Local determination of WA parameters from qS waves [1]

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Summary

An algorithm for local evaluation of weak anisotropy (WA) parameters from measurements of slowness vector components and/or of particle motions of qS waves at individual receivers in a borehole in a multi-azimuthal multiple-source offset VSP experiment is proposed. The formulae are derived under assumption of weak but arbitrary anisotropy of the medium and under assumption that the two qS waves can be recorded separately. In contrast to qP-wave inversion, in which knowledge of a single component of the slowness vector is sufficient for performing an inversion in a medium with an arbitrary overburden, when using qS waves, two components of the slowness vector or an additional information must be available. On the other hand, use of qS-wave data alone or together with qP-wave data may lead to the determination of complete set of 21 WA parameters specifying the medium. General inversion equations are specified for the case of a walkaway experiment. Preliminary results of application of these equations to the walkaway VSP data collected in the Java Sea region are presented.

Key words: Local inversion, qS waves, slowness vector, polarization vector, weak anisotropy, walkaway VSP

1 Introduction

This contribution presents an attempt to extend the algorithm for the local determination of WA parameters from the multi-azimuthal multi-source offset VSP measurements of slowness and polarization vectors of qP waves (Pšenčík and Zheng, 1998; Zheng et al., 2001; Zheng and Pšenčík, 2002) to qS-wave data. The use of qS-wave data makes possible, in principle, determination of a complete set of 21 WA parameters in general anisotropic media. From qP-wave data, only 15 WA parameters could be determined. The use of qS-wave data brings, on the other hand, also certain complications. As it is well-known, qS-wave polarizations vary rapidly in vicinities of the so-called singular directions (Farra and Pšenčík, 2002) and thus are not useful for the inversion. In weakly anisotropic media the two qS waves propagate often with similar phase velocities and are coupled together. In the following we assume that we are able to record separately each of the two qS waves

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and that observations out of singular directions are available. We denote the faster wave $qS1$ and the slower $qS2$. Further we assume that we are able to determine all or only some of the components of the slowness vectors p_i and complete polarization vectors g_i of each of the qS waves. For their determination, the parametric wavefield decomposition of Esmersoy (1990) or Leaney (1990) can be used.

The inversion equations are based on the first-order perturbation theory formulae for the phase velocity and for the polarization vector (Jech and Pšenčík, 1989; Farra and Pšenčík, 2002). We briefly review these formulae in Sec.2. In Sec.3, inversion equations for general anisotropy are presented. They are then specified in Sec.4 for the case of a walkaway VSP experiment. In Sec.5, a first attempt to apply the formulae of Sec.4 to real data is made. The real data come from the walkaway VSP experiment in the Java Sea (Horne and Leaney, 2000; Zheng et al. 2001).

We use component notation. All the Roman lowercase indices range over the values 1, 2 and 3 and the uppercase indices over the values 1 and 2. Einstein summation convention is used for the repeated subscripts if not specified otherwise. Voigt notation $A_{\alpha\beta}$ for density normalized elastic parameters, with α, β running from 1 to 6, is used in parallel with the tensor notation a_{ijkl}.

2 First-order perturbation formulae

Since the formulae for both qS waves are similar, we consider only the $qS1$ wave in the following.

Let us consider a Cartesian coordinate system (x, y, z), with positive z-axis pointing down. In a vicinity of a receiver let us define a reference isotropic medium, from which the sought local WA medium differs only slightly. The reference medium is specified by the P and S wave velocities α and β. In the reference isotropic medium, we consider a wave normal n_j, a unit vector specifying direction of the slowness vector of the S wave and two, mutually perpendicular unit vectors $i_i^{(J)}$ situated in the plane perpendicular to n_j and defined as follows

$$\vec{n} \equiv (n_1, n_2, n_3), \qquad \vec{i}^{(1)} \equiv D^{-1}(n_1 n_3, n_2 n_3, n_3^2 - 1), \quad \vec{i}^{(2)} \equiv D^{-1}(-n_2, n_1, 0). \tag{1}$$

Here

$$D = (n_1^2 + n_2^2)^{1/2}. \tag{2}$$

Any two mutually perpendicular unit vectors $e_j^{(1)}$ and $e_j^{(2)}$ situated in the plane perpendicular to n_j can be specified as

$$e_i^{(1)} = i_i^{(1)} \cos\phi + i_i^{(2)} \sin\phi, \qquad e_i^{(2)} = -i_i^{(1)} \sin\phi + i_i^{(2)} \cos\phi. \tag{3}$$

Here ϕ is the angle between $e_i^{(1)}$ and $i_i^{(1)}$. It follows from the above specification that $n_j \equiv e_j^{(3)} \equiv i_j^{(3)}$. In the following, we consider the perturbation $\Delta\Gamma_{jk}$ of the Christoffel matrix Γ_{jk}, see Jech & Pšenčík (1989), caused by both the perturbation of the medium Δa_{ijkl} and of the direction of the wave vector Δn_j. In such a case we have

$$\Delta\Gamma_{jk} = \Delta a_{ijkl} n_i n_l + a^0_{ijkl}(n_l \Delta n_i + n_i \Delta n_l). \tag{4}$$

