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AVOaz response of a fractured medium: Laboratory measurements versus numerical simulations

Mohammed Alhussain[1], Enru Liu[2], Boris Gurevich[1], Milovan Urosevic[1], and Shahid Ur Rehman[1]*
[1]*Curtin University of Technology,* [2]*British Geological Survey (now at ExxonMobil URC)*

Summary

Azimuthal variation of the AVO response (AVOaz response) of fractured reservoirs is usually modeled using equations for reflection coefficients obtained for plane waves. However, the plane wave approximation can break down at long offsets where incidence angle approaches the critical angle. Since azimuthal variation of AVO response is often more noticeable at large offsets (and can be rather weak), spherical wave effects must be carefully analysed and taken into account.

In order to analyse these effects quantitatively we performed an AVOaz laboratory experiment under fully controlled conditions, and then numerically simulated this experiment. The AVOaz response of a physical model is studied in the laboratory with finely layered Plexiglas simulating vertical fractures. Transmission measurements are performed to construct the elasticity tensor for the HTI model. This elasticity tensor is used as an input into numerical simulations which are performed using an anisotropic full-wave reflectivity algorithm.

The comparison of the experimental data with simulations shows a very good match for the isotropic case and good qualitative agreement for the azimuthal variations. The agreement is especially good for critical angles extracted by picking inflection points on AVO curves for at each azimuth. This shows that (1) reflection measurements are consistent with the transmission measurements; (2) the anisotropic numerical simulation algorithm is capable of simulating subtle azimuthal variations with excellent accuracy; (3) the methodology of picking critical angles on seismograms using the inflection point is robust, even in the presence of random and/or systematic noise.

Introduction

In recent years variations of the AVO response with azimuth (AVOaz response) have been increasingly used for the characterisation of fractured reservoirs. However up until now in many cases the interpretation of such multi-azimuthal data set has been qualitative, and focused on estimating fracture and/or stress direction. With novel processing methods which enable preservation of the long offset data, quantitative interpretation becomes feasible. Quantitative interpretation requires a good understanding of the AVOaz response as a function of medium parameters.

Behaviour of plane-wave reflection coefficients in anisotropic media and their azimuthal variations can be analysed using an extension of the Zoeppritz equations to anisotropic media (Musgrave, 1970; Schoenberg and Potazio, 1992), and is well understood. More recently, Tsvankin (1996) and Rüger (1997) have derived concise and robust approximate relationships for reflection coefficients, which extend to anisotropy from the well-known isotropic AVO approximations.

While the theory has been derived for plane waves it is known that seismic surveys utilise localised sources which produce spherical, rather than plane waves. Nevertheless, the plane wave approximation for reflection coefficients is assumed to be quite accurate for typical hydrocarbon exploration target depths and is routinely used in isotropic AVO analysis and inversion. However, it is well known that plane wave approximations can break down at long offsets where the incidence angle approaches the critical angle. Since azimuthal variation of AVO response is often more noticeable at large offsets (and can be rather weak), spherical wave effects must be carefully analysed and taken into account. This can be done either by full-wave numerical simulations (Karrenbach et al., 1997; Urdaneta, 1997; Landro and Tsvankin, 2007) or physical modeling in the laboratory (Fatkhan et al., 2001; Luo and Evans, 2004; Doruelo et al., 2006).

In this paper we combine these two approaches by conducting an AVOaz laboratory experiment under fully controlled conditions, and numerically simulating this experiment. The AVOaz response is studied by physical modelling with a layered model simulating vertical fractures. Transmission measurements are performed to construct the elasticity tensor for the HTI model. This elasticity tensor is then used as an input into numerical simulations which are performed using an anisotropic full-wave reflectivity algorithm. The comparison shows a very good agreement between experiment and simulations.

