Journal of Advanced Research (2016) **7**, 515–524

Cairo University

Journal of Advanced Research

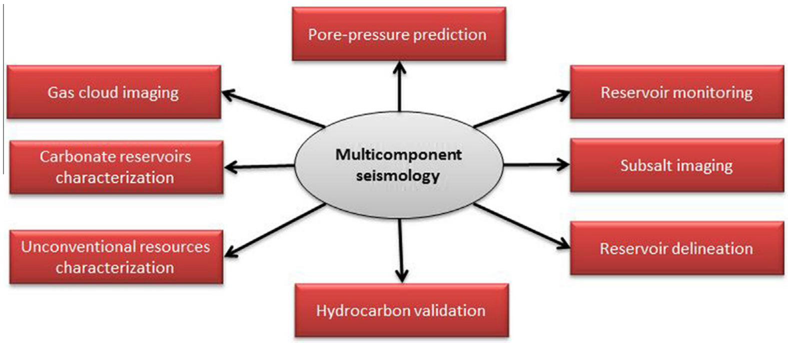
REVIEW

A review on multicomponent seismology: A potential seismic application for reservoir characterization

Mohammed Farfour [*], **Wang Jung Yoon**

Geophysical Prospecting Lab, Energy and Resources Engineering Dept., Chonnam National University, Gwangju, South Korea

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 18 August 2015
Received in revised form
25 November 2015
Accepted 27 November 2015
Available online 30 November 2015

ABSTRACT

Searching for hydrocarbon reserves in deep subsurface is the main concern of wide community of geophysicists and geoscientists in petroleum industry. Exploration seismology has substantially contributed to finding and developing giant fields worldwide. The technology has evolved from two to three-dimensional method, and later added a fourth dimension for reservoir monitoring. Continuous depletion of many old fields and the increasing world consumption of crude oil pushed to consistently search for techniques that help recover more reserves from old fields and find alternative fields in more complex and deeper formations either on land and in

---

[*] Corresponding author. Tel.: +82 10 28083101; fax: +82 (62) 530 1729.
E-mail addresses: m84.farfour@chonnam.ac.kr, m84.farfour@gmail.com (M. Farfour).

Peer review under responsibility of Cairo University.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.jare.2015.11.004

Keywords:
Multicomponent seismology
P-wave
Shear wave
Converted wave
Recent applications
Reservoir

offshore. In such environments, conventional seismic with the compressional (P) wave alone proved to be insufficient. Multicomponent seismology came as a solution to most limitations encountered in P-wave imaging. That is, recording different components of the seismic wave field allowed geophysicists to map complex reservoirs and extract information that could not be extracted previously. The technology demonstrated its value in many fields and gained popularity in basins worldwide. In this review study, we give an overview about multicomponent seismology, its history, data acquisition, processing and interpretation as well as the state-of-the-art of its applications. Recent examples from world basins are highlighted. The study concludes that despite the success achieved in many geographical areas such as deep offshore in the Gulf of Mexico, Western Canada Sedimentary Basin (WCSB), North Sea, Offshore Brazil, China and Australia, much work remains for the technology to gain similar acceptance in other areas such as Middle East, East Asia, West Africa and North Africa. However, with the tremendous advances reported in data recording, processing and interpretation, the situation may change.

Mohammed Farfour is a Postdoctoral Researcher at the Geophysical Prospecting Lab and part-time Lecturer at the Department of Energy and Resources Engineering, Chonnam National University, Gwangju, South Korea. He holds 2nd Cycle University Degree from Boumerdes University, Algeria, and PhD degree from Chonnam National University, Korea. After graduation, he worked for National Company of Geophysics in Algeria as a Reservoir Geophysicist. In the same period, he was a part-time Lecturer at the Department of Geophysics, Boumerdes University. He published several papers in novel applications of Geophysics in Reservoir Characterization and received young geoscientist awards from the Society of Exploration Geophysicist of Japan in 2011 and from Schlumberger in 2014. His area of research includes Reservoir Geophysics (Seismic Attributes, AVO, Inversion techniques, Multicomponent Seismology), Borehole Geophysics (Well Logging and Borehole Seismic). He is a member of the American Association of Petroleum Geologists (AAPG), Society of Exploration Geophysicist (SEG) and European Association of Geoscientists & Engineer (EAGE).

Wang Jung Yoon is a Professor of Geophysics at the Department of Energy & Resources Engineering, Chonnam National University, Gwangju, South Korea. He holds a BS degree in Resources Engineering, MS in Electromagnetic Method and PhD degree in Seismic Geotomography from Seoul National University. He joined Chonnam University since 1985. He supervised a large number of PhD and MS students in variety of geophysical fields (Resistivity, Gravity, Electromagnetic, Tomography, Seismic, and Remote Sensing). He has published many papers in Korean and international conferences and journals. He is a member in Korean Society of Earth and Exploration Geophysicists (KSEG), Society of Exploration Geophysicist (SEG), Korean Society of Mineral & Energy Resources Engineering (KSMER).

Introduction

We have come a long way since the 1920s when vibrations were first induced in the subsurface and transformed into interpretable information about oil reserves. Since then, great efforts were undertaken to understand the science behind seismology and integrate its use into oil industry which resulted in discovering giant oil fields in many basins in the world. The technology has evolved from two to three-dimensional and later to four-dimensional seismic where three-dimensional seismic data are recorded over time for comparison and monitoring bulk rock properties related to fluid changes (production/injection). With the increasing demand for new reserves to ensure the world energy supply, geoscientists started addressing objectives in deep onshore and offshore such as geological formations near salt domes, subsalt formations, tight sands, and source rocks (Fig. 1). In such environments, using one single component (P-wave) demonstrated numerous limitations. Thus, multicomponent seismology came to overcome these limitations and provide more complete image and characterization of subsurface.