Here

$$a^0_{ijkl} = (\alpha^2 - 2\beta^2)\delta_{ij}\delta_{kl} + \beta^2(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}). \tag{5}$$

Inserting Eq.(5) into Eq.(4), we can write:

$$\Delta\Gamma_{jk}e_j^{(K)}n_k = (\alpha^2 - \beta^2)e_j^{(K)}\Delta n_j + B^{(e)}_{K3},$$
$$\Delta\Gamma_{jk}e_j^{(m)}e_k^{(m)} = B^{(e)}_{mm}, \quad \Delta\Gamma_{jk}e_j^{(1)}e_k^{(2)} = B^{(e)}_{12}. \tag{6}$$

(No summation over indices m in B_{mm}.) The symbols $B^{(e)}_{mn}$ denote elements of the weak anisotropy matrix

$$B^{(e)}_{mn} = a_{ijkl}n_jn_le_i^{(m)}e_k^{(n)} - c_0^2\delta_{mn}, \tag{7}$$

in which $c_0 = \beta$ for $m = n = 1, 2$ and $c_0 = \alpha$ for $m = n = 3$. The upper index (e) indicates that the weak anisotropy matrix is defined with respect to the vectors $e_j^{(m)}$. We also use a matrix $B^{(i)}_{mn}$, in which the vectors $e_j^{(m)}$ are substituted by $i_j^{(m)}$. The elements of the two matrices are related by the formulae

$$B^{(e)}_{11} = B^{(i)}_{11}\cos^2\phi + 2B^{(i)}_{12}\cos\phi\sin\phi + B^{(i)}_{22}\sin^2\phi,$$
$$B^{(e)}_{22} = B^{(i)}_{11}\sin^2\phi - 2B^{(i)}_{12}\cos\phi\sin\phi + B^{(i)}_{22}\cos^2\phi,$$
$$B^{(e)}_{12} = (B^{(i)}_{22} - B^{(i)}_{11})\cos\phi\sin\phi + B^{(i)}_{12}(cos^2\phi - \sin^2\phi),$$
$$B^{(e)}_{33} = B^{(i)}_{33}, \quad B^{(e)}_{13} = B^{(i)}_{13}\cos\phi + B^{(i)}_{23}\sin\phi, \quad B^{(e)}_{23} = -B^{(i)}_{13}\sin\phi + B^{(i)}_{23}\cos\phi. \tag{8}$$

Folowing Jech and Pšenčík (1989), we can express the phase velocity c_1 of the $qS1$ wave in the following way:

$$c_1 \sim \beta + \Delta c_1 = \beta + \frac{1}{2\beta}B^{(e)}_{11}. \tag{9}$$

The formula for the polarization vector can be expressed in several alternative forms. Jech and Pšenčík (1989) presented a formula which was based on the choice of the angle ϕ in Eqs.(3), for which $B^{(e)}_{12} = 0$. Such a choice leads to the first-order approximation of the polarization vector with three, generally non-zero, components. Here we follow Farra and Pšenčík (2002), see the conditions in their Eq.(17) specified for $n = 1$. If the conditions are satisfied, the first-order expression for the polarization vector $g_j^{(1)}$ has the following form:

$$g_j^{(1)} \sim e_j^{(1)} + \frac{\Delta\Gamma_{jk}e_j^{(1)}n_k}{\beta^2 - \alpha^2}n_j. \tag{10}$$

The first of the conditions of Farra and Pšenčík (2002) yields a second-order equation for the determination of the angle $\phi = \phi_0$

$$B^{(e)}_{12} + \frac{\Delta\Gamma_{jk}e_j^{(1)}n_k\Delta\Gamma_{il}e_i^{(2)}n_l}{\beta^2 - \alpha^2} = 0. \tag{11}$$

The second condition of Farra and Pšenčík (2002) reads in our case

$$B^{(e)}_{11} - B^{(e)}_{22} + \frac{(\Delta\Gamma_{jk}e_j^{(1)}n_k)^2 - (\Delta\Gamma_{il}e_i^{(2)}n_l)^2}{\beta^2 - \alpha^2} > 0. \tag{12}$$

Its satisfaction also indicates that we are out of a singular region.

3 Inversion formulae

Here we use Eqs.(9) and (10) for the derivation of inversion equations. In Sec.3.1 we derive an equation for the determination of the WA parameters from the measured slowness, in Sec.3.2 we derive an equation for the determination of the WA parameters from the measured polarization.

