Near surface S-wave velocity from upholes: an experiment

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ABSTRACT

Data from two uphole surveys are analyzed here to obtain the near-surface S-wave velocity model. It was assumed that the S-wave events analyzed were generated by the source. Support for this claim is provided. Variations in the velocity model with depth were related to lithological characteristics. Differences between the two upholes can also be related to the geology at each location. Complex behaviour of the S-wave field was also identified, which could give useful details about the S-wave field structure. The uphole data were also compared to data from a 2D seismic line acquired at the same place. The latter gives indications about the characteristics of probable S-wave refractions. However the frequency content of the land data is much lower, and the complex variations noticed in the uphole data are simply part of the ground-roll here.

INTRODUCTION

The S-wave is strongly affected by the heterogeneity of the near surface in land, making it difficult to obtain images of deep targets from the surface with this wave mode. A method to compensate for this drawback during converted wave processing is the application of a static correction based on common receiver stacks: if all the other delay times are corrected, a delay time in the common receiver stack would be the receiver static for each receiver, that is to say the S-wave delay for converted waves (e.g. Cary and Eaton, 1993). Although effective in many cases, this method depends on statistical properties and has limitations such as assuming a mild geology, and that the source statics and the NMO correction are appropriate.

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.

The S-wave near-surface velocity model can be obtained from shallow boreholes and from surface seismic data.Surface seismic methods can use surface waves and refractions. A method that uses Rayleigh waves called Multichannel Analysis of Surface Waves or MASW has been applied successfully (e. g. Xia et al., 1999; Al Dulaijan, 2008). However it has limitations in its horizontal resolution (Socco et al., 2010). Refraction of S-waves has also been tried, although its use is not quite extensive, in comparison with the analogous approach used for P-waves, which has been accounted for difficult event picking (Al Dulaijan, 2008).

An advantage of the borehole based surveys is that the velocity information can be related to depth and to lithological properties. A limitation is that it is relatively expensive and the data obtained is local. There are two kinds of borehole surveys: downhole, with sources at the surface and receivers inside the borehole, and uphole, the other way around (Cox, 2000). Downhole surveys have had engineering applications. A pure S-wave source of energy have been implemented in this case, (e. g. Kim et al., 2004). Upholes appear less commonly used, and the difficulty to generate appropriate *S*-waves in this case has been mentioned in the literature (Bang and Kim, 2007).

This article is intended to explore the uphole information and how it could contribute to obtain a better velocity model for the near-surface S-wave propagation, and for converted wave processing. Ecopetrol carried out an experiment that included the acquisition of two uphole surveys and 3C surface seismic data, intended to obtain correlation between the uphole events and the lithology of the near surface, and to get information useful for statics correction in the processing of converted (PS) waves for an experimental 3D 3C survey. A first approach to the analysis of these data is presented in the following.

FIELD DATA

The experiment

The data used in this work was generated at two shallow boreholes, These uphole data were acquired in conjunction with a 3C surface survey which included a 2D 3C line. The two boreholes were approximately 3 Km apart. They are identified in the following by numbers 1 and 2, as shown in Figure 1(a). The terrain was different for each one, since borehole 1 was located in a flat area, about 400 m away from a river and on its flood plain, and borehole 2 was located in moderately rough terrain, about 50 m above the level of the river. Geologically borehole 1 is located on a Quaternary Formation and borehole 2 on a Tertiary Formation.

