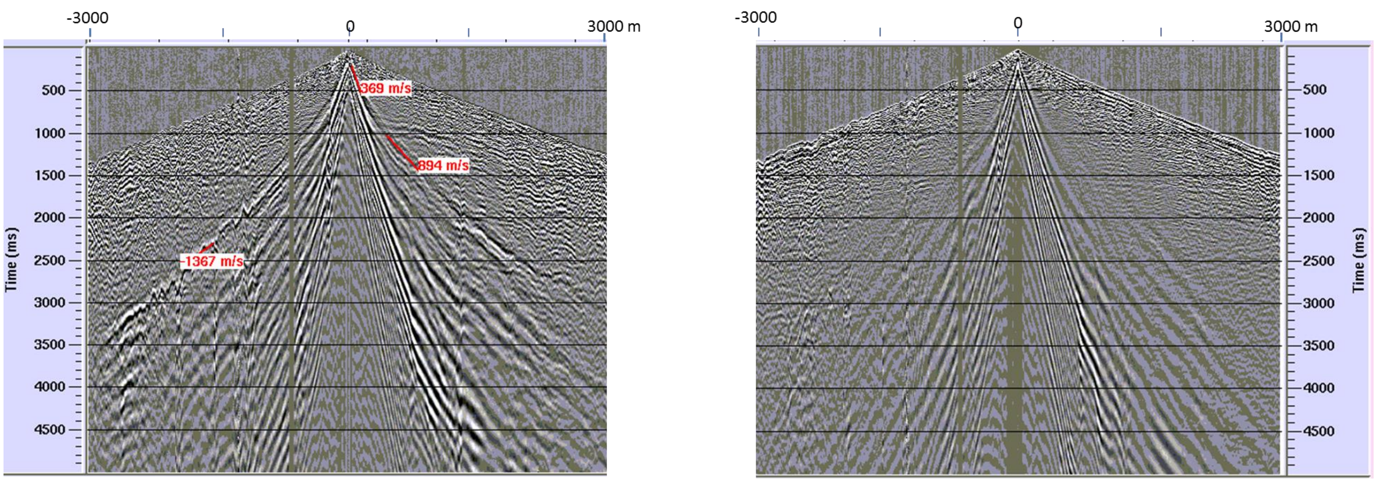

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Figure 6. Surface 2D 3C data from a source located at 20 m from the borehole. (a) Horizontal component (b) vertical component.Notice the events whose velocity is labeled in the horizontal component.

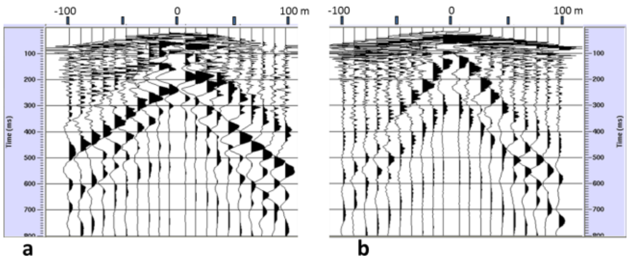

Figure 7. Zoom of the 2D record, for a maximum offset of 100 m and maximum time of 0.8 s. (a) Horizontal component (b) Vertical component.

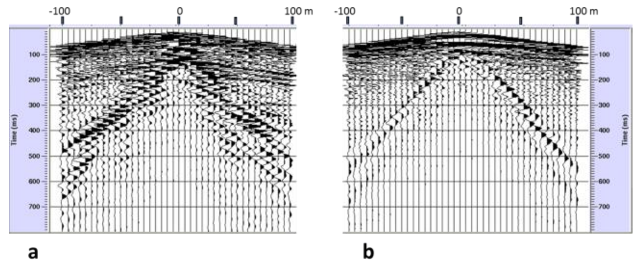

Figure 8. Uphole data from the 10 m depth source (a) Horizontal component (b) Vertical component.

Discussion

It was possible to obtain a near-surface S-wave velocity model based on the uphole data using the zero-offset picks on the horizontal component of the event identified as S-wave generated directly from the explosive source. S-waves generated by explosive sources are supported by theoretical studies. Besides that, the events have strong amplitude and horizontal linear polarization, and the NMO curve agrees with the velocity model. A more detailed study of the complete wavefield generated (including the energy source variations) can provide additional evidence for this hypothesis.

The velocity model obtained can be related to the lithological profile (Fig. 2) and to events identified as refractions that were observed on a 3000 m shot gather with the energy source 20 m away from the uphole (Fig. 6). A possible velocity inversion in the Vs uphole model could be explained with the lithological model. This inversion could not be detected by the refraction method, because of its own theoretical assumptions.

However, the S-wave event picking has noticeable uncertainty and is prone to errors compared to the FB picking used for P-waves from upholes, mostly because mixed wave modes, especially at shallower depths. The shallower weathering layer (i. e. about 10 m depth in this case), causes an important time delay for the S-wave, (about 100 ms), but can hardly be characterized in detail with this method. Some of these events can be related to anisotropy in the near surface, which could be tested with analyses in other directions. Due to these uncertainties additional testing of the model obtained seems advisable.

These results can be related to an analogous experiment carried out in Alberta, Canada, presented by Parry, 1996. In that work, events picked in the horizontal component were identified as P to S-wave conversions. Higher resolution and difference in the energy of the events of the two components can be noticed in our case. These differences can be explained by differences in the energy source (low energy explosives), in the receivers (accelerometers vs. geophones), and probably in the terrain characteristics (tropical vs. temperate).

Conclusions

Events on the uphole horizontal component were identified as S-waves generated at the source. They enabled us to obtain a near-surface Vs model from the uphole data.

An S-wave events picking method analogous to the zeros offset first-breaks picking method used for P-wave velocity surveys was used. However, the picking of events for S-wave analysis is harder than the FB picking used for P-waves.

The uphole data appear to provide additional data that can be related to the 2D seismic line and to the available lithological profile. The surface methods, besides their own assumptions, have resolution limitations. Information on the near surface S-wave velocity field from upholes can be related to surface reflection seismic data to generate a more extended model.

The S-wave events picking was even harder for the shallower events. However, the most shallow layer, in this case less than 15 m deep, produces a larger effect on the time delay because of its lower velocity and typically higher heterogeneity.

Techniques like geological modeling and tomography could help to obtain information from this type of survey. Additional information on the wave field could also be obtained.

Acknowledgements

We thank ECOPETROL S. A., that acquired the data presented here and authorized the publication of this work. Also to Don Lawton for his suggestions and to the CREWES sponsors and the CREWES staff for their support.

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