F-21 VSP-DERIVED VP/VS RATIOS FOR PRESSURE PREDICTION AHEAD OF THE BIT

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Summary

VSP techniques have long held out the promise of ahead-of-the-bit pressure predictions, but a variety of data acquisition and interpretation issues have limited this potentially important application. In particular, P-wave velocities ahead of the bit, if determined from inversion of upcoming reflected amplitudes, contain the assumption that the up-hole velocity trend can be simply extrapolated downward. This assumption is inappropriate in a case where a deeper pressure seal causes a reversal of the trend.

However, a simple interpretation technique (Thomsen, 1992), requiring only the picking and registration of upward traveling (i.e., reflected) P-waves and mode-converted S-waves allows straightforward determination of Vp/Vs ratios ahead of the bit using only zero-offset VSP data. The Vp/Vs ratios are derived without explicit knowledge of either the interval P-wave velocities or the interval S-wave velocities.

Vp/Vs ratios are lower in the presence of higher effective stress (lower pore pressure) (Mueller et al., 1991). Vp/Vs ratios can be interpreted for pore pressure in several ways, including comparison against local Vp/Vs compaction trends (as measured by dipole sonics). Vp/Vs ratios appear to be more sensitive than P-wave interval velocities to effective stress variations, especially at low effective stress (hard over-pressure) Eberhart-Phillips et al. (1989).

Introduction

VSP methods can give P-wave interval velocities when the depth to a given reflector is known, or when an offset VSP is performed and an NMO-like analysis can be applied. These P-wave interval velocities can then be related to the stress state ahead of the bit. For vertical geometry VSPs, an additional tool to determine stress state is desirable. Since virtually all modern VSPs record all 3 components of particle motion, it is useful to extract extra information from the Converted waves that lie on the historically- underutilized horizontal components. This can be done by registering P-wave and C-wave events to a common reflector, and applying some simple algebra to picked interval times.

Method

Thomsen proposed a method (1992) for deriving interval Vp/Vs ratios from VSP seismic data by comparing time intervals of registered P-wave and C-wave events. (C-wave here is defined as a downgoing P-wave mode-converted to an S-wave on reflection.)

For an idealized vertical well geometry, the time taken for a P-wave (originating at the surface and hence downgoing) to pass a receiver at the bottom of a well, and then reflect back from a flat horizon to be recorded by that well-bottom receiver is

$$t_{P1} = \frac{Z_1}{V_{P1}} + \frac{Z_1}{V_{P1}} = \frac{2Z_1}{V_{P1}} \qquad \text{where} \qquad (1)$$

t_{P1} is the 2-way P-wave transit time, Z_1 is the depth below the receiver to reflector 1, and V_{P1} is the interval P-wave velocity between the receiver and reflector 1. Similarly,

$$t_{C1} = \frac{Z_1}{V_{P1}} + \frac{Z_1}{V_{S1}} \qquad (2)$$

where t_{C1} is the two way transit time of a downgoing P-wave that reflects back as an S-wave from reflector 1, and V_{S1} is the S-wave interval velocity corresponding to V_{P1}.

The interval Vp/Vs ratio, here equal to V_{P1}/V_{S1}, can be found without knowing the depth to the reflector. The ratio of observed transit times is

$$\frac{t_{C1}}{t_{P1}} = \left[\frac{Z_1}{V_{P1}} + \frac{Z_1}{V_{S1}}\right] / \left[\frac{2Z_1}{V_{P1}}\right] = \left[\frac{1}{V_{P1}} + \frac{1}{V_{S1}}\right] / \left[\frac{2}{V_{P1}}\right] \qquad (3)$$

and the unknown depth Z_1 cancels out! Re-arranging terms produces

$$\frac{V_{P1}}{V_{S1}} = \frac{2t_{C1}}{t_{P1}} - 1 \qquad (4)$$

Now the desired quantity (interval Vp/Vs) has been obtained directly from observed quantities (t_{P1} and t_{C1}) without any knowledge of the depth of the reflector (Z_1) below the receiver, nor, indeed, any explicit knowledge of the interval velocities V_{P1} and V_{S1}.
For multiple horizons, reflector 2, reflector 3, etc. we can also calculate the interval Vp/Vs ratio by taking the ratio of the time intervals of the received P-wave and C-wave arrivals. It is clear that a similar method can also be used to find interval velocity ratios from surface data (P-wave and C-wave) as well.

Example

A 3-component VSP was acquired in a well during a halt in drilling operations. The seismic data were filtered in the frequency-wavenumber domain using bp's freely available USP software (www.freeusp.org) to produce two sections: one with enhanced upward propagating P-waves, and one with enhanced upward propagating mode-converted S-waves (i.e. C-waves). Due to space limitations, only the P-wave section is shown here (Fig. 1). The P-wave events are picked to be parallel with the event tracks in this un-migrated data set. On the C-wave-enhanced section, C-wave events are also picked, leading to a pair of events for each reflector.

These two events must intersect at the borehole. The point of intersection is designated the "pivot point". The straight lines shown in the figure indicate that the velocities are constant in the (up-hole) section shown. The linear extrapolation of these events ahead of the bit to the pivot point, if taken strictly, would imply the assumption that the velocities are also constant where they were not measured. However, this linear extrapolation is only intended as a guide to the registration; in fact the extrapolated lines might better curve to reach the pivot point. But the derived ratio depends only on the ratio of observed times and the interpreted registration, not on these assumed slopes.