Recording multimode data dates back to the early 1970s when Conoco began to test and demonstrate its horizontal vibrator. The development of the technology has slowed during the early 1980s. In the late 1980s, the technology gained attention from academia (e.g. CREWES Project at the University of Calgary, Canada; RCP Colorado School of Mines, United States (US); and Delphi at Delft University, Netherlands) and from a number of service and oil companies [1]. As a result, several case studies have been published from onshore US (e.g. [2,3]) and Canadian basins (e.g. [4,5]) where the technique was evolved and first applied, as well as from other geographical areas outside North America e.g. the North Sea (e.g. [6]). With the advent of land and marine seismic data acquisition and processing particularly the development of the digital multicomponent sensors, more successful applications have been reported in many new fields worldwide such as those in the Gulf of Mexico [7–9], Canada (e.g. [10,11]); the North Sea (e.g. [12–14]); China (e.g. [15–17]); the Caspian Sea [18]; the North Africa [19,20]; and the Middle East [21–23].

Multicomponent seismology: new information leads to new reserves

Seismic exploration for hydrocarbons starts by emitting a compressional P-wave using vertical vibrational truck or dynamite. The reflected wave's signal, once appropriately acquired and well processed, can carry information about structure, lithology, saturating fluids (water, oil, gas) of subsurface formations. As attention has been drawn to deeper, old and complex subsurface objectives, P-wave has encountered numerous

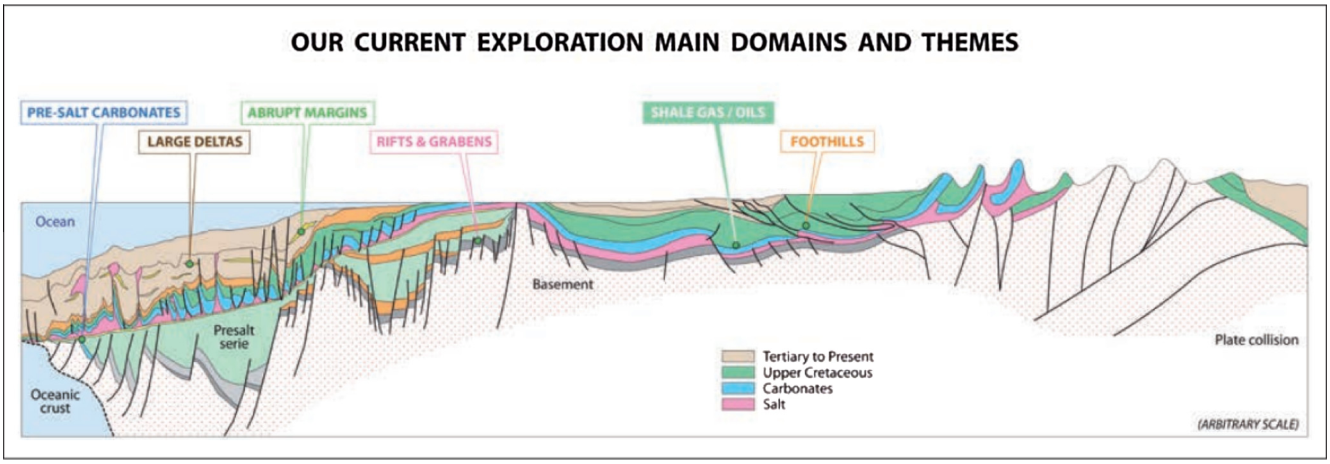


Fig. 1 Examples of geological formations targeted for hydrocarbon exploration [50].

difficulties in imaging subsalts, formations beneath volcanic rocks, formations with low acoustic impedance contrast. Thus, generating and recording more complete vibrations in the earth to complement efforts done in P-wave was introduced and demonstrated to be a promising solution.

Unlike P-wave that can be affected by changes in rock's rigidity, density and compressibility, S-wave is sensitive only to rock rigidity and density as illustrated in Eqs. (1) and (2):

$$V_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} \tag{1}$$

$$V_s = \sqrt{\frac{\mu}{\rho}} \tag{2}$$

where μ, λ are Lamé parameters of rigidity (shear modulus), and incompressibility (inverse of bulk modulus) respectively. ρ is the density of the rock. In addition, while the P-wave compresses volumes, S-wave only modifies their shapes (Fig. 2). The latter key difference was learned since the early days of S-wave [24] and provides nowadays great assistance to geoscientist to differentiate fluid-saturated formation expressions from expressions pertaining to lithological changes, and to image gas cloud zones where gas traces mask subsurface formations. This has resulted in finding new reserves, hundreds of millions of barrels of oil and tens of billions of cubic feet of natural gas that have not been seen using P-wave alone [25]. Another important aspect of the S-wave is its ability to image rock fracture densities and orientation. The knowledge of fracture direction and fracture density can be critical to exploration and characterization success. Since shear waves are sensitive to a rock's shear modulus, they respond to changes in rock stiffness and strength. When stiffness and strength changes have preferential orientations, shear waves undergo birefringence (shear wave splitting). This can occur also in the presence of fractures in the rock [26,27]. In fact, unlike isotropic medium where S-wave polarizations (SV and SH) are determined by source–receiver geometry, in fractured medium as S-wave passes through fractures, it splits into two S-waves. The first is fast S-wave, polarized parallel to the direction of fractures. The second is slow S-wave, perpendicular to the fractures plane. It is standard practice to measure travel time variation of both waves (SV and SH) recorded at different acquisition azimuths as shown in Fig. 3. For SV section, angle at which the wave shows later arrival time is interpreted to be the direction perpendicular to fractures. On the other hand, angle at which the wave arrives at earlier time is attributed to be the direction of fractures. In the SH section, amplitude drops to zero and phases reversal can be observed at both directions determined on SV section [28]. Note that also micro-cracks aligned with local stress direction can be detected by these polarization analysis methods.

