Elliptical eigen Shear wave mode after normal incidence and subcritical incidence reflection on an isotropic interface, propagated in a homogeneous medium, with or without attenuation.

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Content:

Section A) exposes theoretical arguments in exclusion of elliptically polarized eigen body waves in anisotropic medium propagation.

Sections B) and C) illustrate the only linear polarization reliably observed for single/eigen seismic mode propagated in the subsurface at seismic frequencies and in rock samples with body wave ultrasounds.

Section D) focuses on the heterogeneities of the immediate borehole proximity, altering the birefringence measurement in the sonic range.

Section E) Discussion

Section F) is a short list of the diverse applications using the linear polarization property of P and S body waves.

Section G) Acknowledgements

Section H) References

A) Theoretical investigations

The phenomenon of seismic body wave normal incidence reflection at the plane interface between two isotropic media, for a linearly polarized P or S wave, is illustrated on Figure 1

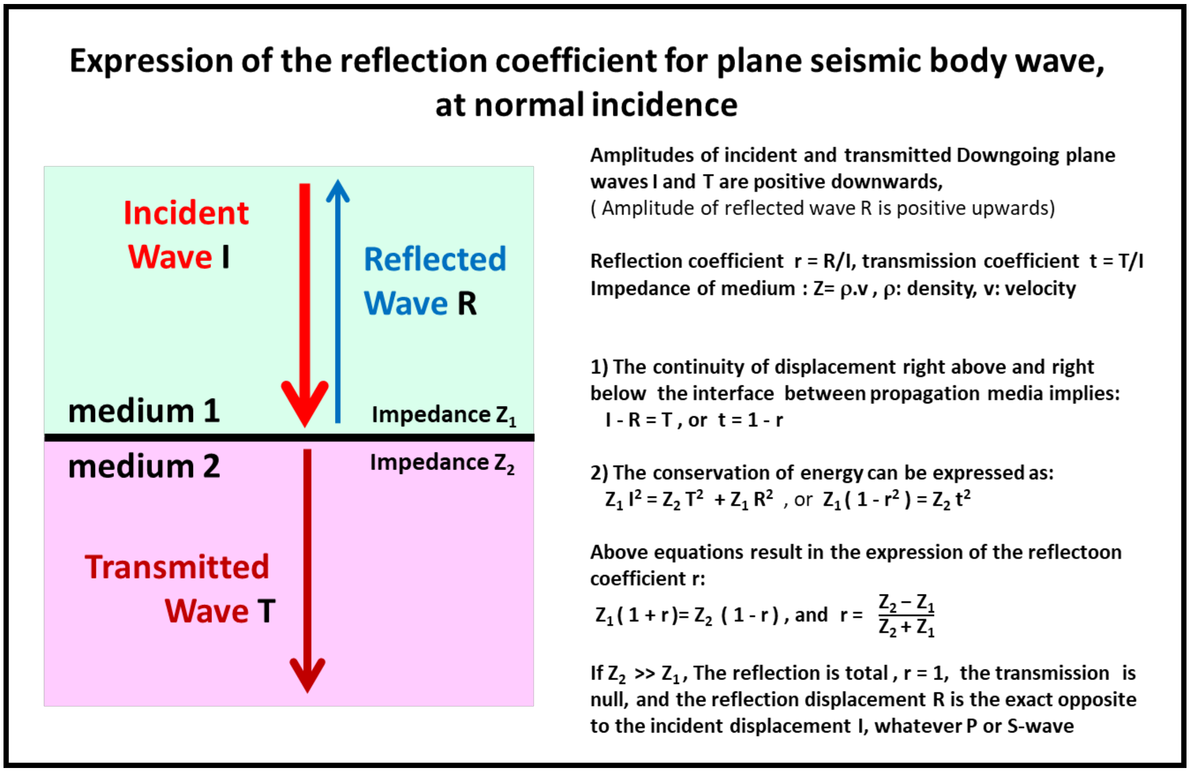

Figure1: R*eminder of reflection principle for a plane wave at normal incidence.*

Thus the reflected wave motion vector R(t) = [Xr(t), Yr(t)] is opposite to the Incident wave motion vector I(t) = [Xi(t), Yi(t)] , at any time (t) : R(t) = - I(t) = [Xr(t), Yr(t)] = [-Xi(t), -Yi(t)]

Following the above relationship between the incident wave amplitudes and the P or S reflected amplitudes on an isotropic matrix reflecting interface at normal incidence, Figure 2 illustrates that angular rotation of a reflected elliptical waveform is the SAME as the incident elliptical waveform. The reflection features described in Figure 2 can actually be observed on Shear wave VSP datasets recorded by a zero-offset source in a vertical well, in an axisymmetric VTI / Vertical transverse isotropic 1D medium, such as a horizontally stratified sedimentary geological context. In such medium, all vertical zero incidence shear waveforms can be considered as principal or eigen, either with linear, elliptical or circular shape of particle motion, and whatever their angular rotation, CW or CCW. The total reflection simply generates only a reflected wave with opposite elliptical waveform components, which does not alter the angular rotation direction. Consequently, any seismic wave reflected at normal incidence propagates in the opposite normal incidence direction, as the identical eigen elliptical S-wave mode, whatever the isotropic or anisotropic nature of the homogeneous medium of propagation, with or without viscoelastic attenuation.