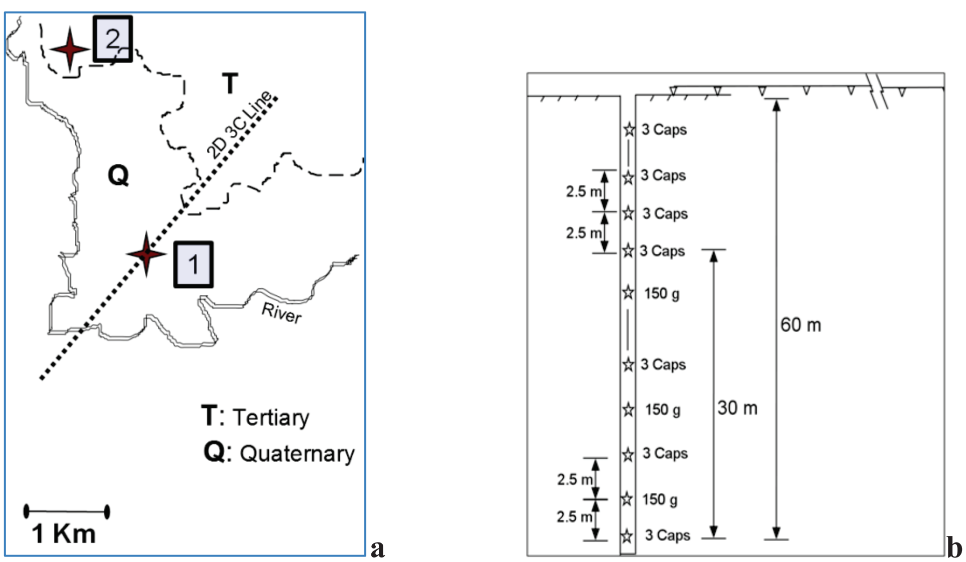


FIG. 1. Upholes field layout: (a) Location. The boreholes are identified by numbers. A river, an sketch of the surface geology and the 2D 3C seismic line location are also illustrated. (b) Profile of the borehole, showing the typical sources distribution and charge.

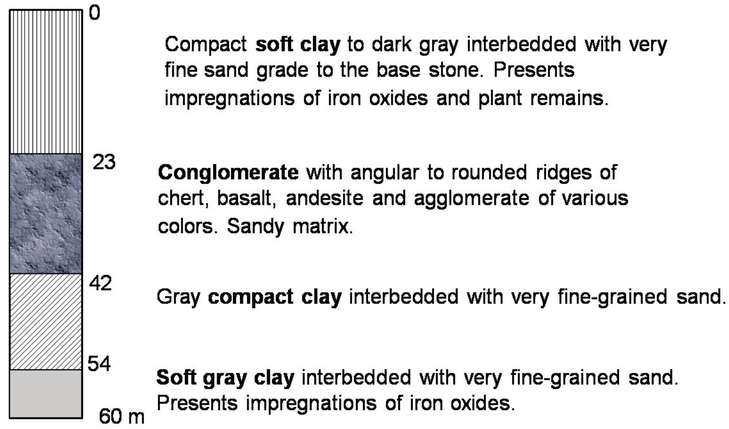


FIG. 2. Stratigraphic profile of borehole 1 from drilling cuttings.