3.1 Slowness formula

Using Eq.(9), we can express the square of the slowness c^{-2} as follows

$$c^{-2} \sim \beta^{-2}(1 - \frac{B_{11}^{(e)}}{\beta^2}). \tag{13}$$

The square of the slowness can be also expressed in an alternative way

$$c^{-2} = p_i p_i \sim \beta^{-2}(1 + 2\beta^2 p_i^0 \Delta p_i), \tag{14}$$

where Δp_i denotes the difference between the observed and reference slowness vectors $p_i - p_i^0$. Comparing the RHS of Eqs.(13) and (14) and using the expression for $B_{11}^{(e)}$ from (8) specified for ϕ_0 satisfying Eq.(11) yields the sought slowness formula

$$B_{11}^{(i)} \cos^2\phi_0 + 2B_{12}^{(i)} \cos\phi_0 \sin\phi_0 + B_{22}^{(i)} \sin^2\phi_0 = -2\beta^4 p_i^0 \Delta p_i. \tag{15}$$

The equation (11) itself or its linearized form,

$$(B_{22}^{(i)} - B_{11}^{(i)}) \sin 2\phi_0 + 2B_{12}^{(i)} \cos 2\phi_0 = 0. \tag{16}$$

can be used as an additional constraint which the sought WA parameters must satisfy. Thus if the angle ϕ_0 and components of the observed slowness vector p_j are known, Eq.(15) can be used for the determination of WA parameters and Eq.(16) can be optionally used as an additional auxiliary equation.

3.2 Polarization formula

Multiplying successively Eq.(10) by $i_j^{(1)}$ and $i_j^{(2)}$, we get

$$g_j^{(1)} i_j^{(1)} = \cos\phi_0, \qquad g_j^{(1)} i_j^{(2)} = \sin\phi_0. \tag{17}$$

Eqs.(17) are important equations for the determination of the angle ϕ_0. This angle can be obtained by projecting the observed polarization vector $g_j^{(1)}$ on the vectors $i_j^{(1)}$ and $i_j^{(2)}$. Multiplying Eq.(10) by n_j, taking into account Eqs.(6) and using the expression for $B_{13}^{(e)}$ from (8) specified for ϕ_0 we get

$$B_{13}^{(i)} \cos\phi_0 + B_{23}^{(i)} \sin\phi_0 = \beta(\beta^2 - \alpha^2)(g_j^{(1)} p_j^0 + i_j^{(1)} \Delta p_j \cos\phi_0 + i_j^{(2)} \Delta p_j \sin\phi_0). \tag{18}$$

This is the sought polarization formula. During its derivation, we substituted n_j by p_j^0 using $n_j = \beta p_j^0$, and we took into account that $\Delta n_j e_j^{(K)} = \beta \Delta p_j e_j^{(K)}$.

3.3 Inversion

Eqs.(15), (17), (18) and, possibly, (16) are equations which can be used for the inversion of observed slowness and polarization data into the WA parameters. They can be used for an inversion in an inhomogeneous arbitrarily anisotropic medium if components of the observed slowness and polarization vectors are known. The angle ϕ_0 is determined from Eqs.(17). Before the inversion, it is necessary to test if the angle ϕ_0 satisfies the condition (12). If not, the angle ϕ_0 must be increased by $\pi/2$. The knowledge of the angle ϕ_0 makes Eqs.(15), (16) and (18) linear. If only vertical component of the slowness vector p_j is known, which is mostly the case, the above equations cannot be used without further additional information or assumptions.

4 Inversion formulae for walkaway VSP

Here we specify the above formulae for the walkaway VSP experiment. In the following, we limit ourselves to the plane (x, z) containing the walkaway profile. In accordance with the real data we assume that the polarization of the studied wave is confined to the plane (x, z), i.e. we assume that $g_2^{(1)} = 0$. This means that we can call the $qS1$ wave the qSV wave in the following. We also assume that the observed slowness vector is confined to the plane (x, z) so that $p_2 = 0$. This assumption allows us to consider an arbitrarily inhomogeneous overburden. We choose the wave vector n_i in the reference isotropic medium so that it is perpendicular to the observed polarization vector $g_j^{(1)}$. This is very convenient choice which excludes components of the polarization vector from inversion equations, and which avoids necessity to perform ray tracing in the reference isotropic medium in order to get n_i. Under the above assumptions, Eqs.(17) yield $\phi_0 = 0$ and Eq.(15) reduces to

$$B_{11}^{(i)} = -2\beta^4 p_1^0 \Delta p_1 - 2\beta^4 p_3^0 \Delta p_3, \tag{19}$$

and Eq.(18) to

$$\frac{B_{13}^{(i)}}{\beta^2 - \alpha^2} = \beta^2 (p_3^0 sgn(p_1^0) \Delta p_1 - |p_1^0| \Delta p_3). \tag{20}$$

Multiplying Eq.(19) by $\frac{1}{2}(p_3^0/\beta^2) sgn(p_1^0)$ and Eq.(20) by p_1^0 and summing up resulting equations, we get

$$\frac{B_{13}^{(i)} |p_1^0|}{\alpha^2 - \beta^2} - \frac{p_3^0}{2\beta^2} B_{11}^{(i)} = p_3 - p_3^0. \tag{21}$$

Eq.(21) can be supplemented by Eq.(16).