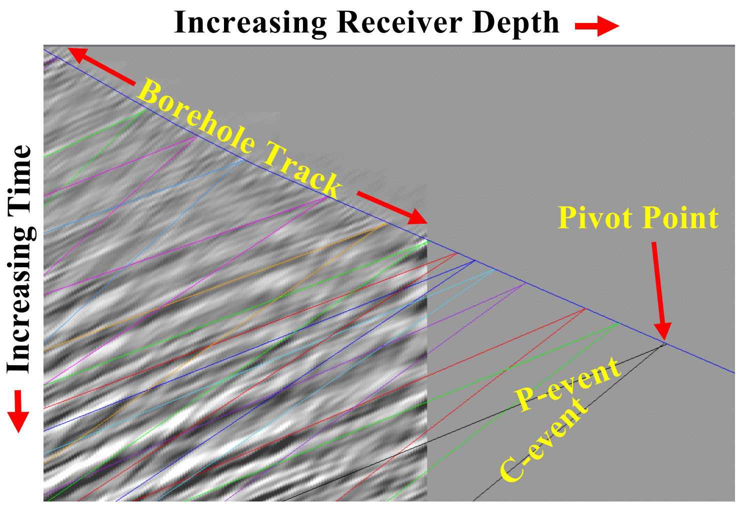

Fig.1 Vertical component of VSP , f-k filtered to enhance the upward-traveling P-waves. P-wave and C-wave picks are overlain on the data, along with the borehole track.

P-wave and C-wave interval times can be picked for pairs of P-wave events and C-wave events. These P-wave and C-wave interval times can then be inverted to interval Vp/Vs ratios using equation (4).

As a test of the accuracy of the method, the interval Vp/Vs ratios derived for 5 pairs of events were compared against log-derived Vp/Vs ratios. As can be seen in Figure 2 (next page), the correspondence of the VSP-predicted values to the measured log values is good, although the VSP method seems to be sensitive to extremal Vp/Vs values over a given depth interval.

Pressure prediction

In principle, any method (e.g., Hottman-Johnson, equivalent-depth, etc.) for predicting pore pressure using Vp can form the basis for an analogous method using Vp/Vs. In fact, all such Vp-based predictors are ambiguous, since, although high pore pressure causes low Vp, so does high porosity, soft lithology, or the presence of hydrocarbons. Hence, it is useful to have an alternative predictor, based on new data, to limit the ambiguity (Scott and Thomsen, 1993). The independent estimate of Vp/Vs, described here, should be useful for this purpose.

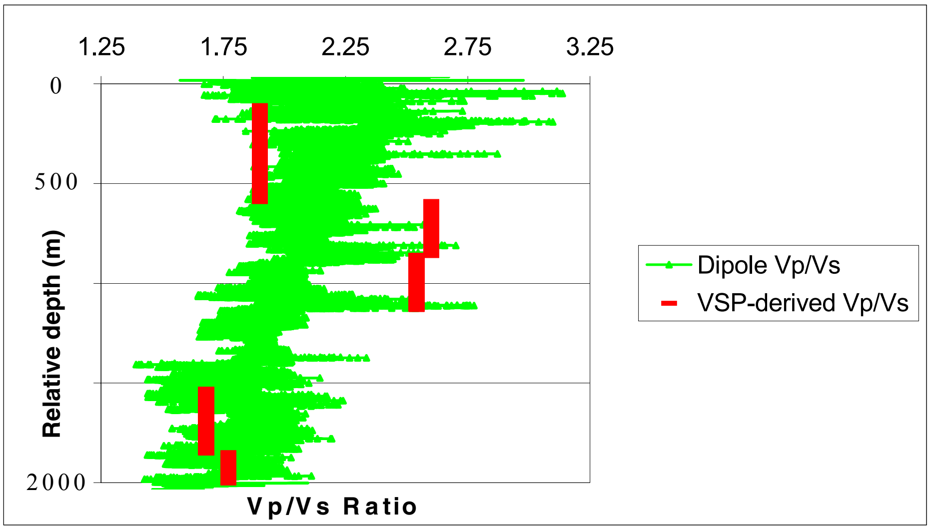

Figure 2. Comparison of log-derived Vp/Vs ratios (background trend) to VSP-derived interval Vp/Vs ratios (vertical bars). Depth increment is 500 m for each tick line.

Conclusions

Vp/Vs ratios in clastic rocks tend to monotonically decrease as a rock compacts. Deviations from this behavior can, of course, be caused by the presence of non-siliceous minerals, gas in the pore space, or complicated stress histories. These caveats aside, increases in interval Vp/Vs ratios are more diagnostic of overpressure than the more commonly interpreted decreases in P-wave interval velocity. A quick way to confirm the extra sensitivity of S-wave velocities to pore pressure changes is to note the coefficients in the Eberhart-Phillips regressions (1989). Relative to the constant leading term, the coefficient for velocity changes against effective stress is 26% larger for S-waves compared to P-waves. A consequence of the greater S-wave sensitivity is the greater sensitivity of the Vp/Vs ratio to pressure compared to simple interval P-wave velocities. The VSP method outlined here allows the calculation of Vp/Vs ratios ahead of the bit, and so provides a more sensitive tool for the estimation of ahead-of-the-bit pressures.

References

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