Experiment

Seismic wave propagation and partitioning of energy at an interface can be effectively studied by using physical modeling, whereby models are constructed in such a way that they resemble real geological structures taking into account the scale factor. Hence, by using scaled models in a controlled environment, it can be assumed that the response from the models is the same as it would have been obtained from realistic earth materials.

An advantage of laboratory experiments is that real seismic waves propagate through models with no approximations made to the propagation process. Laboratory experiments are conducted using the Curtin University Physical

Modeling Laboratory equipment (Luo and Evans, 2004). The crux of the system is a set of computer controlled ultrasonic piezoelectric transducers, operating as seismic source and receivers. Movement of transducers is controlled in three-dimensions by high-precision stepping motors. A Lab View data acquisition program enables versatile source-receiver configurations, which can be transmission measurements, 2-D, 3-D and VSP surveys.

Physical properties of model materials need to be considered carefully to ensure successfully built physical models. For solid media this includes P and S-wave velocities and density. Plexiglas is often a material of choice since it is intrinsically isotropic but at the same time can be cast in very fine layers which can be pressed together to simulate a fractured (anisotropic) medium. Plexiglas has P-wave velocity of about 2700 m/s which provides good velocity contrast with a water column. Its density of 1.2 g/cc allows the material to be positioned deep into a water tank.

The objective of this laboratory experiment was to analyze the variations of P-wave reflectivity with incidence angle and azimuth caused by a set of vertical fractures embedded into an otherwise isotropic medium. Thin Plexiglas plates (2mm thickness) were used to simulate vertical fractures. The surfaces of the Plexiglas sheets were roughened to establish asperities. Then the plates were pressed together under water to make sure that no air bubbles were trapped inside. With a scaling factor of 1:10000, the model simulated a 500 m thick fractured medium, with 20 m fracture separation, over an area of 1500 × 1200 m. A solid block of Plexiglas of the same dimensions was used for calibration.

The first step after designing the presumably HTI model is to check that it shows expected anisotropy (Urosevic, 1985). Transmission measurements were first performed in order to construct the stiffness matrix of such HTI medium by inverting the group velocity measurements. The results are shown in Table 1.

Table 1. Elastic parameters of the solid (isotropic) and fractured (anisotropic) Plexiglas models. Velocities are in km/s and densities in g/cc.

Solid Model	V_P	V_S	ρ	**Water**	V_P	ρ
	2.724	1.384	1.2		1.484	1
Fractured Model	$V_P(0)$	$V_P(45)$	$V_P(90)$	$V_s(fast)$	$V_s(slow)$	ρ
	2.704	2.660	2.709	1.382	1.320	1.2
Anisotropic parameters	ε^V	γ^V	δ^V			
	-0.0011	-0.044	-0.068			

The first reflection experiment was performed for the water/solid Plexiglas interface. The recorded AVO response was used for calibration and to compare the radiation pattern of transducers with numerical modeling.

The solid block of Plexiglas was submerged in a water tank. Omni-directional P-wave transducers with a 220 kHz dominant frequency were also submerged in water and positioned 24 cm (2.4 km, scaled) above the model. Common mid-point (CMP) recording was employed for data acquisition. The minimum offset was 2 cm and source and receivers were moved apart at an increment of 1 mm in the opposite directions. A total of 270 CMP traces were recorded over the model. At each position, 20 CMP traces were repeated and vertically stacked to increase the signal-to-noise ratio. With a scaling factor of 1:10000, this model simulated 20 m trace spacing, and a dominant source wavelet of 22 Hz reflecting from an interface at a depth of 2.4 km. The acquisition parameters and the resulting CMP gather are shown in Figure 1a,b.

For AVOaz reflection experiments, all acquisition parameters were kept the same as in the previous experiment over the isotropic model, but instead of recording a single 2-D CMP line, a total of seven 2-D lines were recorded along different azimuths with the middle CMP being at the centre of the fractured model. The azimuths were measured with respect to the symmetry axis direction, starting from zero azimuth (perpendicular to fractures) up to 90 degrees azimuth (parallel to fractures) with an increment of 15 degrees. For every 2-D CMP line, the model was rotated 15 degrees with respect to the symmetry axis. Figure 2 illustrates three azimuthal recordings at 0, 45 and 90 degrees. The black dotted line is the symmetry axis and the red lines are the 2-D CMP lines corresponding to three azimuthal directions.