In the next section, we invert the qS-wave data together with qP-wave data. For this purpose, we present equations for qP waves obtained by specification of corresponding equations of Zheng and Pšenčík (2002) for the assumption of zero transverse components of the slowness and polarization vectors:

$$\frac{B_{13}^{(i)} |p_1^0|}{\alpha^2 - \beta^2} - \frac{p_3^0}{2\alpha^2} B_{33}^{(i)} = p_3 - p_3^0, \tag{22a}$$

$$B_{23}^{(i)} = 0. \tag{22b}$$

When comparing Eqs.(21) and (16) with Eqs.(22), please rememeber that the wave and slovness vectors used in the former equations denote the wave and slowness vectors of the qSV wave while the same vectors in Eqs.(22) denote the wave and slowness vectors of the qP wave.

For completness we present here the expressions for the elements of the weak anisotropy matrix, which appear in the used formulae, for the above specification:

$$B_{11}^{(i)} = 2\alpha^2[(\epsilon_{15} - \epsilon_{35})n_1 n_3^3 + n_1^2 n_3^2(\epsilon_x + \epsilon_z - \delta_x) + (\epsilon_{35} - \epsilon_{15})n_1^3 n_3] + 2\beta^2\gamma_x,$$

$$B_{12}^{(i)} = \alpha^2[(\chi_x - \epsilon_{34})n_1^3 n_3^2 + (\epsilon_{16} - \chi_z)n_1^4 n_3 - \epsilon_{56} n_1^3] + \beta^2\gamma_y n_3^2,$$

$$B_{13}^{(i)} = \frac{\alpha^2}{|n_1|}[2\epsilon_z n_3^5 + \epsilon_{35} n_1 n_3^4 + \delta_x n_1^2 n_3^3 + (4\epsilon_{15} - 3\epsilon_{35})n_1^3 n_3^2 + (2\epsilon_x - \delta_x)n_1^4 n_3 - \epsilon_{15} n_1^3],$$

$$B_{23}^{(i)} = \frac{\alpha^2}{|n_1|}(\epsilon_{34} n_1 n_3^3 + \chi_z n_1^2 n_3^2 + \chi_x n_1^3 n_3 + \epsilon_{16} n_1^4),$$

$$B_{33}^{(i)} = 2\alpha^2[\epsilon_x n_1^4 + \epsilon_z n_3^4 + \delta_x n_1^2 n_3^2 + 2\epsilon_{15} n_1^3 n_3 + 2\epsilon_{35} n_1 n_3^3]. \tag{23}$$

We can see that for our specification the weak anisotropy matrix depends on 12 WA parameters:

$$\epsilon_x = \frac{A_{11} - \alpha^2}{2\alpha^2}, \quad \epsilon_z = \frac{A_{33} - \alpha^2}{2\alpha^2}, \quad \delta_x = \frac{A_{13} + 2A_{55} - \alpha^2}{\alpha^2},$$

$$\epsilon_{15} = \frac{A_{15}}{\alpha^2}, \quad \epsilon_{16} = \frac{A_{16}}{\alpha^2}, \quad \epsilon_{34} = \frac{A_{34}}{\alpha^2}, \quad \epsilon_{35} = \frac{A_{35}}{\alpha^2}, \quad \epsilon_{56} = \frac{A_{56}}{\alpha^2},$$

$$\chi_x = \frac{A_{14} + 2A_{56}}{\alpha^2}, \quad \chi_z = \frac{A_{36} + 2A_{45}}{\alpha^2}, \quad \gamma_x = \frac{A_{55} - \beta^2}{2\beta^2}, \quad \gamma_y = \frac{A_{44} - \beta^2}{2\beta^2}. \tag{24}$$

Eq.(21) together with (16) and Eq.(22) are equations used for the inversion of qSV-wave and qP-wave data in the next section. From Eqs.(16) and (22b), and from the expressions for $B_{12}^{(i)}$ and $B_{23}^{(i)}$ in Eq.(24) we can find immediately that for our specification,

$$\epsilon_{16} = \epsilon_{34} = \epsilon_{56} = \chi_x = \chi_z = \gamma_y = 0. \tag{25}$$

Remaining 6 WA parameters, ϵ_x, ϵ_z, ϵ_{15}, ϵ_{35}, δ_x and γ_x can be found from Eqs.(21) and (22a).