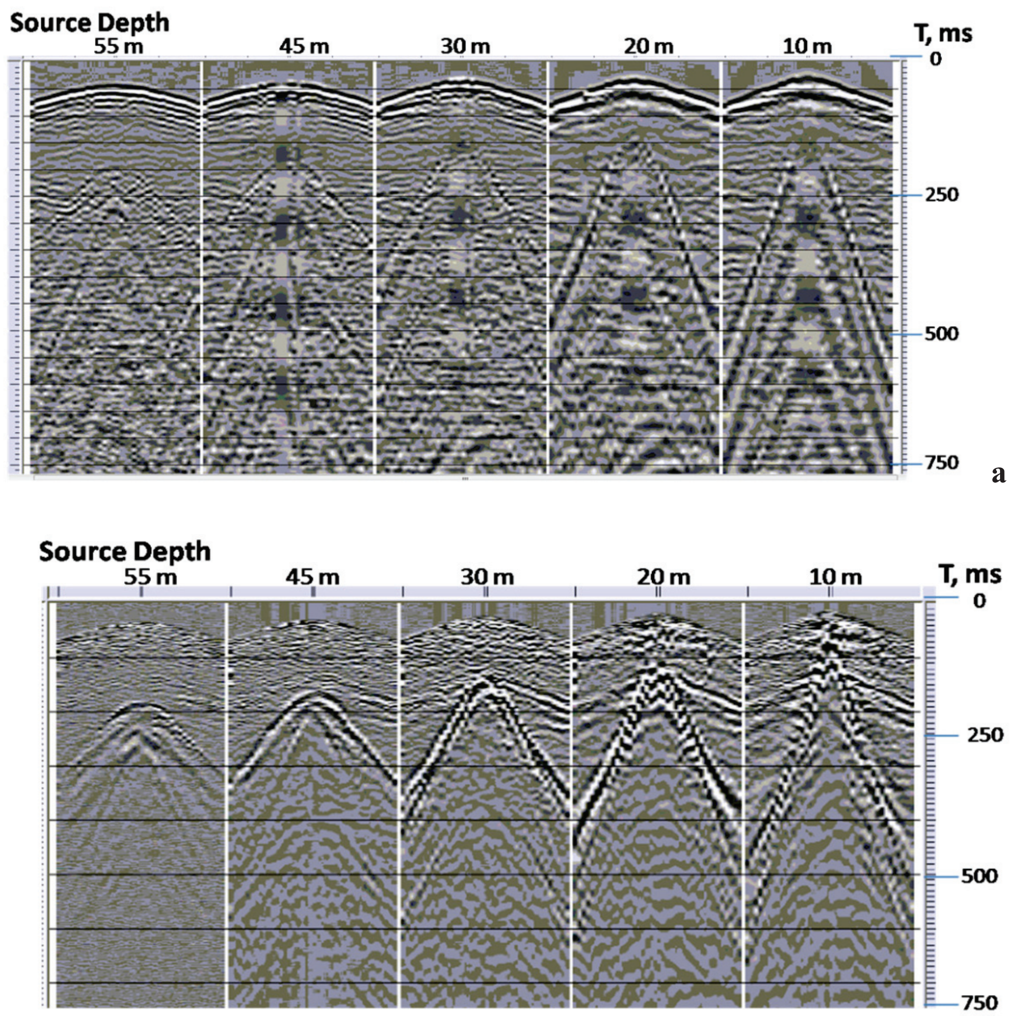


FIG. 3. Records from Uphole 1 for some selected depths.(a) Vertical Component (b) Horizontal component. The strong event on the horizontal component was selected for S-wave analysis.

The total depth of each borehole was about 60 m. Small explosions inside the borehole were used as an energy source. Dynamite charges of 150 g were interspersed with caps. These charges were separated by 2.5 m in depth from each other, as illustrated in Figure 1(b). On the surface 3C receivers (accelerometers) were deployed along three lines centered at each borehole in directions separated by 60º, and with a maximum offset of 200 m. A receiver line for each borehole, with maximum offset of 100 m, was selected for the following analyses. Along the 100 m closer to the borehole the receivers were separated by 5 m in borehole 1 and by 2.5 m in borehole 2.

The analysis presented here is focused in Uphole 1. Figure 2 shows a lithological profile of this borehole, obtained by analyzing the drilling cuttings. It can be noticed that 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 First Breaks (FB) on the Vertical component and a later hyperbolic, high energy event in the Horizontal component. Figure 4 corresponds to similar data from borehole 2, with sources at 55, 42.5, 30, 22.5 and 15 m. A more complex seismogram can be observed here, since there are more events, which are more irregular, non-hyperbolic. However, similarly to borehole 1, strong first breaks on the vertical component and a delayed strong event on the horizontal can also be identified.

DATA ANALYSIS

S-wave events and the velocity model for uphole 1

Besides the strong event on the vertical component (First Breaks) which corresponds to direct P-waves generated by the source, the strong event on the horizontal component can correspond analogously to S-waves. Supporting this hypothesis is its horizontal linear polarization, and other indications from the data and the literature presented later in this article (see the Discussion section).

According to this working hypothesis, the events for zero offset were picked and velocity models with depth were obtained for P and S-waves. Figure 5 shows the picking corresponding to uphole 1 and Figure 6 the resulting velocities.