Experimental results

The AVOaz experiment described above produced seven seismograms (one for each recording azimuth) similar to the one shown in Figure 1b. Rpp amplitudes for water/HTI interface were picked, calibrated and plotted against angle and azimuth as shown in Figure 3. The following features can be observed in this figure:

- Fracture induced anisotropy has a negligible effect on amplitudes for incidence angles up to 25 degrees. This focused our analysis towards large angle/offset reflection coefficients close to the critical angle.
- The reflection amplitude peak (close to the critical angle) shifts towards larger incidence angles from azimuths 0° to 45°, and then reverts back to its original position for azimuths 45° to 90°.

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Numerical simulations

The elastic parameters extracted from transmission measurements were used as an input to numerical simulation algorithms. The first idea was to compute plane-wave reflection coefficients for the water/solid Plexiglas interface using the anisotropic Zoeppritz equations (Schoenberg and Potazio, 1992). However, it is clear from analysis of Figures 3 and 4 that the azimuthal variation can only be observed at offsets where the match of the measured reflection coefficients with the theoretical plane-wave solution is poor. This discrepancy is most likely caused by spherical wave effects (Doruelo et al., 2006).

In order to make a precise quantitative comparison between experiment and theory, we employed a full-wave reflectivity algorithm to simulate both isotropic AVO and anisotropic AVOaz responses numerically using the same elastic properties and acquisition geometry. The simulations were performed for a point source with a spherically symmetric radiation pattern. As a result we obtained a series of CMP seismograms for each recording azimuth. Then, the amplitudes were picked on the seismic traces in the same manner as on the experimental traces. The resulting reflection coefficients are shown in Figures 4 and 5.

Comparison of experiments and simulations

The AVO response obtained from simulations for an isotropic Plexiglas block is shown in Figure 4 (along with experimental response and plane wave reflection coefficients). The AVOaz Rpp amplitudes for different azimuths are plotted against angles in Figure 5.

There is an excellent agreement between laboratory measured AVO response for the water/solid Plexiglas interface and the isotropic AVO numerical simulations. This shows that the spherical approximation of the radiation pattern of the transducers is appropriate.

Now we compare the two sets of AVOaz curves as shown in Figures 3 and 5. The two data sets show good agreement for azimuths 90°, 75°, 60°, 45° and 30 ° degrees. On the other hand, for azimuths close to the symmetry axis, (15° and 0°), the physical modeling data show higher amplitude (by up to 7.5%), especially for large incidence angles. Possible reasons for the discrepancy are as follows.

- Finite fracture separation (violation of the effective medium approximation).
- Possible spatial heterogeneity of the model caused by the fact that the stress exerted by brackets used to hold Plexiglas sheets together is not uniform.
- Deviation of the radiation pattern of the cylindrical transducers from spherical in the transverse direction
- Effect of the edges of the rectangular Plexiglas model.

One way to mitigate the effect of amplitude distortions is to analyze the azimuthal variation of the critical angle (Karrenbach et al., 1997, Landro and Tsvankin, 2007). Landro and Tsvankin (2007) suggested that a robust method of picking a critical angle from the AVOaz curves is to pick the point of the fastest amplitude increase of the reflection coefficient. Critical angles calculated from the laboratory experiments and numerical simulations using this technique are shown in Figure 6. Also shown is plane-wave critical angles computed from the equation:

$$\frac{\sin\theta_{cr}}{V_{p1}} = \frac{1}{V_{p2}(\phi)} \qquad (1)$$

where θ_{cr} is the critical angle, V_{p1} is the velocity of the upper medium (water), and $V_{p2}(\phi)$ is the phase velocity as a function of azimuth which can be calculated in terms of anisotropic parameters:

$$V_{p2}(\phi) \approx \alpha(1 + \delta\sin^2\phi\cos^2\phi + \varepsilon\sin^4\phi) \qquad (2)$$