5 Inversion of Java Sea data

The data consist of couples of vertical components of slowness and polarization vectors of downgoing and upgoing (reflected) qP and qS waves measured at a receiver in a borehole at the depth of 1.63 km (Horne and Leaney, 2000). The components were determined using the parametric inversion approach of Esmersoy (1990) and Leaney (1990). The waves were generated by sources distributed along a profile on the Earth's surface, which we identify with the x-axis of a right-handed Cartesian coordinate system in the following. The z-axis coincides with the borehole and is positive downwards. The sources extend from -2.5 to 2.5 km with approximately 0.025 km spacing. From the data for 228 downgoing and upgoing qP and qSV waves we selected 207 and 183 for downgoing and upgoing qP waves, respectively, and 186 for both downgoing and upgoing qSV waves. In this way we had a system of 390 equations if only qP wave is considered, 372 equations if only qSV wave is considered and 762 equations if both qP and qSV waves are considered. We solve these equations for the above mentioned 6 WA parameters except γ_x if only qP waves are considered and for all 6 parameters including γ_x if qSV wave only or both qP and qSV waves are considered. The results of the preliminary test are shown in Figs.1-8.

Figure 1 shows observed data ($\times$) in the form of the plot of vertical components of the slowness vector of the qP and qSV waves versus the corresponding polarization angle in degrees in the way used by Horne and Leaney (2000). The polarization angle for the qP wave is the angle between the polarization vector and vertical. The polarization angle for the qSV wave is the angle between the polarization vector and horizontal. The data include both downgoing and upgoing (reflected) waves. The data corresponding to downgoing waves have polarization angles between -90^0 and 90^0. We can see greater scatter of data related to upgoing waves. This is reflected in the inversion by the use of estimated error of the upgoing arrivals twice as large as the error of the downgoing arrivals. We can also see considerable worse illumination in the case of qSV-wave data.

In Figure 2, the observed qP-wave data ($\times$) are compared with the results of the inversion of *only* qP-wave data. The three curves shown correspond to the inversion of all qP-wave data (solid line), data corresponding to downgoing (short dashed line) and upgoing (long dashed line) qP waves separately. The sections of qP-wave phase velocity derived from the WA parameters obtained from the inversion are shown in Figure 3. Note nonsymmetric character of the curves indicating different anisotropy than VTI.

Figure 4 shows the same as Figure 2 but for the qSV wave *only*. The meaning of the curves is the same as in Figure 2. Resulting sections of qSV-wave phase velocity are shown in Figure 5. In contrast to Figure 3, the section is more symmetric, axis of symmetry being slightly shifted to positive polar angles.

Figures 6-8 show results of the joint qP and qSV-wave data inversion. If we consider the inversion of all data (downgoing and upgoing waves) we can see that the phase velocity sections of qP and qSV waves have now a similar character. They are symmetric with the axis of symmetry slightly shifted to positive polar angles. This seems to indicate importance of the joint inversion of qP- and qSV-wave data. Anisotropy of the qP wave is found to be approximately 9%, anisotropy of the qSV wave is approximately 15 %.

6 Conclusions

Formulae for local determination of WA parameters from the multi-azimuthal multi-source offset VSP measurements of slowness and polarization vectors of separate qS waves were presented. They are based on the first-order perturbation theory. The formulae are generally sensitive to the complete set of 21 WA parameters. If an arbitrarily inhomogeneous overburden is considered and only vertical component of the qS-wave slowness vector is available, an additional information or assumption is necessary to make the inversion applicable. As an example of such an assumption we considered zero transverse component of the slowness vector in the inversion of data from a walkaway VSP experiment. The resulting equations were tested on real data from Java Sea region. Further tests of the data and interpretation of the results are planned.

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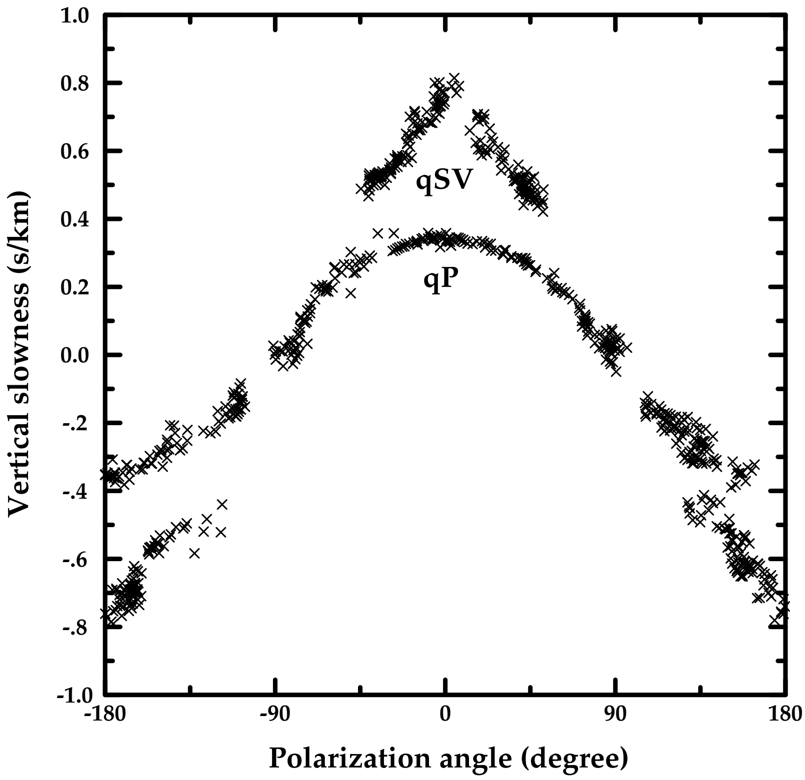