It can be observed that it is difficult to pick this strong event on the horizontal component data from the shallower boreholes (approx. depth less than 20 m), since a mix of wave modes is present there. (Figures 3b and 10 can also illustrate this issue).

The resulting model of Figure 6 shows a steep increase in the velocity for both wave modes at about 20 m depth, which agrees with the change in lithology from the profile in Figure 2. Also there is a strong velocity increase for P-waves at about 8 m depth, without too much correlation for S-waves. This event agrees with the expected near surface behavior according to some authors, such as Stümpel et al., (1984) and Molotova and Vassiliev (1960), since the water table generates a strong effect on P-wave data, but not on S-wave.

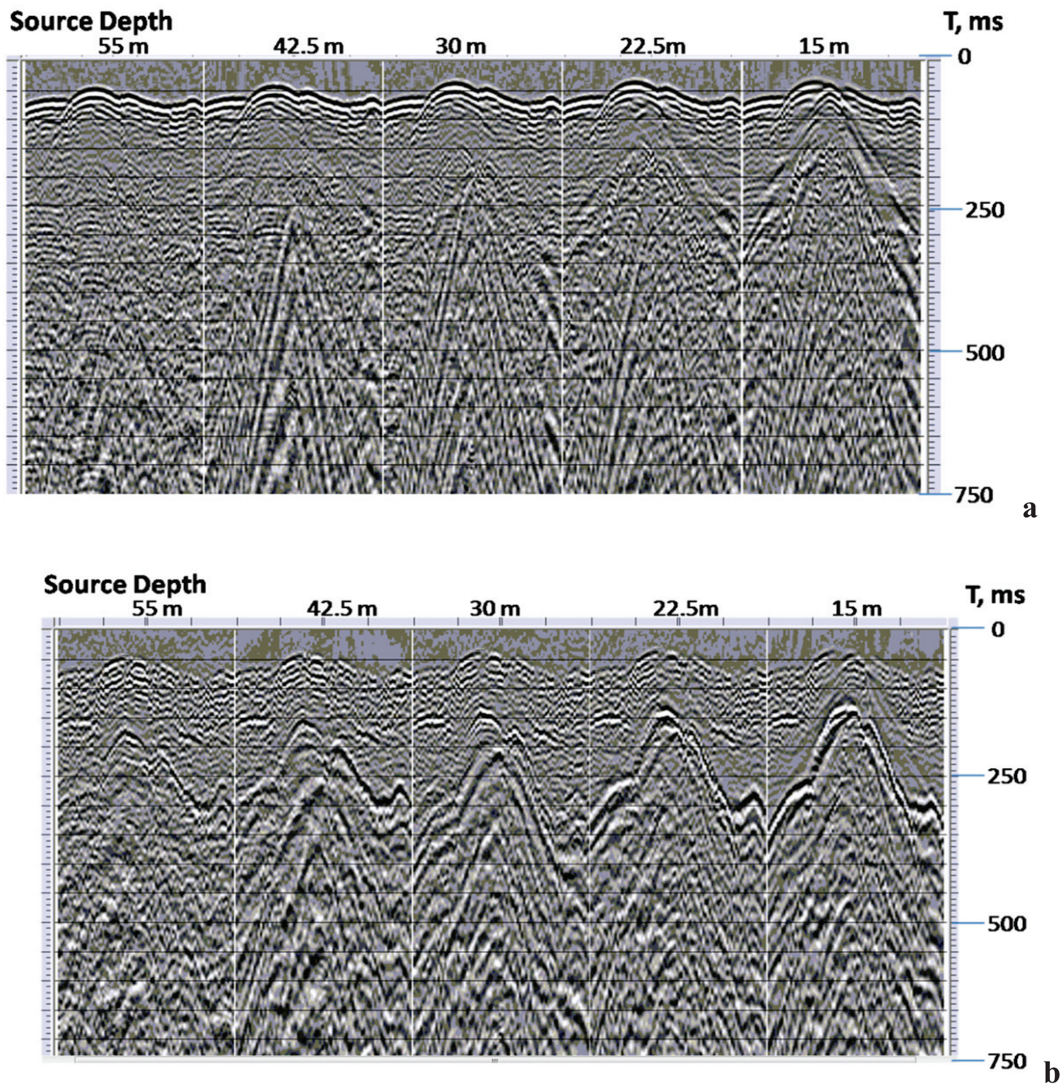


FIG. 4. Records from uphole survey 2 for some selected depths.(a) Vertical Component (b) Horizontal component.

Velocity model test: NMO curve from the S-wave velocities

A test for the velocity field obtained would be to reproduce the time variation with offset of the real data by using this velocity model. These curves can be calculated using the Dix NMO equation:

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

where $z_s \equiv$ source depth,

x_s , $x_r \equiv$ source and receiver surface location

V_{ave}, $V_{rms} \equiv$ average and RMS velocities.

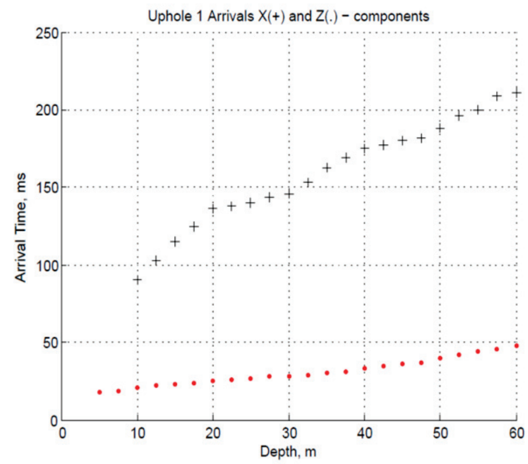


FIG. 5. Picking of the strong energy arrivals selected in the two components of Uphole 1. Red dots correspond to the vertical component and black crosses to the horizontal.

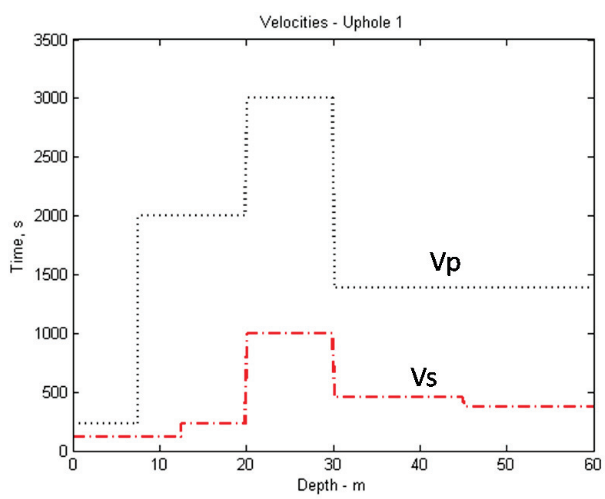


FIG. 6. The velocity model for Uphole 1 calculated from the picking of Figure 5.

Figure 7 illustrates the resulting calculations together with the corresponding seismic data gathers for the source depths of 45, 30, 20 and 10 m. A good agreement can be observed for 45 and 30 m depth. For sources at 20 and 10 m depth the curve agrees with high energy events for short offsets, however not for larger offsets. This difference can be attributed to the probable presence of a refractor at 23 m, as shown by the velocity model (Figure 6) and the stratigraphic profile (Figure 2). For these larger offsets the direct S-wave could be embedded in other events.