(Mavko, 1998), where α is P-wave velocity along the symmetry axis, ε and δ are anisotropic parameters extracted from transmission measurements. All curves are symmetric about 45° azimuth, which is expected for a liquid-filled fractured medium with very small ε (Rüger and Tsvankin, 1997). An excellent agreement is observed between the three different data sets at the critical angle.

Conclusions

In this paper we performed laboratory measurements and full-waveform numerical simulations of the azimuthal variation of AVO response for a fractured Plexiglas medium. The comparison of the experimental data with simulations shows that (1) Reflection measurements are consistent with the transmission measurements (which are used as input into numerical simulations); (2) the anisotropic numerical simulation algorithm is capable of simulating subtle azimuthal variations with excellent accuracy; (3) the methodology of picking critical angles on seismograms using the inflection point is robust, even in the presence of random and/or systematic noise.

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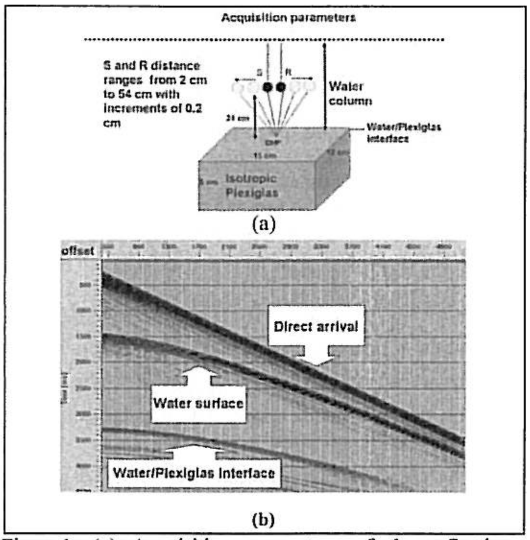

Figure 1. (a) Acquisition parameters of the reflection measurement for water/Plexiglas interface producing CMP gather (b) with three seismic events indicated by arrows.

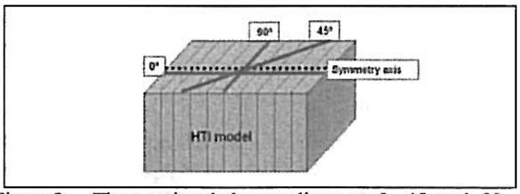

Figure 2. Three azimuthal recordings at 0, 45 and 90 degrees with respect to the symmetry axis.

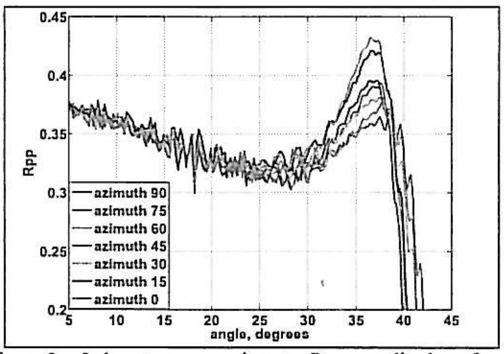

Figure 3. Laboratory experiment R_{PP} amplitudes for different azimuths plotted against angles of incidence.

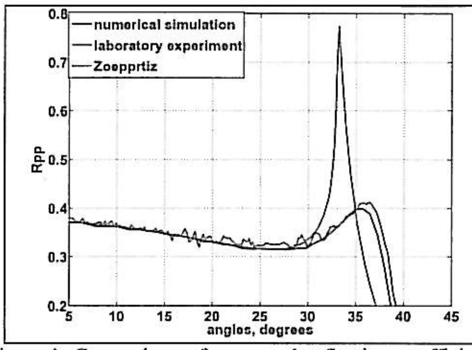

Figure 4. Comparison of measured reflection coefficients versus incidence angles for water/Plexiglas interface with plane-wave response computed using Zoeppritz equations and a point-source numerical simulation.