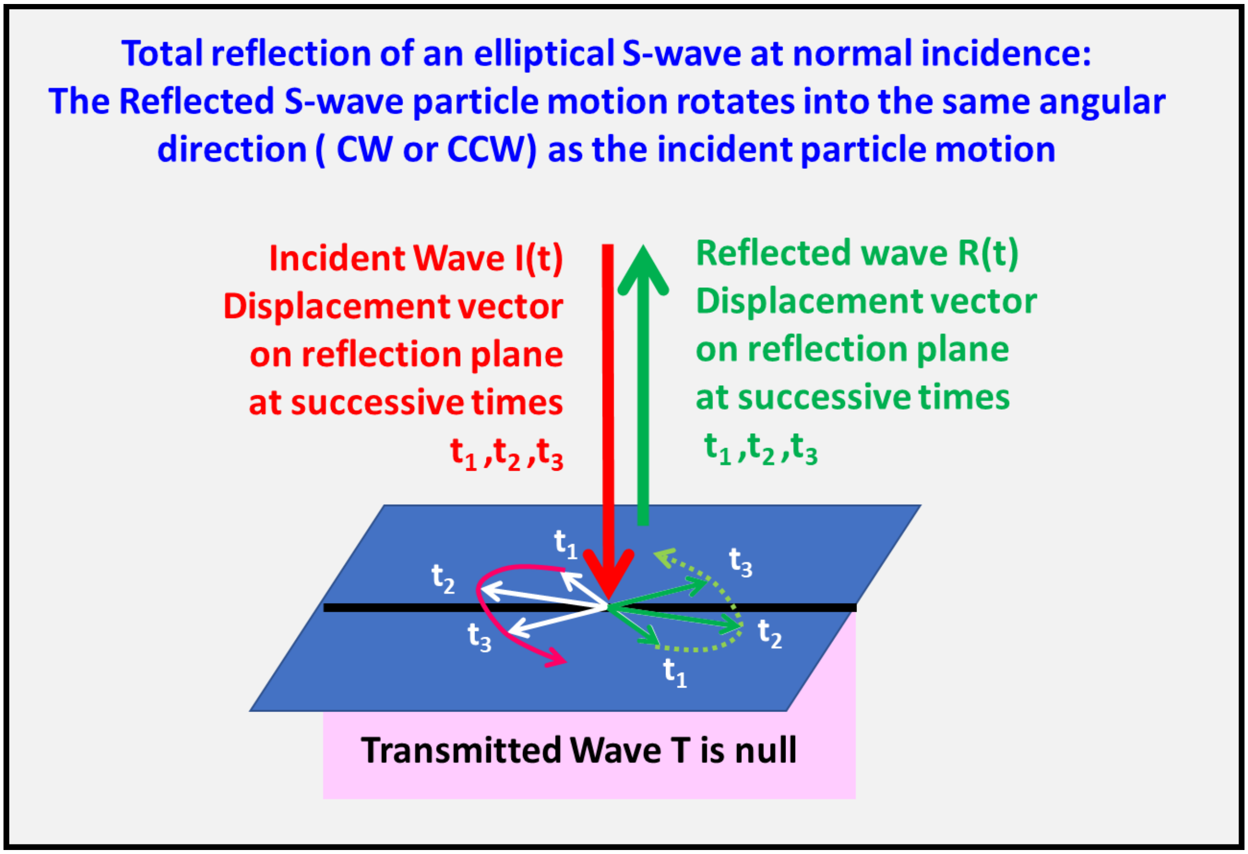

Figure2: *The reflected particle motion presents the same angular rotation as the incident wave motion, seen from above the reflection plane, or by the same observer.*

The angular rotation can be related to the angular momentum, (or the **spin)** of the rock volume involved in the rotational displacement generated by the shear elliptical particle motion. Let us follow the Wikipedia's definition of the angular momentum: " *The three-dimensional angular momentum for a point particle is classically represented as a pseudovector* ***r*** × ***p***, *the cross product of the particle's position vector* ***r*** *(relative to some origin) and its momentum vector; the latter is* ***p*** = *m****v*** in *Newtonian mechanics". Unlike linear momentum, angular momentum depends on where this origin is chosen, since the particle's position is measured from it".*

In the present case, the origin is the position of the point/particle before /after the passage of the seismic wave. Thus, on Fig.2, if the vertical axis Z is pointing upwards, the angular momentum linked to the incident and reflected shear wave is POSITIVE and does not depend on the direction of propagation.

Therefore, an eigen elliptical Shear wave mode can be totally reflected into the same waveform, with similar angular rotation as observed before reflection, whatever the direction of propagation along the same ray, downwards or upwards. Consequently, two observers located on a the same ray path , for example on both sides of a reflector, would naturally see the particle motion of an elliptical eigen S-wave particle motion with opposite angular rotation, as illustrated on Figure 3: since there is no physical basis for the direction of angular rotation (or the sign of the angular momentum if this latter is not null) to be specifically defined for any ray path direction through the considered propagation medium, it can be stated that the above theoretical results violate the symmetry of seismic body wave propagation through a homogeneous medium. Indeed, the particle motion of a S-wave eigen mode propagating through an anisotropic viscoelastic medium should be undistinguishable for the two observers located at the extremities of a given ray path followed by an eigen S-wave train. In other words, an elliptical particle motion implies that an eventual non-zero value of its kinetic momentum would be attached to any given ray path, even the rays belonging to the medium symmetry planes, whatever the direction of propagation: **this contradiction results into a NULL angular momentum, therefore a linear particle motion for the eigen shear waves.**

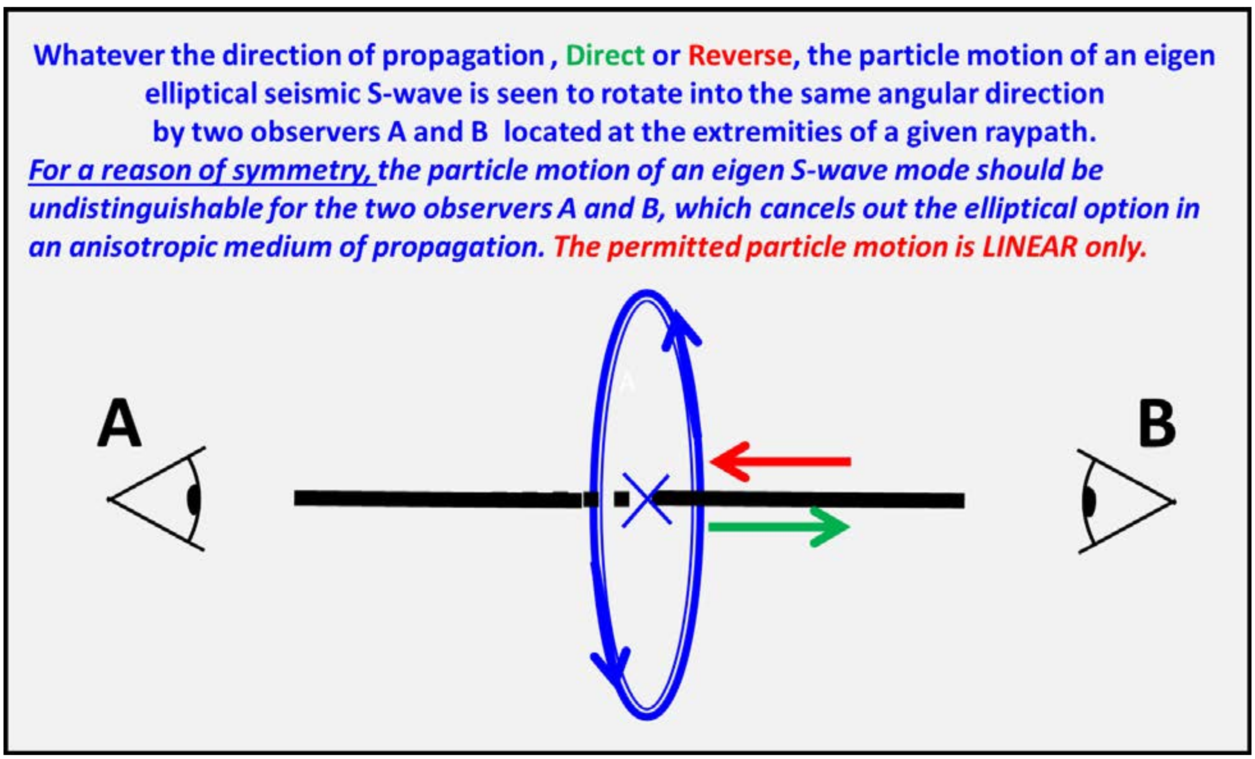

Figure3: *The particle motion of an elliptical eigen S-wave is invariant with the propagation direction. However, the angular rotation appears to be opposite for observers A and B*

The above observation and considerations constitute a **"*Proof by ABSURD*"** of the inexistence of ellipticity in the common domains of seismic propagation in anisotropic media, for all seismic frequency ranges: oil & gas surface seismic surveys (0-150Hz), sonic logging (0.5-20kHz), or even ultrasonic frequencies used on cores and rock samples (50kHz to 1 MHz), and earthquake frequencies (0.01- 5Hz).