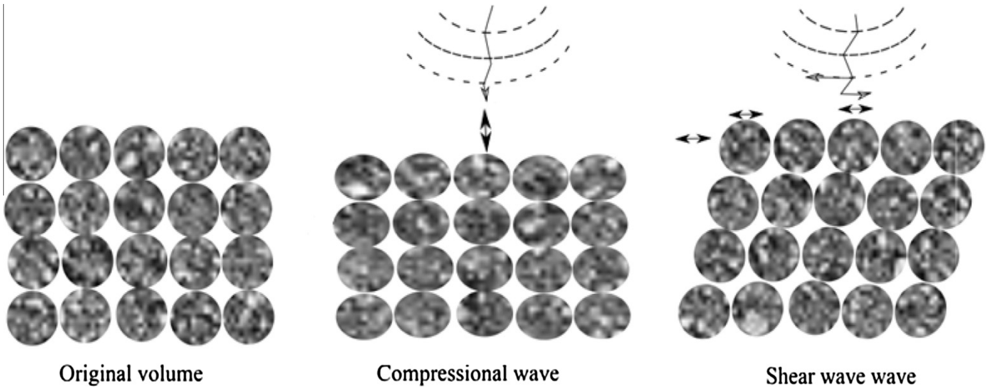


Fig. 2 Deformations resulting from P and S wave propagation.

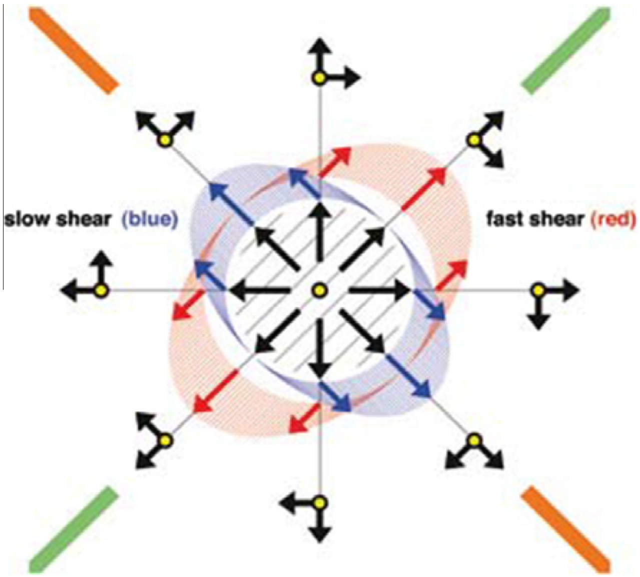


Fig. 3 Illustration of S-wave splitting from Bale et al. [27]. Black arrows in the center represent converted wave generated from P-to-S conversion point. Fast and slow S-waves are shown in blue and red colors, respectively.

Multicomponent data acquisition, processing and interpretation

There is a variety of multicomponent seismology geometries in industry. This involves, for example 3C/2D, 3C/3D, 3C/4D, 4C/2D, 4C/3D, 4C/4D and 9C3D (3-component shear source recorded by 3-component sensor). Using full wave-field vibrational sources (3C), various shear-wave (S-wave) images can be made from 9C3D seismic data (Table 1). Only one S-wave image can be produced from 3C/3D survey, that being a Converted-wave (C-wave) image. However, as near surface proved to be generally unfriendly to S-wave and causes increasing costs in S-wave acquisition, processing and interpretation, P-wave with its generated components (3C) is winning out over 9-C [29].

Conventional coil geophones have been used as the standard sensors since the beginning of seismic exploration. With the need to record more motions, special multicomponent sensors have been developed for land and for marine seismic.

Current marine multicomponent sensors, known as 4C, were first used commercially in 1996. The recording system uses traditional air-gun sources to generate pressure wave (P). The 3C receivers are placed on the sea floor to record the 3-D vector field (Fig. 4). The fourth component is a hydrophone recording the pressure field. With advances in marine seismic equipment, seismic data can be recorded at thousands of meters in deep sea. For example, recent autonomous wireless ocean-bottom recorders (OBX) by Geospace Technologies can operate at 3400 m deep in the sea, while the new ocean bottom seismometers (MicrOBS) by Sercel can work down to a deep of 6000 m.

In land seismic acquisition, a variety of innovative 3C sensors have been developed for multicomponent seismology applications by different manufacturers (Geospace Technologies, Sercel, Input/Output and others). Micro Electro Mechanical System, or MEMS offered by Sercel and Input/Output Inc. provides many advantages over common coil-based geophones. These include but not limited to the following: single point recording, direct digital output, improved vector fidelity, and measurement of sensor tilt [30]. Note that advances have also been achieved in S-wave source development; however, their applications are still predominantly in research mode [25].

Toward the end of the 1980s, experience showed that P-wave can be an inexpensive source of converted S-wave. This came from observations in borehole seismic measurements [2]. Compressional waves undergo partial conversion to S-wave at the subsurface interfaces and can be detected as a normal S-wave. Thus, it is very common practice in today industry to use P-wave sources to generate both P-wave and converted P to vertical S-wave (P–SV).

Recently, experiments by Hardage and Wanger [31] have demonstrated that other S-wave modes can be produced using vertical vibrators namely, SV–P and SH–SH. The authors also showed that S-wave generated from P-wave sources has wider range of frequencies, thus higher resolution than direct S-waves produced by horizontal vibrators.

The fundamentals of converted wave processing have been developed in the 1980s to early 1990s. Processing PS-waves data are known to be more complicated than those of processing P-waves. This stems from the flowing fact. For a P-wave reflecting at a geological interface, according to Snell's law, the reflection angle equals the incidence angle. Therefore, the P-wave takes advantage of the fact that reflection point is at the mid-point between source and receiver. This is not the case for PS-wave. An S-wave always reflects with a smaller angle than the P-wave does, as a result of its low velocity Vs relative to Vp (Fig. 5). Therefore, the conversion point is closer to the receiver. This asymmetry makes the PS reflection points vary in depth as a function of P and S velocities for any given source–receiver offset, and thus complicates the processing of the converted wave data.

Other major differences with P-wave data processing involve the partitioning of energy into orthogonally polarized components, and also the differences in geometries and conditions of source and receiver. For example, in the case of sea-

Table 1 Different components measured in 3D/9C. In case of 3D/3C only the last raw is applicable.