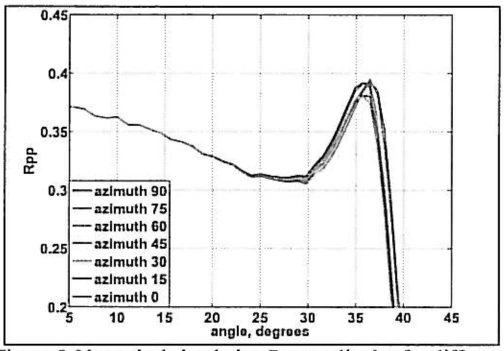

Figure 5. Numerical simulation R_{PP} amplitudes for different azimuths plotted against angles of incidence.

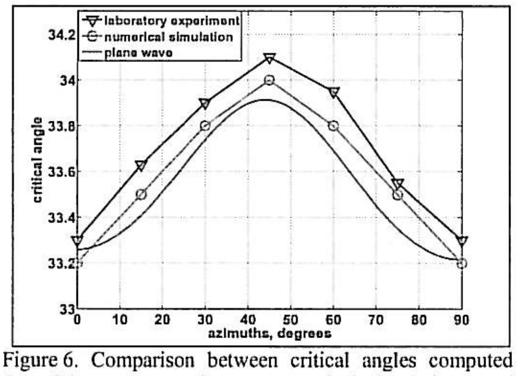

Figure 6. Comparison between critical angles computed from laboratory experiments, numerical simulations, and plane wave solutions at different azimuths.

EDITED REFERENCES

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Theory and Methods

AVO 2.1 **(0239-0243)**

Estimation of the fluid indicator from azimuthal AVO gradient variations at a fractured reservoir

Joost van der Neut*, Delft U and Indian School of Mines U; Ranjit K. Shaw, Indian School of Mines U; Mrinal K. Sen, U of Texas Inst for Geophysics, John A. and Katherine G. Jackson School of Geosciences

AVO 2.2 **(0244-0248)**

Is there a basis for all AVO attributes?

Zhengyun Zhou*, Center for Applied Geosciences and Energy, U of Houston; Fred Hilterman, Geokinetics

AVO 2.3 **(0249-0253)**

Experimental verification of spherical wave effect on the AVO response and implications for three-term inversion

Mohammed Alhussain*, Boris Gurevich, and Milovan Urosevic, Curtin U of Technology

AVO 2.4 **(0254-0258)**

AVOaz response of a fractured medium: Laboratory measurements versus numerical simulations

Mohammed Alhussain*, Curtin U of Technology; Enru Liu, British Geological Survey; Boris Gurevich, Milovan Urosevic, and Shahid Ur Rehman, Curtin U of Technology

AVO 2.5 **(0259-0263)**

Fracture-properties inversion from azimuthal AVO using singular value decomposition

Isabel Varela*, U of Edinburgh; Sonja Maultzsch, TOTAL E&P UK, Geoscience Research Center; Xiang-Yang Li and Mark Chapman, British Geological Survey

AVO 2.6 **(0264-0268)**

Common-angle processing using reflection angle computed by kinematic prestack time demigration

Didier Lecerf*, Philippe Herrmann, Gilles Lambaré, Jean-Paul Tourré, and Sylvian Legleut, CGGVeritas

AVO 2.7 **(0269-0273)**

AVO modeling with nonzero-phase spherical waves

Charles P. Ursenbach* and Arnim B. Haase, Crewes, U of Calgary

AVO 2.8 **(0274-0278)**

Time-lapse AVO modeling for enhanced coal-bed methane production

Jason McCrank*, Don C. Lawton, Han-xing Lu, and Kevin Hall, U of Calgary

SEG Annual Meeting 2007 news coverage

SEG Technical Program features full slate, new Special Session

Sylvie Dale

23 September 2007—The SEG Annual Meeting Technical Program begins on Monday afternoon with a full slate of 646 accepted papers (505 oral and 141 poster).