B) Linear P-wave particle motion commonly observed on 3-Component VSP's

Following the above fundamental result, let us consider elliptical orthogonal shapes for the particle motions of the P-wave and S2 wave eigen vectors propagating along a wave vector k , lying in the plane orthogonal to linear particle motion S1; the nullity of the scalar product ($^{t}P*S2 = 0$) leads to the same violation of symmetry evidenced above. Indeed, the high linearity of particle motion of direct P-wave arrivals is observed and reported on numerous oriented 3C VSPs regularly recorded and analyzed by the borehole seismic industry worldwide. Sometimes the field zero-offset 3 component VSP dataset exhibits direct P-wave arrivals present on the vertical component only, as on Figure 4 hereafter, attesting a linear vertical polarization even if the geological medium of propagation is known to be anisotropic (examples in Kazemi 's thesis, Gerard et al.).

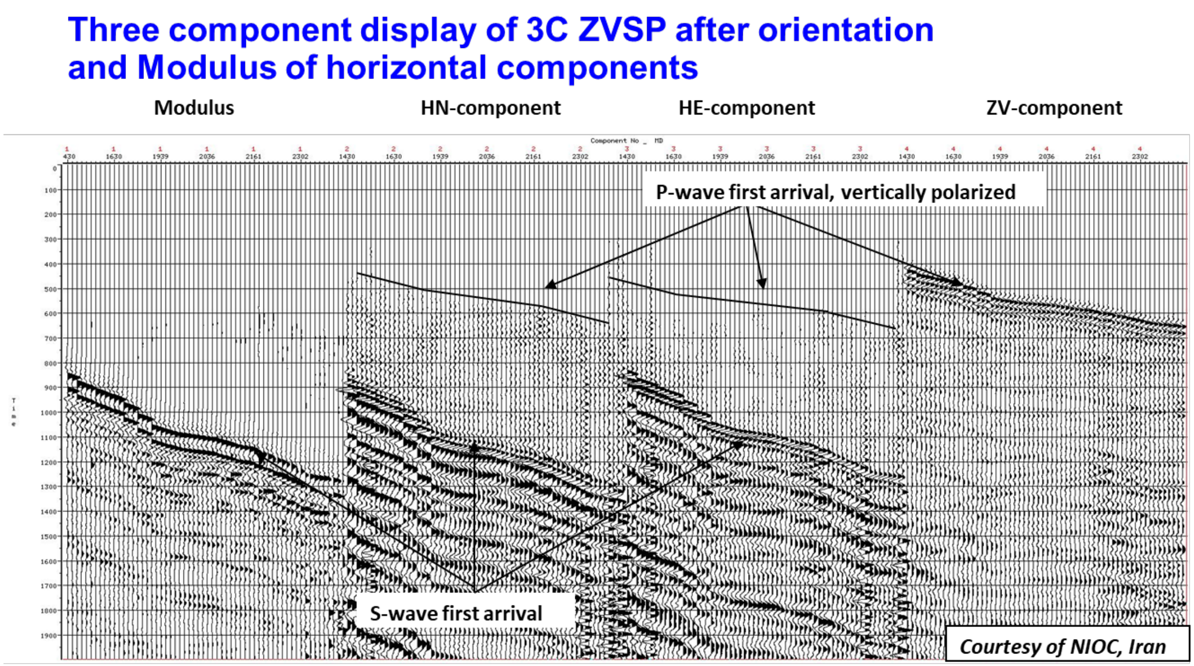

Figure 4: *Display of 3C Zero-offset VSP (ZVSP) oriented in geographical system. Note the linear polarization of the direct P-wave arrival, visible on the vertical component only. Figure reproduced from* Kazemi*, 2009, Fig.8, p.159*

In 1988, a workshop was held by the EAGE in Budapest, Hungary, which proceedings were edited by the journal 'Geophysical Transactions' in a "SPECIAL ISSUE 'ANISOTROPY, SHEAR WAVES AND POLARIZATION MEASUREMENTS', now online. A summary of the seismic exploration status has been compiled by Prof. Gérard Grau in his tutorial contribution entitled: S-WAVES AND SEISMIC ANISOTROPY: Paragraphs 6 (Anisotropic, anelastic solids), and 7 (Anisotropic, inhomogeneous, elastic solids), and a short Glossary in pages 37- 42, recall the definition of the all the terms useful to S-wave seismic anisotropy conversations, including: homogeneity, viscoelasticity, symmetry, etc... In 1988, dipole sonic logging tools did not exist yet! A historical example of O-VSP study showing a linearly polarized P-arrival is given on Fig.2, page 123 of Naville C. & Omnes, G.

Further reading about the common usage of three components of VSP datasets is suggested in the thesis of **Meltem** A., 2016: 3C VSP recording, orientation of three components, examination of Shear wave and S-wave splitting effects are exposed, using the linear properties of P and S-wave body waves propagated in the subsurface. On Figure 1 of his paper **"***The polarization of* P-*waves in anisotropic media* ", 1982, S. **Crampin** recalls the distinct directions of the energy vector (group velocity), the propagation vector (phase velocity) and the intermediate linear P-wave polarization expected in an anisotropic medium.

Figure 5 below attests the linearity of the direct Pressure body wave signal from a VSP recorded in a complex layered sedimentary domain located in the near proximity of a salt diapir, with the P-wave particle motion or 'hodogram' at a deep recording depth (**Li** & al., 2002).

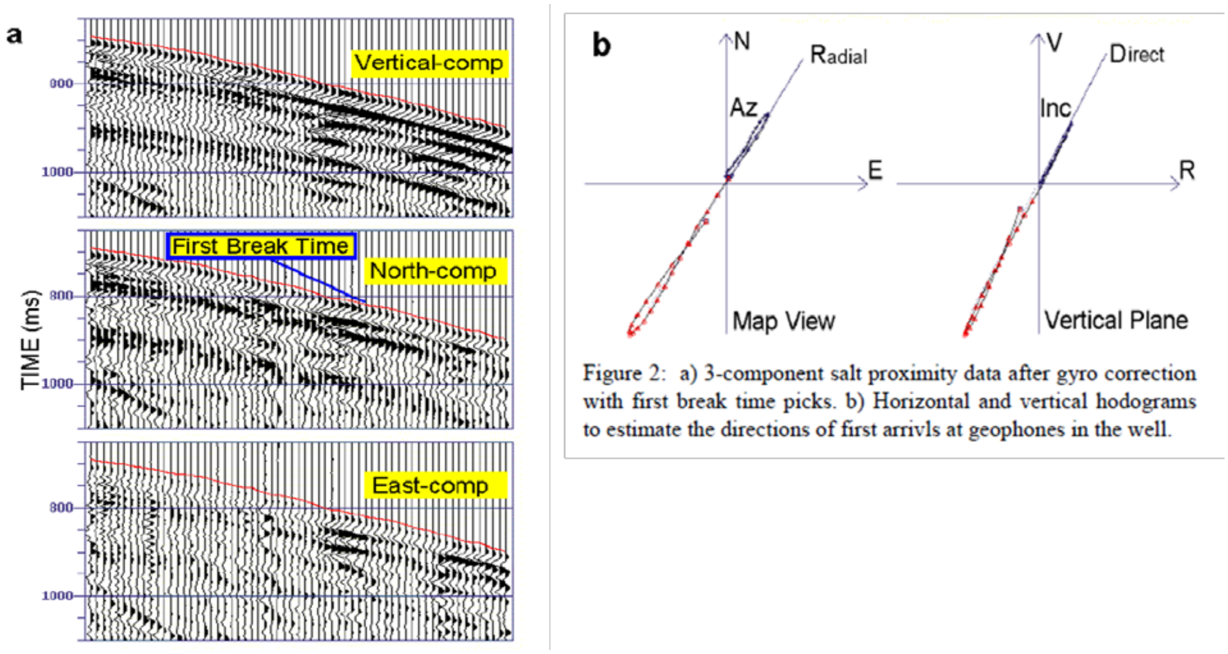

Figure 5: *Illustration of highly linear direct P-wave arrival on VSP dataset in a complex salt proximity survey in the Gulf of Mexico. Figure reproduced from* Li *& al., 2002*

Another typical example of the usefulness of observed linearity of P-wave arrivals recorded by a modern downhole VSP toolstring is illustrated in the complex structural context of Salt Proximity VSP surveys: see: the paper " Reflection Salt Proximity", by **Li, Y. and Hewett B.** , 2014 and 2016.