	Source	Receiver	Captures modes
9C	XYZ	XYZ	P–P, P–SV, SV–SV, SV–P, SH–SH,
6C	YZ	XYZ	P–P, P–SV, SH–SH
4C	Z	XYZH	P–P and P–SV
3C	Z	XYZ	P–P and P–SV

Where SV and SH refer to vertical and horizontal S-wave. X, Y and Z are the horizontal and vertical recording directions, respectively. Note that for marine seismic a hydrophone H is used with the three components XYZ.

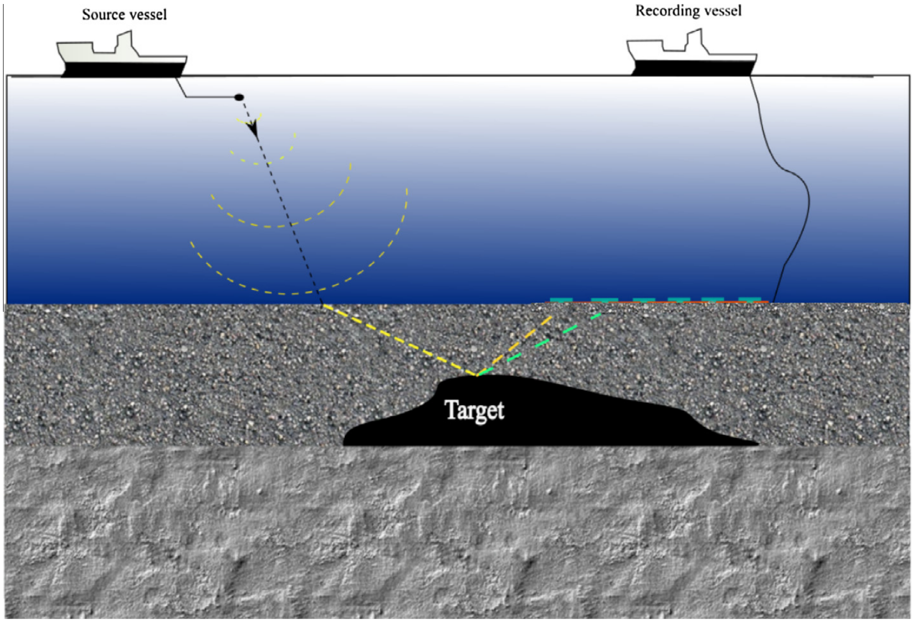


Fig. 4 Marine multicomponent sea-floor data acquisition. The recording vessel is stationary and records motion detected by sensors planted in the sea-floor.

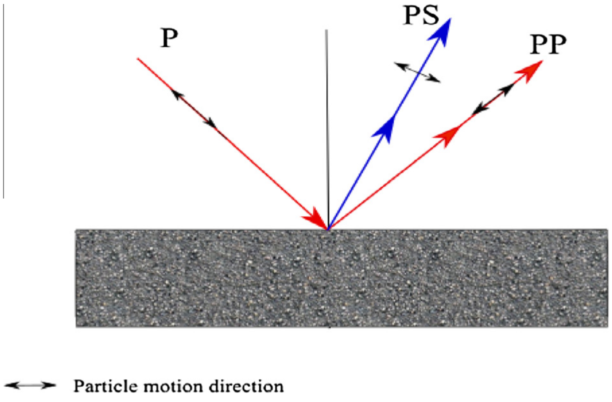


Fig. 5 Incident P-wave and its corresponding reflected P and converted S-waves.

floor acquisition, sources are towed near the surface whereas receivers are placed at the deep sea floor [32]. The improvements in PS understanding and success in PS data processing have allowed retrieving another converted wave that has been ignored for decades. SV–P wave has been considered for long time as undesired noise. However, experience proved that SV–P is as informative as P–SV and as valuable as it. In addition, the former has another advantage over the latter. In fact, SV–P can be recorded using conventional P-wave receivers and extracted from P-wave without having to acquire new seismic data using multicomponent sensors [33].

From interpretation perspective, it is worth to note that the integration of PS-wave was not straightforward process. Basically, PP and PS sections display different seismic reflections, from the same geological formations, but at different times (Figs. 6 and 7). This is due to the fact that the former measures contrast in P impedance (density × P-wave velocity), while the latter records contrast in S impedance (density × S-wave velocity). Time in PS sections measures the travel time required for the wave to descend as a P-wave and reflects as an S-wave. As S-waves are slower than P-waves, PS-times are larger than PP-times. Thus, PS sections appear stretched relative to PP sections (Figs. 6 and 7). Typically, both P-wave and converted wave data must be converted to depth using synthetic traces derived from well control. Derived time–depth functions are then used to correlate P-wave events with PS-events and to compress PS sections for comparison with their corresponding PP images. This process of events matching is known as registration. Although the squeezing does improve the apparent vertical resolution, but it often remains difficult to register all events in the sections. The extracted travel time measurements from picking the P and PS events can be used to calculate Vp/Vs ratio maps through the following relationship:

$$\lambda = \frac{2\Delta t_{ps} - \Delta t_p}{\Delta t_p} \tag{3}$$

where Δt_p and Δt_{ps} are the interval travel time of PP and PS waves, respectively, measured between two reflections of interest.

Note that several workflows have been proposed to correlate S-wave reflections with their P-wave counterparts and integrate PS data in common qualitative and quantitative interpretation of workstations (e.g. [34–37]).

Another challenge while deploying PS data is how to invert the data from both waves for elastic rock properties. Several approaches have been introduced in this regard. Stewart [38] suggested inverting both data jointly using least squares approach which can be accomplished after establishing a relationship between PP and PS reflections. Hampson et al. [39] proposed a model-based approach which is an extension to their work in model-based inversions. Dual inversion is also a simultaneous inversion technique proposed by Garotta et al. [40]. The latter approach converts simultaneously PP and PS seismic data to Vp/Vs and elastic rock properties using simulated annealing scheme.