This year's Technical Program is a strong one, commented Bob Hardage, Technical Program Committee chairman. The committee's task was to pare down the more than 800 abstracts received to 646 oral papers and posters.

"We have to go through a rather rigorous peer review process to go through this," Hardage said. A total of 478 peer reviewers participated in the abstract selection process, and combined with the cochairs and session monitors, that number jumps to about 690 people—more than the number of accepted papers.

"I don't think there is any other SEG activity that gets that many members involved."

Some more numbers:

- Accepted papers are from roughly 44 countries around the world.
- More than 200 students submitted papers.
- There are 165 accepted student papers, meaning the student is the primary author of the paper (this number does not include students that may be listed as secondary authors).

A new Special Session has debuted this year and, if it goes well, may be a permanent addition. *Special Session 2, Science and Technologies, the Horizon and Beyond,* is similar in scope to the very popular *Special Session 1, Recent Advances and the Road Ahead.* They are both suited to a more general audience and deal with cutting-edge technologies and methods of the future.

The Technical Program consists of 63 Technical Sessions scheduled Monday through Thursday with a maximum of 11 concurrent Technical Sessions scheduled at any time during the program period. Topic areas that had high abstract submissions, and thus will have several scheduled sessions, include EM exploration, near-surface and environmental, rock properties, seismic inversion, seismic processing: migration, seismic processing: multiples, and time lapse.

Poster sessions will be effective this year because the layout of the Henry B. Gonzalez Convention Center in San Antonio allows us to distribute posters along the major traffic area between the Exhibit Hall (Floor 1) and the Technical Sessions (Floor 2). It remains to be seen if the expected high rate of foot traffic through the poster area will aid or disrupt poster presentations, but we are hopeful that this decision will return a positive response.

When asked if anything about the submissions surprised him, Hardage said he was surprised the program didn't receive more papers on what he terms multi-azimuth technology. The technology is new enough that the experts are still working out the proper terms, but in a nutshell, it is a seismic acquisition method using more than one source and more than one vessel and involving multiple tows in the same area.

"It is a red-hot topic for subsalt imaging—arguably the most challenging imaging problem that the industry has in the Gulf of Mexico, and in other areas where subsalt is a big part of the subsurface layers. That's going to control the destiny of subsalt hydrocarbon exploration for the next decade or so."

Hardage said it will be a great session and plans to attend it, but it may take some time for the topic to attract a lot of papers because people are probably going to need a little more experience, and there may be some confidentiality issues this early in the process.

The usual topics got a lot of papers, including rock physics, seismic migration, and imaging, potential fields (gravity and EM).

A new no-show policy is being tested this year in San Antonio. The Executive Committee, with guidance from the Technical Program Committee, has voted that oral paper authors must give sufficient notice if they cannot present their paper as scheduled. If they do not, they are barred from consideration for the next two SEG Annual Meeting Technical Programs. SEG leaders are hoping this will reduce gaps in the program when a paper cannot be presented at the scheduled time.

Incidentally, attendees may notice that the Steering Committee has largely the same makeup as that of SEG 2001, which also was held in San Antonio but was interrupted by the passenger jet attacks of 11 September 2001. Because they set up a great program in 2001 but were unable to carry it out, everyone but the general chairman agreed to finish what they started in San Antonio this year. If the attitude of the Technical Program Chairman is any indication, the 2007 meeting should be very successful.

Expanded Abstracts

Many of the *Expanded Abstracts* have been posted to the SEG Technical Program Online site. At the conclusion of the Annual Meeting, this site will be taken offline, but the Expanded Abstracts will continue to be available (full text to members and subscribers, and abstract views only to nonmembers) in SEG's Digital Library. The *Technical Program Expanded Abstracts CD* is also available through the Book Mart (booth #659).