Conversely, if the direct P-wave arrival motion of a VSP appears slightly elliptical on the hodograms, the processing geophysicist is inclined to carefully check the presence of an interference of P-wave seismic arrivals on wiggle trace displays. Figures.6a,b exhibit interfered direct P-wave arrivals often occurring with close apparent velocities and slightly different linear polarizations in VSP's; they are very difficult to separate.

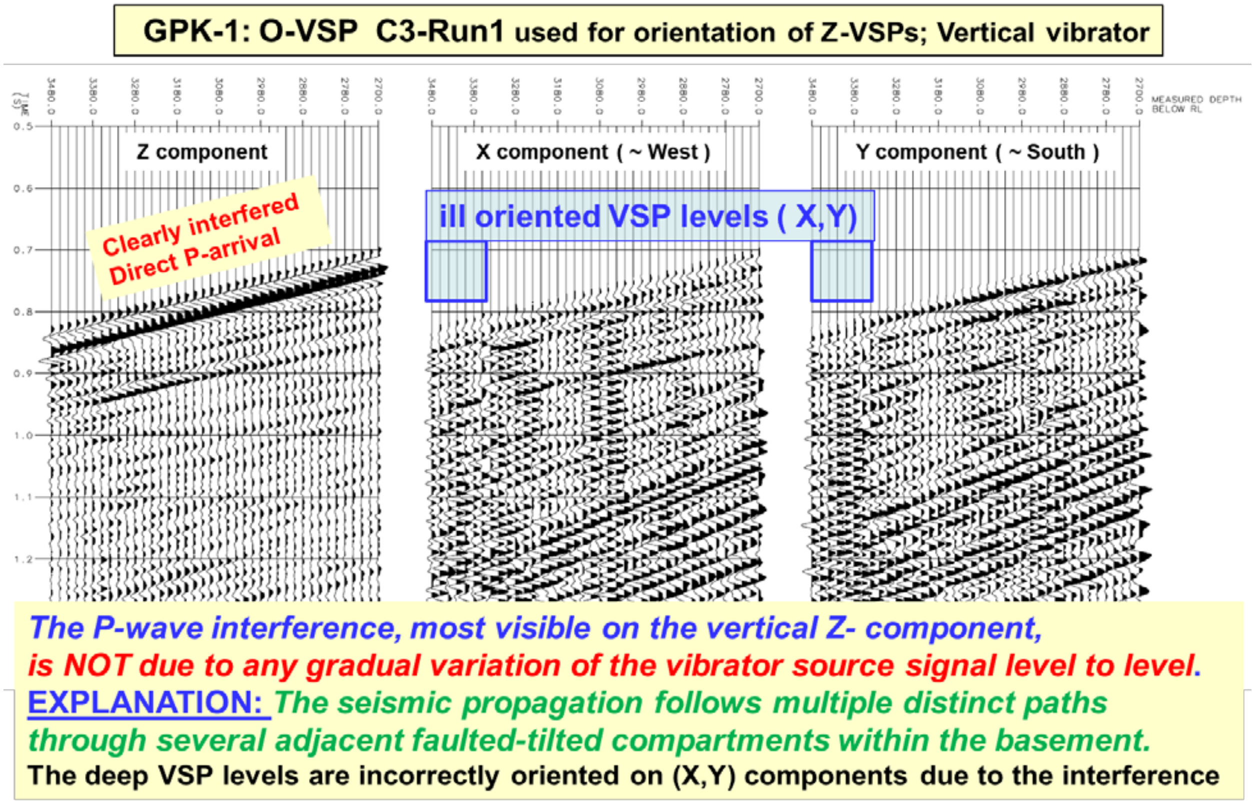

Figure 6a, *Typical example of interfered P-wave arrivals is from a 3C VSP dataset recorded in the faulted-tilted granite basement of Soultz, eastern France. Figure reproduced from* Gérard *et al., slide 16*

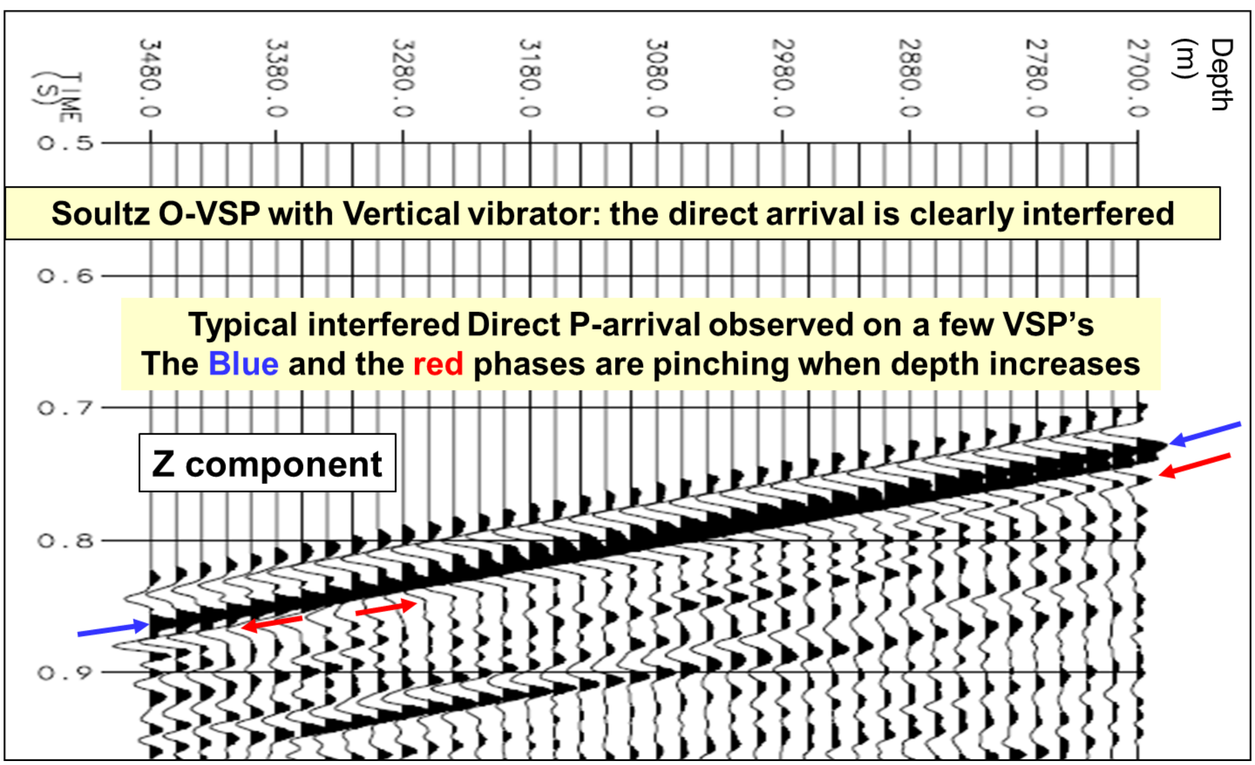

Figure 6b: Enlargement of Fig.6a, vertical component wiggle display.