1.0
0.8
0.6
0.4
0.2
0.0
-.2
-.4
-.6
-.8
-1.0
Vertical slowness (s/km)
qSV
qP
-180
-90
0
90
180
Polarization angle (degree)

Figure 1

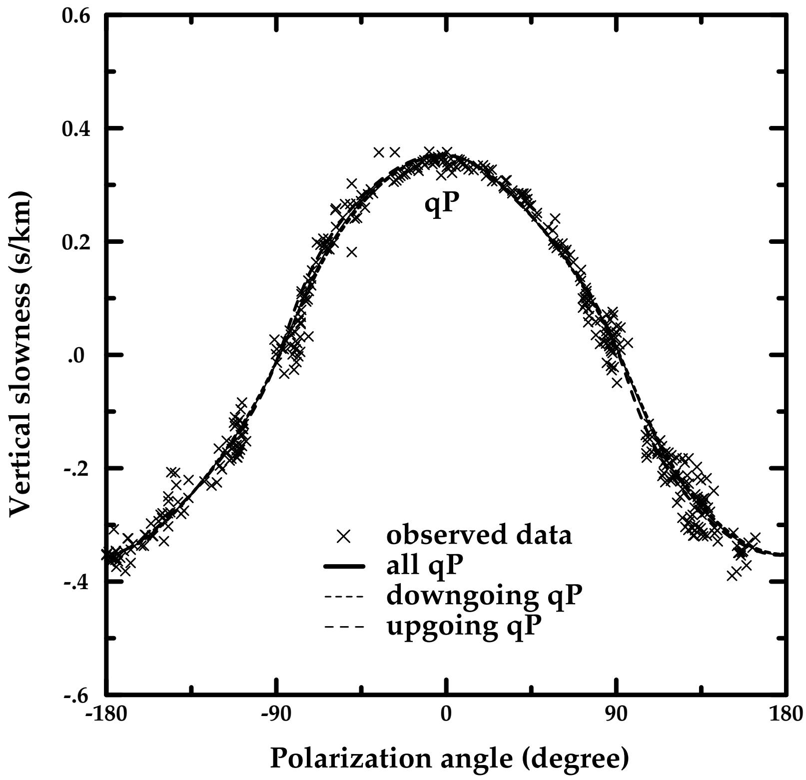

0.6
0.4
0.2
.0
-.2
-.4
-.6
-180
-90
0
90
180
Vertical slowness (s/km)
Polarization angle (degree)
qP
observed data
all qP
downgoing qP
upgoing qP

Figure 2

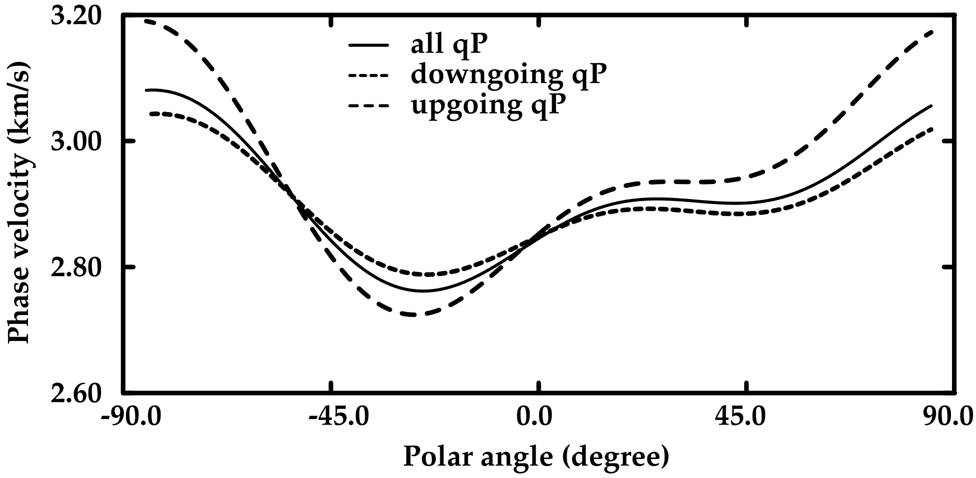

3.20
3.00
2.80
2.60
Phase velocity (km/s)
all qP
downgoing qP
upgoing qP
-90.0
-45.0
0.0
45.0
90.0
Polar angle (degree)