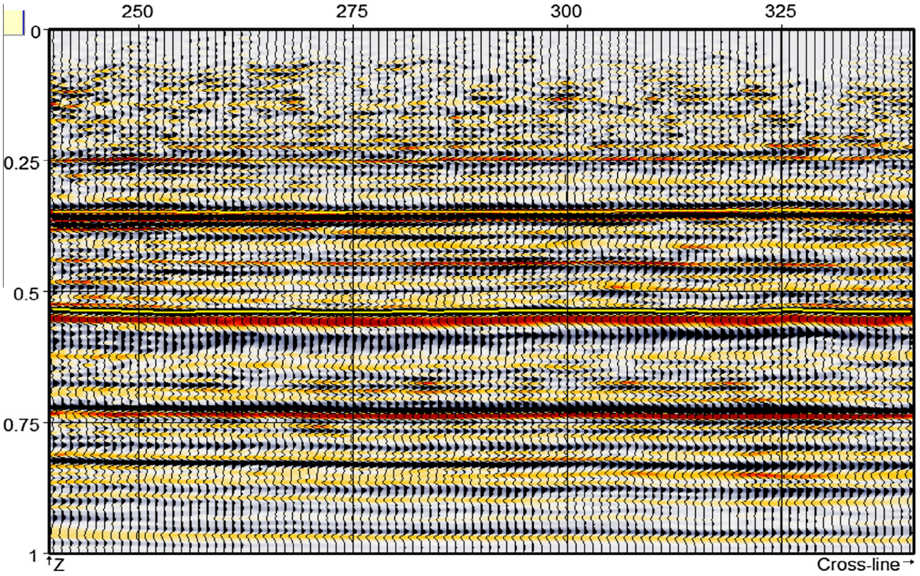


Fig. 6 Target horizons (reservoir's top and base) interpreted in P-wave data are shown in yellow.

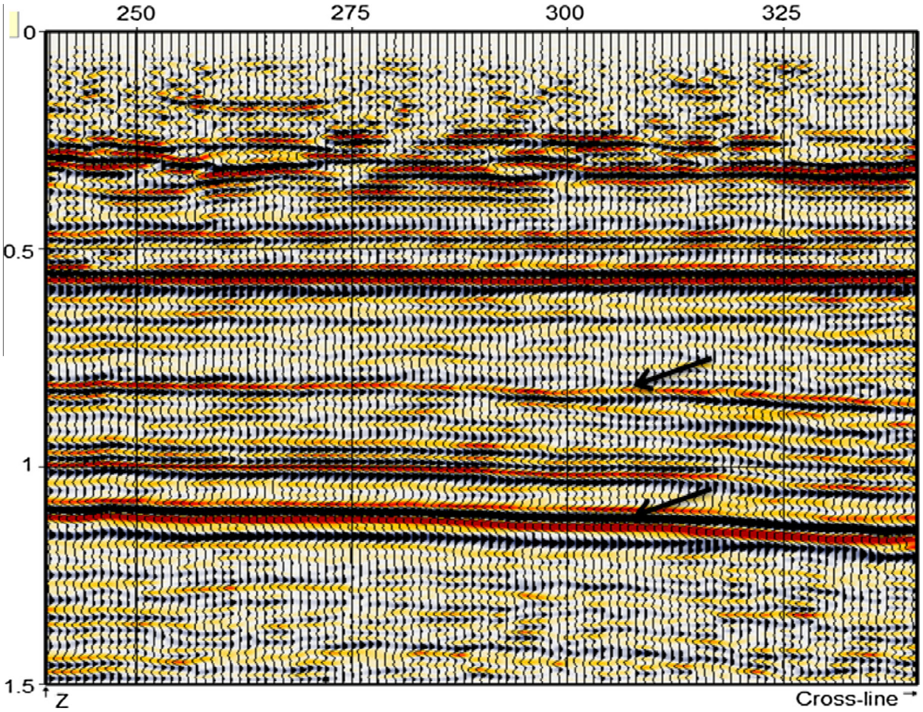


Fig. 7 S-wave before being calibrated to PP time. Notice that targets (marked with black arrows) are located at later time in the PS section relative to the above PP section.

Applications of multicomponent seismology (Converted wave)

Recently, multicomponent seismology has gained wide acceptance due to increasing number of successful case studies in many areas around the globe. Table 2 shows some recent applications of the technique in many regions in the world. Figs. 8–10 are selected from cases in Table 2. The first example is from Offshore North Sea [43]. The target is a hydrocarbon-bearing sandstone reservoir. Due to the low contrast impedance between the reservoir and the surrounding rocks, P-wave data failed to image the reservoir reflection. Converted wave has showed clear anomalies associated with the reservoir. Interestingly, the reservoir seismic response to the converted wave is found consistent with well logs information [43]. In the second example from Offshore Brazil, a flat spot associated with fluid contact is clearly visible on the P-wave image. The anomaly is not found on the converted wave section. This was attributed to the fact that S-wave does not respond to fluid

Table 2 Some applications of the technology with examples from the world are summarized in Table 1.