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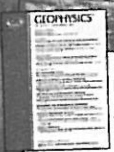

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▸ **Yearbook:** *Published annually and available only to SEG members, the SEG Yearbook is an alphabetical and geographic directory of all members. It includes lists of the Society's committees, meetings, educational opportunities, awards, publications, historical records, and governance documents. It is published on a CD-ROM that also includes the previous year's journal articles, and it is distributed to all members. Information in SEG's Yearbook also is available on the SEG Web site or can be purchased in print through the SEG Book Mart.*

Meetings & Expositions

▸ **Annual Meeting:** *SEG's Annual Meeting and Exposition is the world's premier geophysical event, featuring more than 700 technical paper presentations and an exposition showcasing the latest in geophysical products and services. It regularly brings together more than 8,000 exploration industry professionals from around the globe.*

▸ **Development and Production Forum:** *This annual event brings new and emerging development and production technologies into open discussion, with the dual purpose of education and exchange of ideas.*

▸ **Summer Research Workshop:** *Held annually, this workshop examines, clarifies, and promotes research in a wide range of applied geophysics topics.*

▸ **International meetings:** *More than 50 percent of SEG's members live outside the United States, and one of the ways SEG serves them is through a growing international meetings program.*

Professional Development

SEG offers many professional development opportunities in a variety of settings.

▸ **Continuing Education courses:** *SEG offers public and contract continuing education courses on many aspects of applied geophysics.*

▸ **SEG/EAGE Distinguished Instructor Short Course:** *Each year a new instructor of renown is selected to teach worldwide a course of broad relevance. Registration fees for members are minimal.*

▸ **Distinguished Lectures:** *SEG-sponsored Distinguished Lectures on geophysical topics of high interest are presented in dozens of locales throughout the world.*

▸ **Regional Lectures:** *This new program brings geophysical topics of relevance to geophysicists in local regions around the world.*

▸ **Annual Meeting:** *The SEG Annual Meeting includes more than 500 technical paper presentations covering the latest developments in the geosciences.*

▸ **Geoscience Center:** *The SEG Geoscience Center in Tulsa, OK, captures the history of exploration geophysics and provides visitors young and old with hands-on learning experiences. The center also develops and distributes K-12 Earth Science teaching aids. With its online presence and in partnership with SEG sections, the Geoscience Center brings youth outreach programs and resources to members and the public around the world.*

Foundation

▸ *As an integral partner of SEG, the Foundation and its generous donors work to help support programs and projects directly related to the mission and vision of SEG. These mission-related programs benefit our professional and student members, support projects within our global community, and teach and inspire the geoscientists of tomorrow. All programs fall into the following broad categories:*

- PROFESSIONAL DEVELOPMENT
- STUDENT SUPPORT
- YOUTH OUTREACH

SEG Foundation

Recognizing the Remarkable

▸ Maurice Ewing Medal: *The recipient of this award is recognized for having made major contributions to the advancement of the science and the profession of exploration geophysics.*

▸ Virgil Kauffman Gold Medal: *This award is given to an individual who has made an outstanding contribution to the advancement of the science of geophysical exploration as manifested during the previous five years.*

▸ Cecil Green Enterprise Award: *The Society names an individual who has demonstrated courage, ingenuity, and achievement while risking his or her own resources and future in developing a product, service, organization, or activity which is recognized as a distinct and worthy contribution to the industry.*

▸ Reginald Fessenden Award: *Since its inception, this award recognizes an individual who has made a specific technical contribution to exploration geophysics, such as an invention or a theoretical or conceptual advancement.*

▸ J. Clarence Karcher Award: *A young geophysicist (younger than 35 years of age) of outstanding abilities is given this award for significant contributions to the science and technology of exploration geophysics.*