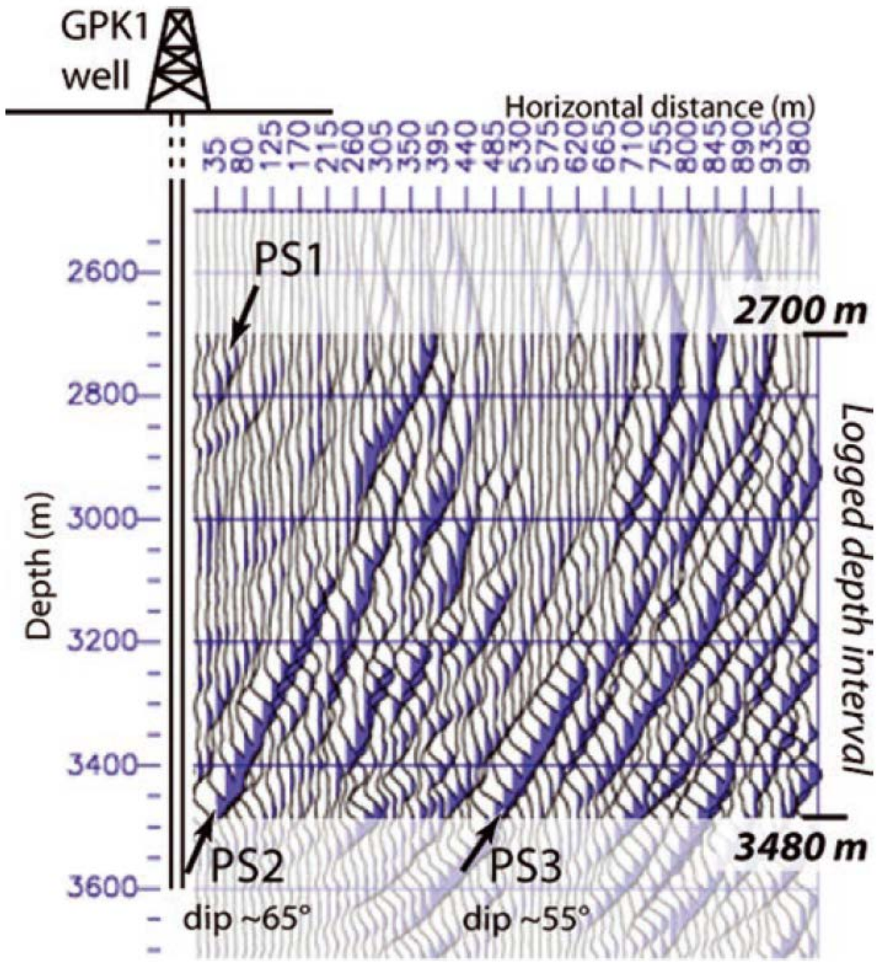

Figure 6c: *Fault intersecting the well at 3490m, illuminated by P-S converted reflection, processed by Baker-Hugues/Vsfusion, London. Figure reproduced from Figure.6 of* [Place](#) *et al. ,2011*

The fault intersecting the well at 3490m can be illuminated using P-S reflection (Figure 6c) built from the Zero-offset VSP. A similar fault generates the interference on the O-VSP raw data on Fig.6b, mainly because the top basement located around 1400m is a **rugged unconformity accompanied with a high seismic velocity contrast,** so that any fault thrust at this level makes a cliff step/ linear hard rock fault corner located laterally to the well , by which a secondary focused P-wave arrival propagates, a classical phenomenon observed in refraction seismic, called "multipathing".

Spectacularly interfered Direct P-wavetrain with, near vertical, very close by linear polarizations is illustrated on the presentation document **OA02-More info from VSP** prepared by Anna Rivet et al. , slides 24-26. The non-stability of the P-waveshape versus depth makes it impossible to obtain clear seismic reflections far below the downhole receivers. The interference is clearly linked to a plurality of P-wave ray paths between the surface source and the downhole VSP tool receivers.

C) Unknown existence of acoustic eigen wave modes with elliptical polarization

Elliptical acoustic modes of propagation in rocks may occur in the physical world, when electromagnetic fields with appropriate values are applied to certain kinds of solids, and generate what is called gyroscopy (**Chichinina** and Obolentseva, 1988), a common phenomenon in optics, for which the eigen elliptical modes actually have orthogonal elliptical shapes, with the same ellipticity and opposite angular rotation of particle motion (CW/CCW). In this case, the anti-symmetrical structure of the imaginary part of the complex stiffness tensor generates the counter rotative orthogonal eigen S-wave propagation modes.

The presence of an appropriate Electro-Magnetic acoustical coupling can generate the gyroscopic effect. However, the viscoelastic attenuation alone does not seem to be the cause of such an asymmetry in the propagation of seismic and sonic body waves in earth rock formations, considering the commonly observed linear polarizations of direct P, S, and PS converted body wave observed on commercial and academic oriented 3 component VSP datasets. Applying a strong enough magnetic field on a porous rock sample containing ionic bearing fluids might generate altered shear wave eigen modes of propagation with altered attenuations and velocities, although such experiment has not been conducted in any laboratory in the son ultrasonic to hypersonic frequency ranges to the author's knowledge.

The physical origin of the gyrotropy eventuality studied by **Chichinina** and Obolentseva is attributed to seismic wave dissipation expressed by a fifth order anti-symmetric tensor. To the author's knowledge, no observation of such gyrotropic effect has been reported to this day. In contrast, several studies clearly show linear P and S propagation of body waves with different velocities and different attenuations on rock samples in the ultrasonic domain (**Tao** & King, 1990, Sondergeld & Rai,1992).

In the paper by **Tao** and King, the figures showing the P, S1, S2 eigen signal waveforms clearly show that the P-wave generates little to no noise on the two orthogonal eigen shear wave axes, and that the fast S-wave generates little to no noise onto the orthogonal S-slow axis.

Sondergeld and Rai further verify more accurately in their experimentally study that the cross energy of a linear eigen S-wave mode excited by a linear S-wave ultrasonic source, then propagated through a highly anisotropic rock sample, is NULL, which confirms the linearity of the eigen S-wave modes: the cross-amplitude to inline amplitude ratio can be visually estimated to 20-30db on figure 7 hereafter.

Similar anisotropic observations were conducted by **Christensen** in 1971 on rock samples such as sedimentary slate, and metamorphic dunite/olivine rock samples, using shear wave transmitters and receivers at 1 MHz frequency: linear S-waves was observed, together with high differential attenuation between S-fast and S-slow eigen modes in the slate rock sample.