Application	Geographical area
Gas cloud imaging	1. East Cameron gas fields, Gulf of Mexico [7] 2. Campos Basin, Offshore Brazil [41] 3. Tommeliten Alpha Field, Norwegian sector of North Sea [42]
Reservoir delineation	1. Sulige gas field, Erdos basin, China [17] 2. Shengli oilfield, China [15] 3. UK sector of North Sea [14]
Hydrocarbons validation	1. Nakhla oilfield, Libya [19] 2. Santos Basin, Offshore Brazil [41] 3. Sulige gas field, China [17]
Imaging of targets of poor PP reflectivity	1. Valhal field, North Sea, Norway [25] 2. Campos Basin, Offshore Brazil [41] 3. Alba field, UK sector of North Sea [41]
Fracture characterization	1. Onshore US [28] 2. South Algeria [20] 3. Sichuan Basin, China [16]
Carbonate reservoirs characterization	1. Idd El Shargi North Dome Field in offshore Qatar [22] 2. Natih field, Oman [21] 3. Offshore Abu Dhabi, UAE [23] 4. Cantarell oilfield, the Gulf of Mexico, Mexico [8]
Unconventional resources (shale's oil/gas, tight sand reservoirs)	1. British Colombia, Canada [10] 2. Marcellus Shale, Pennsylvania, US [44] 3. Shaunavon Tight Oil Reservoir, Canada [11]
Heavy oil characterization and monitoring	1. Alberta, Canada [27] 2. Manitou Lake, Canada [45] 3. Ross Lake heavy oilfield in Saskatchewan, Canada [46] 4. Faja Petrolífera del Orinoco, Venezuela [47]
Reservoir monitoring	1. Delhi Field, Louisiana [48] 2. Ekofisk Field, Norwegian sector of North Sea [12] 3. Valhal field, Norwegian sector of North Sea [13]
Pore pressure prediction	1. Gulf of Mexico, US [49] 2. Atlantis field, Gulf of Mexico [9] 3. Valhal field, North Sea, Norway [13]

presence in the rock. This key difference helped in validating hydrocarbon associated anomaly [41]. The last example depicts the effect of fractures on S-wave propagation. Both radial and transverse component data are displayed. Traces recorded at different angles are shown. Note that the shortest arrival time is observed at 80–260° which is interpreted to be the direction of the fractures. At this direction, transverse component amplitude nulls between polarity reversals as there is no transverse component produced [27].

Discussion

It is readily seen from the real examples above that multicomponent seismology proved to have the potential to overcome many limitations and difficulties that P-wave encountered in complex geological conditions.

As a result of the tremendous advent in acquisition, processing and interpretation of material and techniques, the technology is getting wide acceptance and increases in its understanding and applications in academia as well as in industry. As example, multicomponent is increasingly being deployed in China and offshore Brazil to solve problems faced with P-wave conventional applications and to reveal more features about many promising fields there. In North Sea, several permanent monitoring systems have been installed in the seafloor to monitor reservoirs production and water injection. Due to the excellent repeatability, the data are being processed and interpreted within weeks after final shot. On the other hand, the technology is still being slowly adopted in some

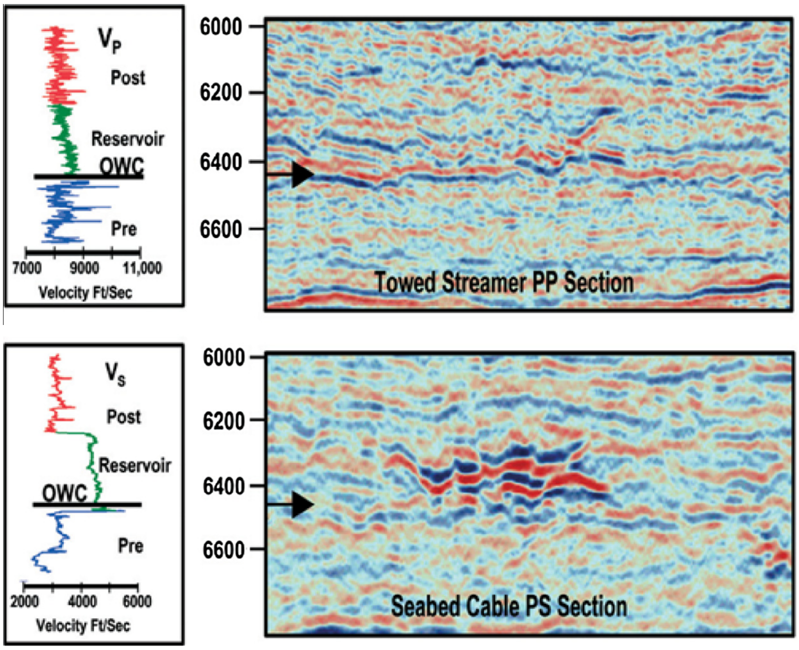


Fig. 8 Data from Alba field. P-wave (up) failed to image the reservoir due to low impedance contrast. Note how reservoir reflections are appearing clear in PS section [43].

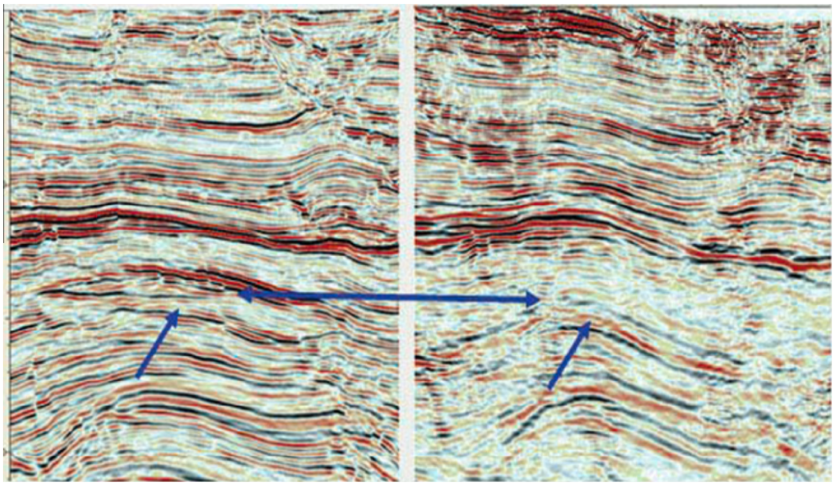


Fig. 9 Example from Offshore Brazil. On the P-wave section (left), notice the flat spot, associated with oil/water contact, and the gas cap above it. These features are not, and should not be, visible on the C-wave section (right). Their absence helps validate them on the P-wave section [41].

other areas such as North and West Africa, Middle East, and Southeast Asia regions. Although there have been some newly published pilot studies (e.g. [19,20]), much work remains before the technology becomes an accepted application in the characterization of reservoirs in these areas.