Figure 3

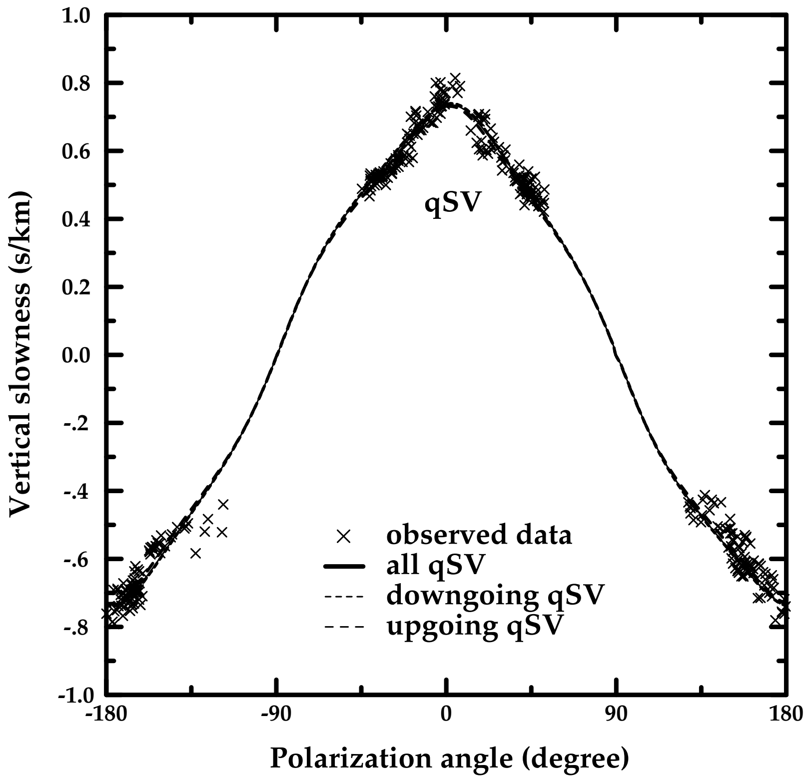

1.0
0.8
0.6
0.4
0.2
0.0
-.2
-.4
-.6
-.8
-1.0
-180
-90
0
90
180
Vertical slowness (s/km)
Polarization angle (degree)
qSV
observed data
all qSV
downgoing qSV
upgoing qSV

Figure 4

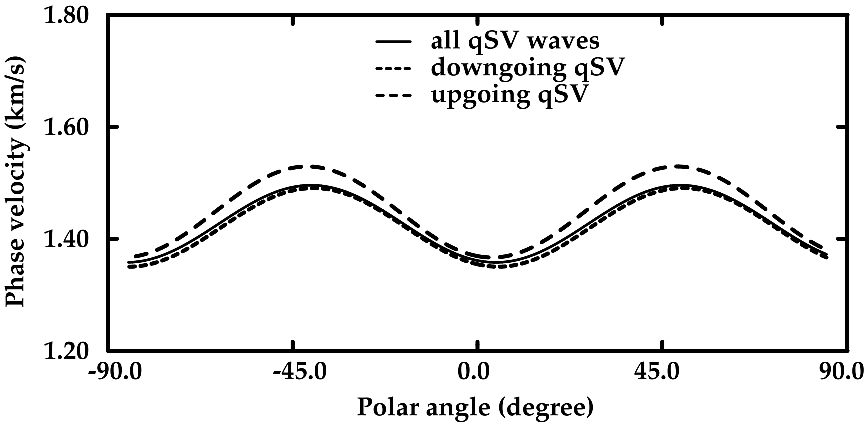
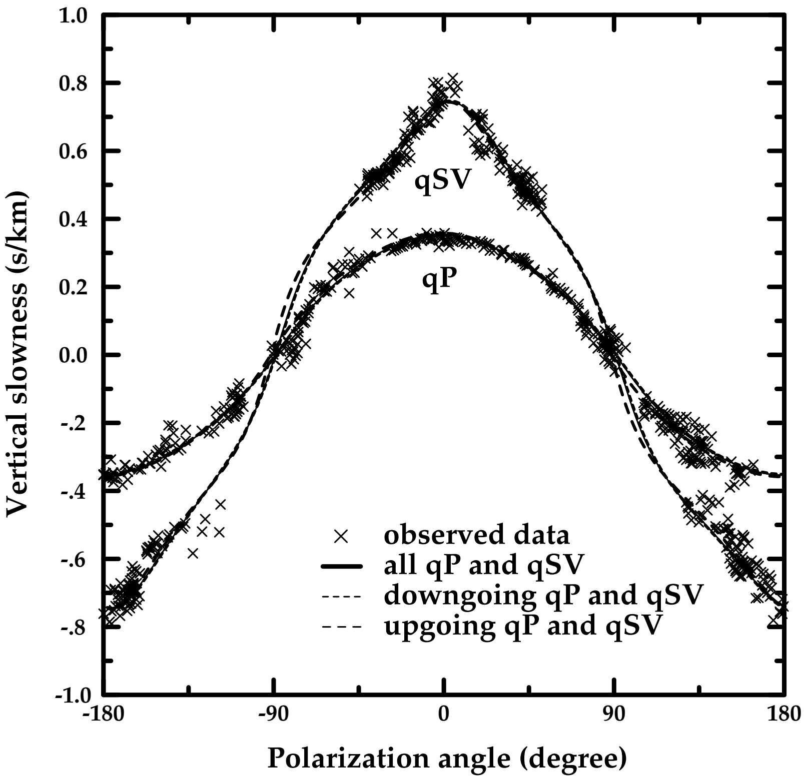