▸ Distinguished Achievement Award: *This award is given to a company, institution, or other organization for a specific technical contribution or contributions, which have substantially advanced the science of exploration geophysics.*

▸ Life Membership and Honorary Memberships: *Awarded to members of SEG for special achievements within the profession. Other Society awards are Special Commendation, Best Student Paper, Best Student Poster, Best Paper Presented at Annual Meeting, Best Poster Presentation at Annual Meeting, Best Paper in* GEOPHYSICS, *Best Paper in* THE LEADING EDGE, *and Distinguished Lecturer.*


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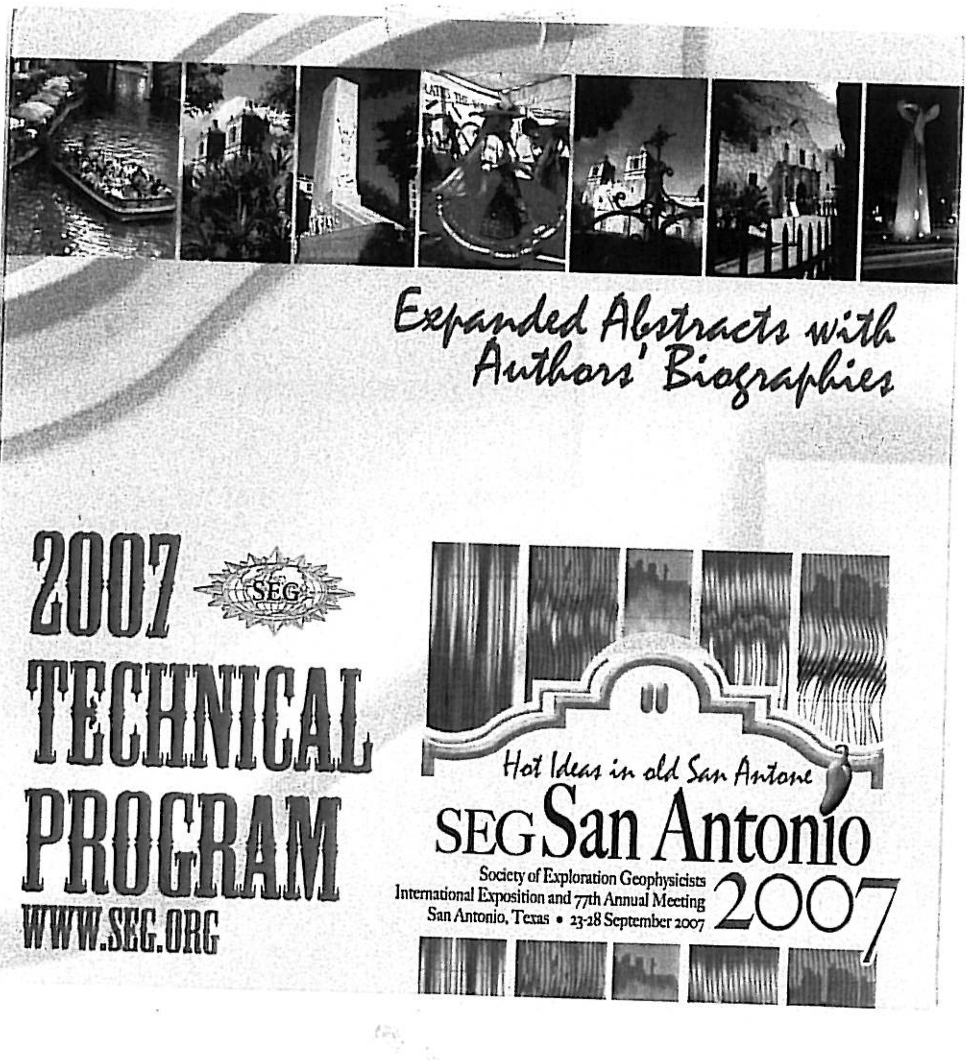
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