Possibly, the fact that P-wave sources proved to have the potential to produce different modes of S-waves will open the doors to deploy multicomponent seismology in new areas where the technology was not considered because of environmental constraints, less availability of horizontal sources or prohibitively high data acquisition costs.

Currently, attention is being paid to the possibility of extracting SV–P from P-wave data which would eliminate the need to acquire multicomponent data from the field. Converted wave data will be extracted directly from P-waves recorded into vertical geophones.

It is important to note that articles published recently about the multicomponent seismology applications and examples are too numerous to cite. Nearly 90% of the published successful applications come from US basins, Canada, North Sea, China, and Latin America.

Conclusions

The remarkable success of multicomponent seismology is indeed the result of tremendous efforts and collaboration

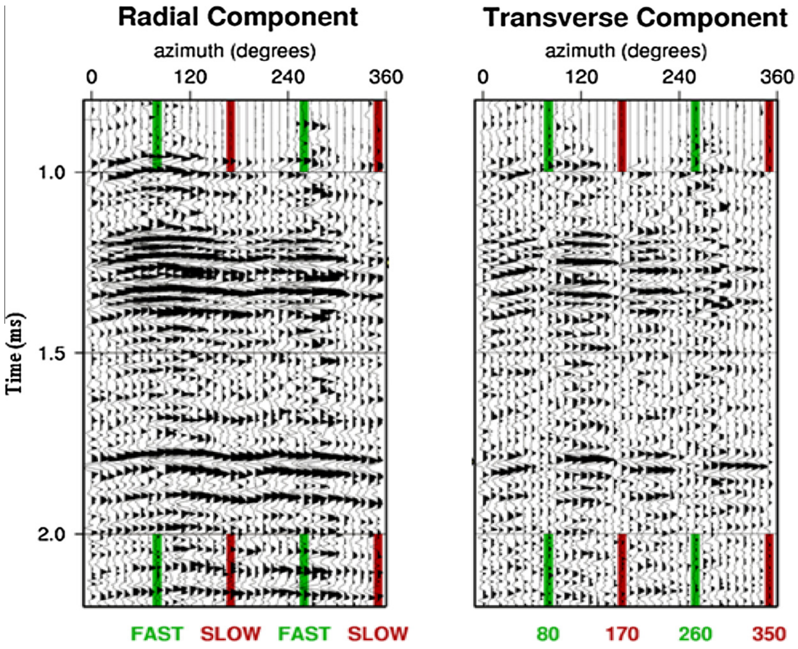


Fig. 10 Fractures orientation detection using shear wave splitting from Mattocks et al. [28]. Fast S-wave's azimuth (shortest travel time) indicates fractures direction. In the transverse component section, phase reversal occurs at the same angle where radial component showing shortest arrival time.

between different players from academia and industry (contractors and clients). The collaboration took place in a variety of disciplines from acquisition, land and sea-floor instrumentation, to processing and interpretation. This has greatly served the world by extending oil reserves life and supply for decades to come.

Conflict of interest

The authors have declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

Acknowledgments

We would like to thank Hampson-Russell software for providing the data used in this study. Our thanks go also to Korean Government for their support under the BK21 Plus program.

References

[1] Hardage BA, DeAngelo MV, Murray PE, Sava D. Multicomponent seismic technology. Tulsa, OK: Society of Exploration Geophysicists; 2011.
[2] Iverson WP, Fahmy BA, Smithson SB. VpVs from mode-converted P–SV reflections. Geophysics 1989;54:843–52.
[3] Frasier C, Winterstein D. Analysis of conventional and converted mode reflections at Putah Sink, California using three-component data. Geophysics 1990;55:646–59.
[4] Geis WT, Stewart RR, Jones MJ, Katapodis PF. Processing, correlating, and interpreting converted shear waves from borehole data in southern Alberta. Geophysics 1990;55(6):660–9.
[5] Lawton DC. A 9-component refraction seismic experiment. Can. J. Explor. Geophys. 1990;26:7–16.
[6] Berg E, Svenning B, Martin J. SUMIC—a new strategic tool for exploration and reservoir mapping. In: 56th EAGE conference & exhibition, expanded abstracts; 1994. p. 653–6.
[7] Nahm JW, Duhon MP. Interpretation and practical applications of 4C–3D seismic data. East Cameron gas fields, Gulf of Mexico. TLE 2003:300–9.
[8] Stewart R. Methods of multicomponent seismic data interpretation. In: 70th EAGE conference & exhibition – Rome, Italy; 2009.
[9] Kao JC, Tatham RH, Murray PE. Estimating pore pressure using compressional and shear wave data from multicomponent seismic nodes in Atlantis Field, Deepwater Gulf of Mexico. SEG technical program expanded abstracts; 2010. p. 1641–5.
[10] Al-Zahrani A, Lawton D. Interpretation of 3D multicomponent seismic data for investigating natural fractures in the Horn River Basin, northeast British Columbia. CREWES Res Rep 2010;22:1–14.
[11] Sandanayake Ch, Bale R. Application of shear-wave splitting analysis to fracture characterization for a Shaunavon tight oil reservoir. CSPG CSEG CWLS convention; 2011.
[12] Van Dok R, Gaiser J, Probert T. Time-lapse shear wave splitting analysis at Ekofisk field. In: Paper G046, presented at the 66th EAGE annual conference and exhibition, Paris, France; 2004.
[13] Van Gestel JP, Kommedal JH, Barkved OI, Mundal I, Bakke R, Best KD. Continuous seismic surveillance of the Valhall Field. TLE 2008:260–5.
[14] Özdemir H, Flanagan K, Tyler E. Lithology and hydrocarbon mapping from multicomponent seismic data. Geophys Prospect 2010;58:297–306.
[15] Qian Z, Chapman M, Li X. Use of multicomponent seismic data for oil-water discrimination in SEG technical program expanded abstracts; 2009. p. 4282–3.

[16] Jianming T, Yue H, Xiangrong X. Application of converted wave 3D/3-C data for fracture detection in a deep tight-gas reservoir. TLE 2009;28:826–37.