1.80
1.60
1.40
1.20
Phase velocity (km/s)
all qSV waves
downgoing qSV
upgoing qSV
-90.0
-45.0
0.0
45.0
90.0
Polar angle (degree)

Figure 5



1.0
0.8
0.6
0.4
0.2
0.0
-.2
-.4
-.6
-.8
-1.0
-180
-90
0
90
180
Vertical slowness (s/km)
Polarization angle (degree)
qSV
qP
observed data
all qP and qSV
downgoing qP and qSV
upgoing qP and qSV

Figure 6

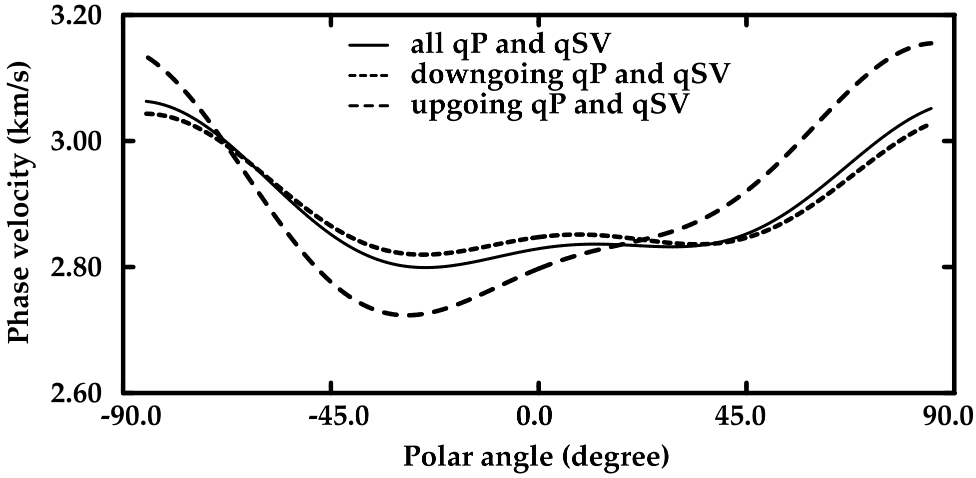

3.20
3.00
2.80
2.60
Phase velocity (km/s)
all qP and qSV
downgoing qP and qSV
upgoing qP and qSV
-90.0
-45.0
0.0
45.0
90.0
Polar angle (degree)

Figure 7

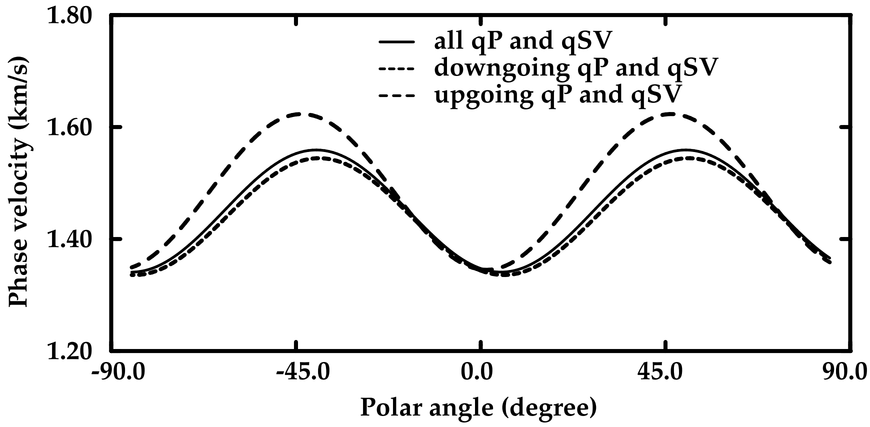

1.80
1.60
1.40
1.20
Phase velocity (km/s)
all qP and qSV
downgoing qP and qSV
upgoing qP and qSV
-90.0
-45.0
0.0
45.0
90.0
Polar angle (degree)

Figure 8