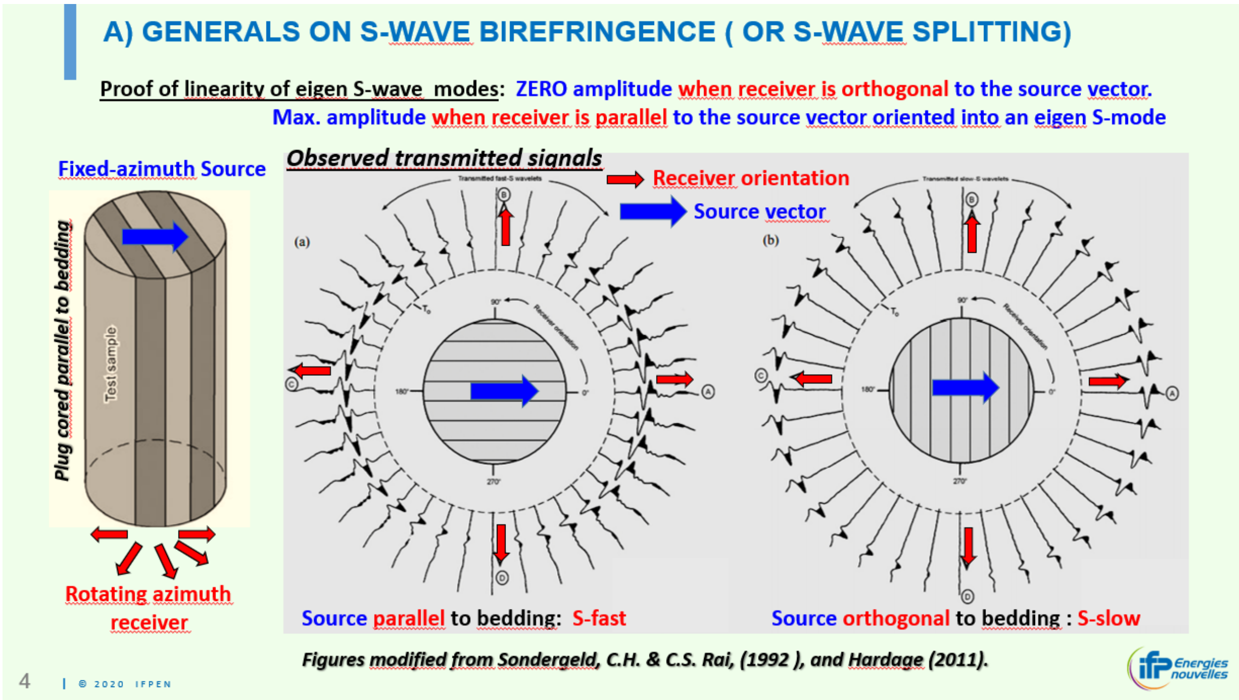

Figure 7: *Evidence of linearity of eigen S-wave modes propagated through anisotropic and attenuating rock samples, measured around 1 Mega-Hertz, along the axis of a ~4cm high homogeneous cylindrical core plug. Figure reproduced from slide 4 of* **ARMA – 21– 1794** *by Naville & al., 2021, modified from* Sondergeld & Rai, 1992 *and* Hardage,2011*,*

At the lower end of the seismic spectrum, seismologists have observed linear polarization of S waves from earthquakes for a long time. A spectacular split S-wave example is given on Figure 8 hereafter:

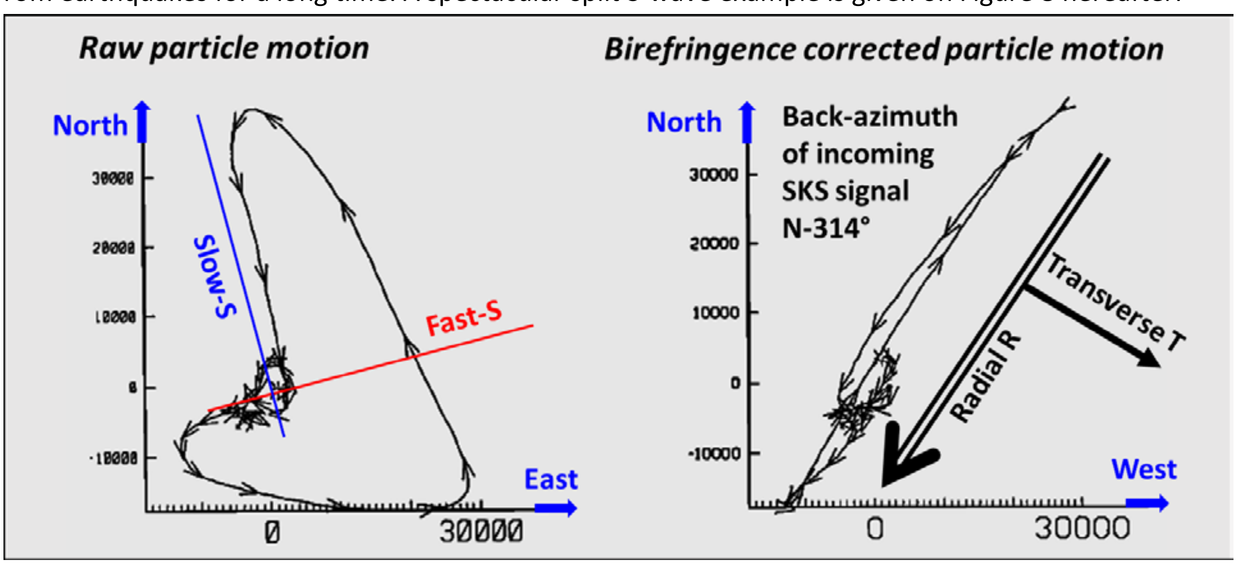

Figure 8: *Horizontal plane particle motion for fast and Slow components uncorrected (left) and corrected (right). Corrections made using estimated values of the Fast-S Azimuth N80°and split S-wave delay 1.8s. Figure modified from Fig2c, p.16,437 , in* Silver & Chan, 1991*.*

Sometimes the azimuth of propagation through the upper mantle and crust coincides with an eigen S-wave direction: this is evidenced by a Null transverse energy on the 3-component seismograms recorded from distant SKS events (Figure A5, p.97 of **Savage**,1999).

Another clear example of separate, orthogonal wiggle signals holding separate, linearly polarized fast-S and slow-S waveform signals generated by a small and shallow islandic earthquake generated 8.2 km deep epicenter is illustrated on Figure 2 of the paper by **Gao** & Crampin, 2008.

Curiously, the differential attenuation (QD for Q-Differential) between linearly polarized fast and slow S-waves remains to be investigated by the S-wave birefringence professionals working from seismic body wave records. Even a small value of split S-wave differential attenuation introduced in the propagation model of SKS/SKKS distant range earthquakes or for the P-S upgoing arrivals converted at the Moho interface could potentially improve the linearity of the particle motion corrected for birefringence effect, even if the single anisotropic layer model without differential attenuation perfectly fit with the observation (ref Fig.2c of **Silver** & Chan, 1991)…

In contrast, the dipole and multipole sonic logging tools record flexural direct S-wave arrivals, which nearly behave as body waves below 3kHz (domain of the “low frequency limit”), but become significantly dispersive above 3kHz, like surface or interface waves.

D) Difficulties for measuring the downhole mechanical parameters of the initially unaltered rock formation in a borehole.