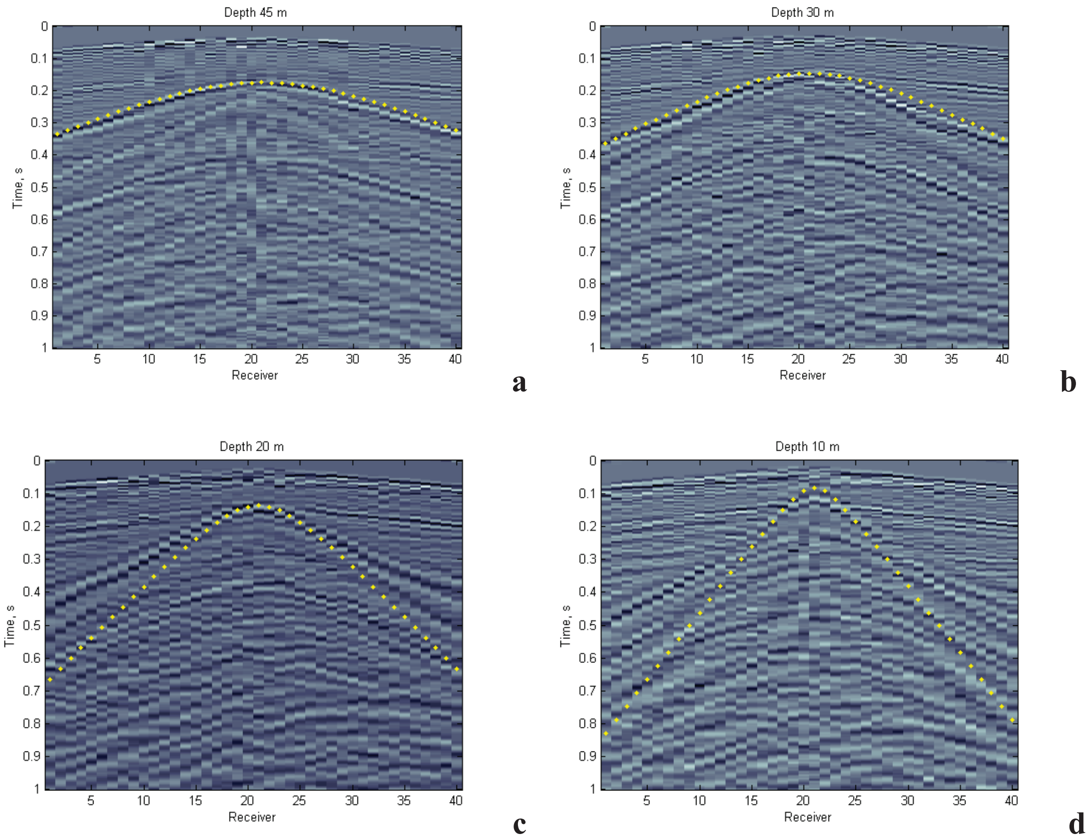


FIG. 7. Comparing arrivals of the event in the horizontal component with the arrivals calculated according to the NMO equation for four depths: (a) 45 m, (b) 30 m, (c) 20 m, (d) 10 m. .

Velocities from uphole 2 and the Vp/Vs ratio

Following a similar approach to that for uphole 1, a velocity model was calculated for uphole 2. The result is shown in Figure 8a. Less marked differences between the P and S wave patterns can be observed, as much as less variation with depth. Comparison of the Vp/Vs ratio with depth of uphole 1 and uphole 2, shown in Figure 8b, confirms this difference between the two upholes.