[17] Zhao B, Wang D, Shi S, Shen X, Wang P. Three-component converted-wave data inversion and application: a case study of Sulige gas field, China. SEG technical program expanded abstracts; 2011. p. 1759–63.

[18] Bouska J, Johnston R. The first 3D/4C ocean bottom seismic surveys in the Caspian Sea: acquisition design and processing strategy. TLE 2005;24:910–21.

[19] Hanitzsch C, deVincenzi L, Heerde W, Michel JM, Semond D. Dual inversion applied to 2D multi-component seismic data onshore Libya. First Break 2007;25:49–54.

[20] Piazza JL, Donati M, Martin FD, Castro J, Gordillo C, Belhouchet T, et al. Multi-component 3D seismic – a successful fracture characterization in Algeria – interpretation of faults and fractures. In: 76th EAGE conference & exhibition; 2014.

[21] Potters J, Groenendaal H, Oates S, Hake J, Kalden A. The 3D shear experiment over the Natih field in Oman. Reservoir geology, data acquisition and anisotropy analysis. Geophys Prospect 1999;47:637–62.

[22] Maili E, Carmen Negulescu C. Multi-component seismic applications for maximizing efficiency and production. In: International petroleum technology conference, 7–9 December, Doha, Qatar; 2009 [IPTC-13692-MS].

[23] Eilly J, Shatilo Andrew P, Shevchek Z. The case for separate sensor processing: meeting the imaging challenge in a producing carbonate field in the Middle East. TLE 2011;29:1240–9.

[24] Ensley RA. Comparison of P- and S-wave seismic data: a new method for detecting gas reservoirs. Geophysics 1984;49:1420–31.

[25] Gaiser J, Strudley A. Acquisition and application of multicomponent vector wavefields: are they practical? First Break 2005;23:61–7.

[26] Barkved O, Bartman B, Gaiser J, Van Dok R, Johns T, Kristiansen P, Probert T, Thompson M. The many facets of multicomponent seismic data. Schlumberger Oilfield Rev. 2004; Summer:42–56.

[27] Bale R, Gratacos B, Mattocks B, Roche S, Poplavskii K, Li X. Shear wave splitting applications for fracture analysis and improved imaging: some onshore examples. First Break 2009;27 (9):73–83.

[28] Mattocks B, Gray D, Todorovic-Marinic D, Dewar J, Bale R. More powerful fracture detection: integrating P-wave, converted wave, FMI and everything. In: EAGE 67th conference & exhibition – Madrid, Spain; 2005.

[29] Stewart R. The measure of full-wave motion: an overview of multicomponent seismic exploration and its value. CSEG Recorder 2009;34(10):34–8.

[30] Kendall R. Advances in land multicomponent seismic: acquisition, processing and interpretation. CSEG Recorder 2006;31:65–75 [special edition].

[31] Hardage B, Wagner D. S–S imaging with vertical-force sources. Interpretation 2014;2:SE29–38.

[32] Caldwell J, Christie P, Engelmark F, McHugo S, Özdemir H, Kristiansen P, MacLeod M. Shear waves shine brightly. Schlumberger Oilfield Rev. 1999;Spring:2–15.

[33] Hardage B, Sava D, Wagner D. SV–P: an ignored seismic mode that has great value for interpreters. Interpretation 2014;2: SE17–27.

[34] Gaiser J. Multicomponent Vp/Vs correlation analysis. Geophysics 1996;61:1137–49.

[35] Gaiser J. Velocity-based wavelet corrections for domain transformation. In: 73rd Conference & exhibition, EAGE, extended abstract B004; 2011.

[36] Gaiser J, Verm R, Chaveste A. Pseudo S-wave broadband response of C-waves after domain change. TLE 2013;32:50–62.

[37] Bansal R, Matheney M. Wavelet distortion correction due to domain conversion. Geophysics 2010;75(6):V77–87.

[38] Stewart RR. Joint P and P–SV inversion. CREWES Res. Rep. 1990;2.

[39] Hampson D, Russell B, Bankhead B. Simultaneous inversion of pre-stack seismic data. Society of exploration geophysicists ann. mtg. abstracts; 2005.

[40] Garotta R, Granger PY, Dariu H. Combined interpretation of PP and PS data provides direct access to elastic rock properties. TLE 2002;21:532–5.

[41] Cafarelli B, Randazzo S, Campbell S, Fiori Fernandes Sobreira J, Gallotti Guimaraes MA, Rodriguez C, et al. Ultra-deepwater 4-C offshore Brazil. TLE 2006;25(4):474–7.

[42] Granli J, Arnsten B, Sollid A, Hilde E. Imaging through gas-filled sediments using marine shear wave data. Geophysics 1999;64:668–77.

[43] MacLeod MK, Hanson RA, Bell CR, McHugo S. The Alba field ocean bottom cable seismic survey: impact on development. TLE 1999;18:1306–13012.

[44] Far M, Hardage B. Interpretation of fractures and stress anisotropy in Marcellus Shale using multicomponent seismic data. Interpretation 2014;2(4):SE105–15.

[45] Varga R, Stewart R. Searching for sand in Saskatchewan: Manitou Lake 3C–3D Seismic Project. CSPG CSEG CWLS Conv. 2008:427–31.

[46] Stewart RR, Xu C, Soubotcheva N. Exploring for sand reservoirs using multicomponent seismic analysis. J Seismic Explor 2007;15(2):1–25.

[47] Calderon J, Ovalles A, Reveron J. Lithology delineation using 3D–3C seismic data. TLE 2014;31:792–6.

[48] Davis Th. Time-lapse multi-component seismic monitoring, Delhi Field, Louisiana. First Break 2015;33:2015.

[49] Sayers CM, Woodward MJ, Bartman RC. Predrill pore-pressure prediction using 4-C seismic data. TLE 2001;20:1056–9.

[50] Biteau J, Blaizot M, Janodet D, de Clarens Ph. Recent emerging paradigms in hydrocarbon exploration. First Break 2014;32:49–58.