The stress and mechanical alteration occurring in the immediate borehole vicinity generates rock medium heterogeneities near the source and receiver positions. The formation velocities generally decrease gradually from the unaltered rock far away from the borehole towards the borehole wall, as exposed by **Tang** et al. using a simplified symmetrical geometric approach around the borehole axis.

Nevertheless, dipole sonic measurements and S-wave anisotropy processing are confronted to difficulties induced by heterogeneities, as pointed out by Dellinger, 2001, page 645, right column: “*In practice the data matrix recorded by cross-dipole logging tools is not symmetric. This could be because of mismatched tool components or uneven coupling. Assuming an ideal instrument, it could also be from heterogeneity (the likely explanation) or, more exotically, gyrotropy (***Chichinina** and Obolentseva*, 1998). Gyrotropy is the elastic analog of optically active compounds in inorganic chemistry* “…

Drilling a borehole in the underground modifies the immediate rock formation mechanical parameters, mainly within a radius of at least 3 times the borehole radius, following Saint-Venant’s principle, illustrated on figure 9.

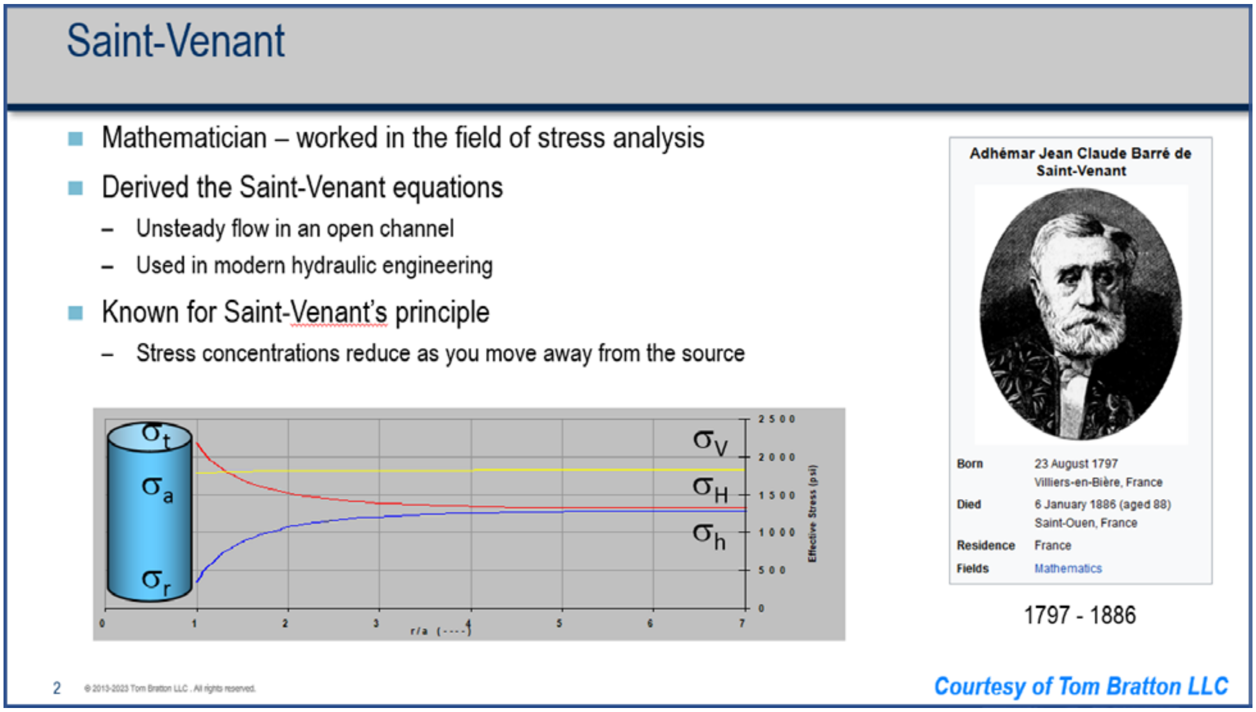

Figure 9: *Classical geomechanics knowledge about the stress alteration around a borehole, mainly within a radial domain of three times the borehole radius. Slide Courtesy of Tom Bratton LLC.*

The unsatisfactory minimization of the cross dipole energy (i.e. minimal values far from zero) used to determine the eigen S-wave directions is NOT due to any ellipticity of the eigen S-wave modes of the propagated flexural waves along the borehole wall, but they are likely attributed to the scattering of the S-wave particle motion generated by rock formation heterogeneities located near the S-wave source position, or in the interval between source and receivers: the presence of borehole washouts, caves, faults, fracture swarms, or any notorious heterogeneity can generate such scattering, resulting in the depolarization of seismic body wave, according to observations by Perrin et al., 2022.

Figure 10 illustrates how difficult it may be to measure the parameters of the unaltered rock formation in the subsurface around a deep borehole, laterally to the borehole, aside from the eventual caves, washouts, and borehole wall rugosities induced by drilling. All drilling induced mechanical rock defects contribute to alter the initial mechanical formation parameters, and alter the measurements performed in the borehole. The interpretation of the geologist and petrophysicist rely on the accuracy and representativity of these measurements and their processing into a readable form.

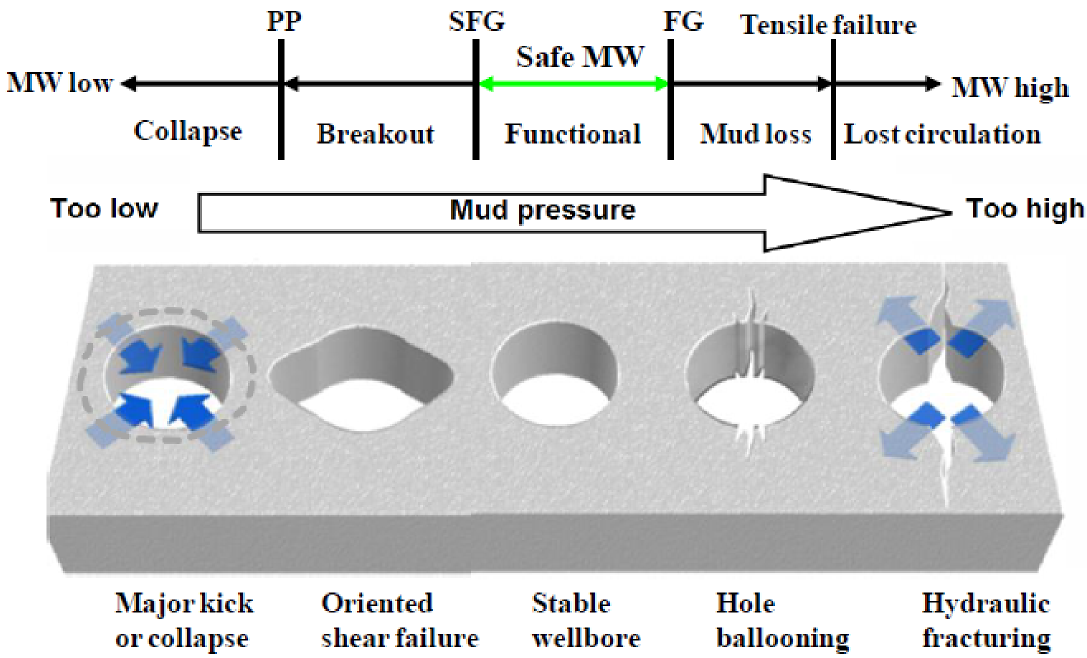

Figure 10: *Schematic relationship of mud pressure (mud weight) , and borehole failure, reproduced from Figure 1 of* [Zhang](), *2009*

The difficulties encountered in measuring the S-wave birefringence parameters with dipole sonic tools make it quite chancy to obtain a fair tie with the birefringence measured by S-wave source VSP's. Therefore, calibrating the birefringence parameters derived from surface seismic are more likely to fit the birefringence values versus depth from S-wave VSP surveys rather than from dipole sonic measurements.