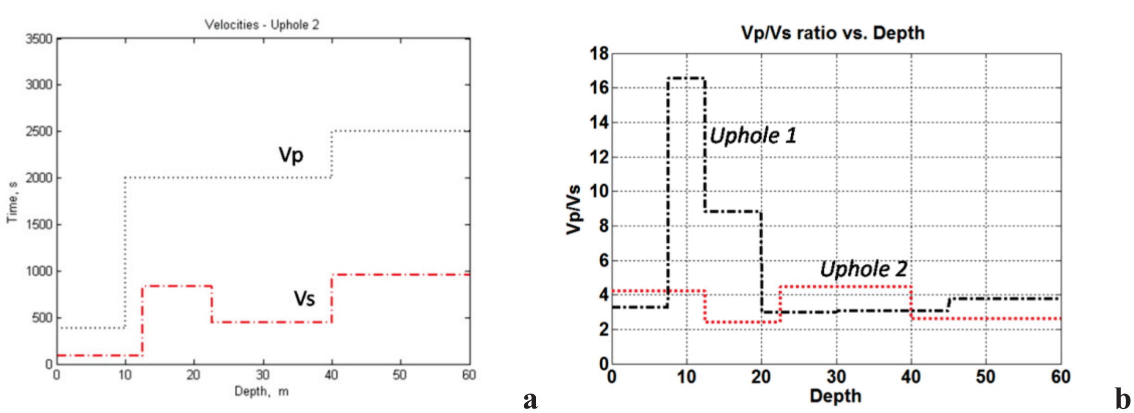
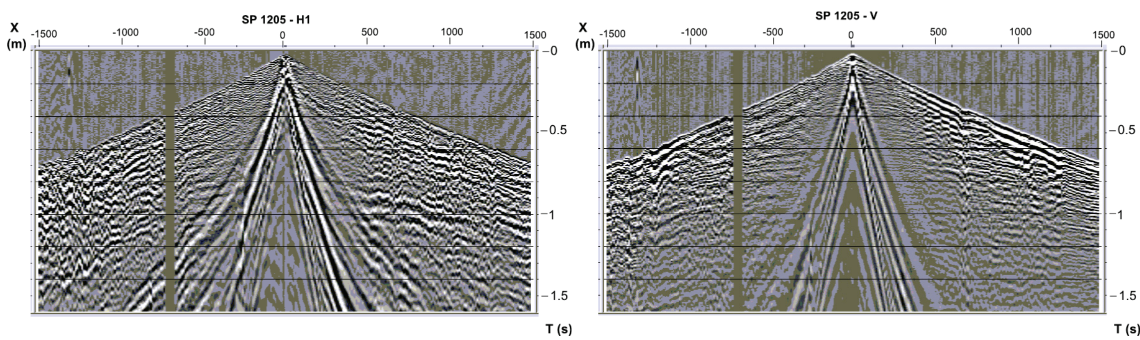


FIG. 8. (a). Velocity model for uphole 2 after a similar procedure as used for uphole 1. (b) Variation with depth of the Vp/Vs ratio for both boreholes.

Relation between the uphole and the surface seismic data

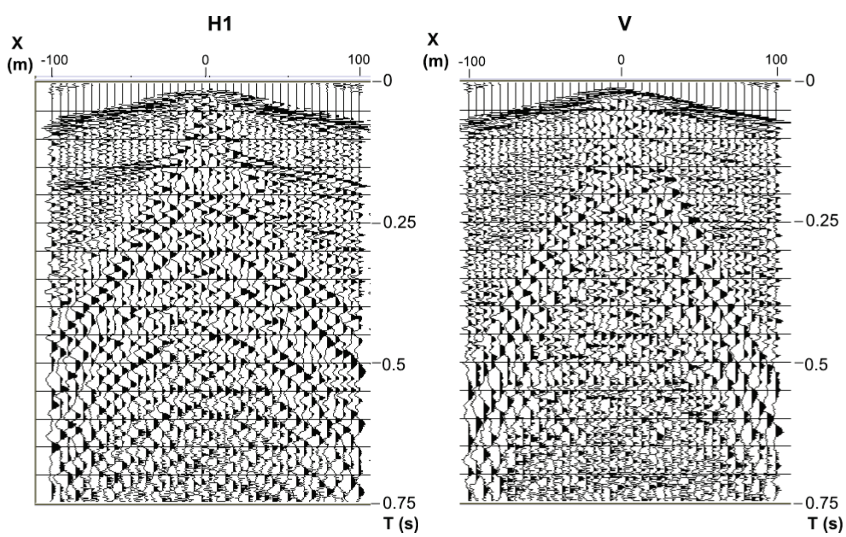
As mentioned before, a 2D 3C seismic line was acquired at the same setting (see Figure 1). A few shots of this line were located at about 20 m from the location of uphole 1. A comparison of the corresponding records is relevant. Figure 8 shows the vertical and horizontal component records of a shot located at 20 m from uphole 1. An explosive source of energy was used in this case, with a charge size of 2700 g and with a borehole depth of 10 m. A noticeable low velocity event can be observed on the horizontal component (Figure 9a), which is hardly present on the vertical one (Figure 9b).