Luckily, the 3 Component VSP measurements present an excellent approach to surface seismic birefringence calibration because the VSP tool clamped in a borehole measures directly the seismic body wave signals.

E) Discussion

The seismic R&D objectives in the late 1970's / early 1980's conducted between CGG (D. Michon, Y. Olivier, G. Omnes, P. Tariel), IFP (P.Y. Layotte), VNII-Geofizika in Moscow (L.Y. Brodov) were focused on improving the 3-component surface and downhole seismic sensors, instruments and methods in the aim to better understand the seismic propagation, in both P and S-wave modes, mostly SH-wave in surface seismic. Three component VSP tools had to be built, horizontal seismic sources consisted mainly in generating imbalanced effects with buried explosives or explosive cord (Syslap method), soon replaced by horizontal mechanical sources (IFP-Marthor horizontal hammer, MERTZ M13 vibrator, Russian horizontal electromagnetic pulsers, etc.…)

On the field, portable digitizing units located closely to the geophones were just emerging in surface seismic, mainly with the newborn SERCEL SN348 recorder. VSP surveys were an academic subject, no downhole Analog/Digital converters existed yet, and mainly P-wave checkshots were currently recorded with a single vertical component geophone downhole tool.

On the theoretical side, geological layering was the sole known cause of anisotropy, affecting mainly in the P-wave velocity. 3 component surface geophone receiver settings had a quite anisotropic response.

Following the first VSPs recorded with a vertical geophone, the surface seismic geophysicists were very surprised to discover the high prevalence of heterogeneities present the shallow low velocity layers (LVL), also called "Weathered Zone" (WZ), in drastic contrast with the homogeneity of deep geological layers buried in the subsurface, evidenced by the very high wave shape stability of the seismic signal propagated along a borehole below 300m depth on VSP datasets. The main objective of borehole seismic was to figure out how to improve the quality of P-wave reflection imaging by surface seismic. The first array sonic tools emerged (implemented with receiver array and source array with the EVA tool developed by ELF and CGG), in the hope to build images on the borehole vicinity within a few tens of meters, after compensating for eventual "P-wave borehole decompressed weathered zone effects". Actually, the borehole LVL or altered zone surrounding the borehole seems to be even more complex for Shear wave propagation than for P-wave propagation, in a manner similar to land surface seismic.

In short, the accessible surface where the source and receiver instruments can be installed is well known as "**the worse place to work**" by the land surface seismic geophysicist and the sonic petrophysicist, due to the mechanical heterogeneities in the immediate vicinity of this working surface of observation, on land surface or inside a borehole…

The author is thankful to the numerous professional field explorationist colleagues (although most of the ones above mentioned unfortunately 'Rest In Peace') for their constant encouragements to '**search further',** in spite of the technical and industrial complexity of the 3 Dimension and 3 component (3D/3C) seismic and sonic wave propagation in the subsurface

F) Practical applications using linear polarizations of P and S body waves

- The industrial and academic applications of the elastic Shear wave in homogeneous viscoelastic media are definitely simplified by the linearity of the P and S body wave eigen modes of propagation in a very wide range of frequencies encompassing the common seismologic and seismic propagation domains, up to the ultrasonic domain, i.e. from a fraction of Hertz to 1 Megahertz or beyond.
- Linear (rather than elliptical) eigen S-wave modes are certainly easier to understand the acoustical birefringence propagation and to manage in the. The reliability of the processed results is improved, by simplifying the 3-component seismic processing operations and the

birefringence detection computer routines applied to dipole sonic data, for the benefit of the geologists and mechanical engineers as interpreters and end-users.

- VSP & borehole seismic: orientation of 3 Component geophone settings using the linear polarity of direct P-wave along the group wave direction (DiSiena & al, 1984).
- The high linearity of the Pressure body waves is illustrated by the direct seismic P-wave arrivals on raw zero-offset VSP records, sometimes visible ONLY of the raw vertical component:
  - Fig 8 of **Kazemi**, 2009.
  - Oriented 3C VSP dataset slides 8,9, 32,33, of*:* **Gerard** *et al., 1993-2020:*
- The interpretation of observed ellipticity of direct P-wavetrain as an interference of at least Two linear P-wave arrivals is clearly illustrated on slides 16,18,24, leftmost panel, Z component of: **Gerard** et al., 1993-2020***.*** Another instructive example of complex interfered P-wave train on oriented 3C VSP data can be seen in slides 24-26 and 28-30 of the **OA02-More info from VSP** presentation file.
- Determination of propagation anisotropy of P-waves. Radial walkaway VSP's and wide to full azimuth 3D surface seismic commonly show P-wave velocity anisotropy versus the ray path vertical incidence and versus the ray azimuth. These anisotropy effects are currently corrected by the industrial seismic processing operators to produce reliable and focused seismic reflection images.
- Dip/azimuth of geological structures in the borehole vicinity: "Seisdip" method " (IFP trademark) of determination of dip/azimuth of seismic reflectors in oriented 3C VSP dataset processing using the measured linear polarization of incident P-wave arrivals and P-P, P-S reflections.
  Ref following IFPEN webpages:
  - https://hal-ifp.archives-ouvertes.fr/hal-01171298/document
  - https://www.ifpenergiesnouvelles.com/brief/ifpen-aps-ppzg-orientation-3-component-rig-source-vsps
  - https://hal.archives-ouvertes.fr/hal-01167330/document
- Estimation of the quality of the isotropy of mechanical coupling response (called 'Vector fidelity') of the 3 component downhole VSP tools: if a single P-wave arrival (often the direct arrival) becomes more elliptical with frequency, the quality of mechanical coupling of some of the components is probably unsatisfactory. Very high quality of vector fidelity of 3C reception downhole instrument has been reached and commercialized by logging service companies. (see *de* Montmollin,*1988, and de* **Montmollin***,* *CSI VSP tool Brochure, 1990,* showing a presently abandoned commercial VSP tool using a small 3 component geophone housing implemented with a Shaker).
- AVO calibration with borehole seismic, using the measured linear polarization of incident and P-P & P-S reflections
- In seismic frequencies (0-100Hz) or in ultrasonic frequencies (1-15 kHz), the directions of S-wave attenuation anisotropy are the SAME as the directions of velocity anisotropy. S-wave attenuation anisotropy can exist ALONE, without velocity anisotropy, which may lead to improvements of industrial S-wave anisotropy detection algorithms and software for surface seismic, VSP, and dipole sonic surveys.

- The differential S-wave attenuation subject has barely been investigated yet...

G) Acknowledgements

The author thanks the IFPEN management, including Mrs Olga Vizika-Kavvadias , Scientific Director, for the opportunity given to publish interesting results about the VSP and borehole seismic techniques and experience. Mrs Pascale Barbey and Nathalie Toullec of the IFPEN documentation department, and Mrs Nicole Chenesseau, have been helpful in helping the construction of the present Note.

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