Figure 10 shows the corresponding uphole data for a source located approximately at the same depth. The uphole data shows higher resolution and on the horizontal component there are high energy events which correspond to S-wave generated at the source, according to our hypothesis. So the strong event on the surface seismic data can be related to the S-wave energy generated at the source in the uphole survey. As shown in Figure 7, this event most probably corresponds to a refraction.



a b

FIG. 9. Record of the 2D 3C seismic survey. (a) The horizontal component. (b) The vertical component.



a b

FIG. 10. Data of uphole 1 corresponding to 7.5 m depth, which is approximately the location of the center of the charge for the shot of Figure 8. The horizontal component to the left hand side and the vertical to the right.

DISCUSSION

The hypothesis assumed in this study is that S-waves were generated by an explosive source of energy inside of a borehole. Usually it is assumed that an explosive source does not generate S-waves. However works on similar type of S-waves has been published (e. g. White and Sengbush, 1963; Lash, 1985) and also shown theoretically (Heelan, 1953; Lee and Balch, 1982).

Another possibility to explain this event would be that the S-wave detected on the horizontal component at the surface was generated as P-wave at the source and converted to S upon its transmission through an interface. However, according to calculations published (see Muskat and Meres, 1940), a low percentage of the energy of a P-wave is transmitted as S-wave, compared to other modes generated at an interface, which does not agree with the strong event observed. But instead the transmitted S-wave energy of an incident S-wave is high. These previous studies together with the test using the Dix NMO equation (see above) support the hypothesis about the presence of S-waves generated by the source in the upholes.

This S-wave event was used to build a near-surface S-wave velocity model. However this method has some shortcomings. So, the picking of this event is more difficult and prone to errors than the FB picking used for P-waves: for depths shallower than 15 m a pick for zero offset can be hardly identified, since many different events appear, and in general it is more difficult to pick the events of the horizontal components than the FB in the vertical component, perhaps excluding the deeper events. This shortcomings cause uncertainty in the resulting velocity models, and reduce its resolution.

Related to the resolution a query appears, which is how much detail would be required on a near surface velocity model of the S-wave. For a typical 2D survey, the frequencies span from 10 Hz to 60 Hz (perhaps less for S-waves, according to experience). If the velocity is 150 m/s, the wavelength would be 5 m for 30 Hz, which could be related to the size of the near surface geological variations that can affect waves from deeper layers. It would increase the importance of a better velocity model for the shallower 15 m.

Conventional surface seismic data, typically shot with stronger energy sources and a shallower source depth, shows different character, especially lower frequency. However they can be related to the uphole data. A strong event on the surface seismic survey, identified as a refraction, can be related to S-wave energy generated at the source, It could be used to extrapolate the uphole information on S-wave velocity to a more extended area. However it doesn't have information about the weathering layer, which is the zone that generates the more important delay.

CONCLUSIONS

Events on the horizontal component that appear as S-waves generated at the source enabled us to obtain a near-surface velocity model for the upholes.

The velocity model of uphole 1 agrees with the lithological profile available. Differences between the two upholes can be related to the geological setting of each one.

Information on the near surface S-wave velocity field from upholes can be related to surface seismic data, which can contribute to generate a more extended model.

The picking of events for S-wave analysis appears harder than the FB picking used for P-waves. This issue is even more difficult for the shallower 20 m, which is the zone that produces a greater effect because it typically has high heterogeneity and low speed.

Techniques like geological modeling, and tomography could help interpret the information from the two surveys. Also inversion of the uphole data can contribute with additional information and a velocity model with more resolution.

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