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Chapter 11

Seismic Technology and Law: Partners or Adversaries?[1]

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Synopsis

Part 1 by Dr. John Pigott

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1 This article updates previously published articles: Owen L. Anderson, "Geophysical 'Trespass' Revisited," 5 *Tex. Wesleyan. L. Rev*. 137 (1999) and Owen L. Anderson and Dr. John D. Pigott, "3D Seismic Technology: Its Uses, Limits, & Legal Ramifications," 42 *Rocky Mt. Min. L. Inst.* 16-1 (1996). Professor Pigott prepared Part 1 of the article and Professor Anderson prepared Part 2.

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Part 2 by Professor Owen L. Anderson

Part 1
§11.01. Introduction: Posing the Problem.

During the past three decades, reflection seismic[3] technology has revolutionized the way people look at the earth, be it for academic study of the Earth or for the profitable extraction of its energy resources. There are two methods: one is termed 2D seismic (for two-dimensional) and is the classic approach, and the newer is termed 3D seismic (for three-dimensional). They are both powerful non-invasive (without drilling) methods for imaging the makeup of the earth much as one non-invasively (without surgery) images the human body using contemporary medical technology. Indeed, the quality of the image may be stated that 2D seismic

[3] While properly an adjective, we will occasionally use the term "seismic" as a noun. While seismic is not properly used as a noun, personnel in the oil and gas industry commonly use the term as both a noun and an adjective.

is to an x-ray two dimensional photo as 3D seismic is to a CAT-scan of the body's volume. In particular, the recent advances in seismic technology (specifically the 3D method) have been so powerful that they have changed the very way the petroleum industry conducts exploration and exploitation, and in the very way it thinks.

> The yearly increase in 3D seismic data collection has accelerated to the point that this wonderful new technology has significantly dropped the price per barrel to find oil. It has also resulted in surprising increases in the production of oil from existing fields. Perhaps the solution to the impending push to get more oil to market, faster, will come not from increased exploration success, but from new uses of 3D seismic data that maximize recovery efficiencies from existing oil and gas fields.[4]

Not surprisingly, as the use of 3D seismic technology expands and becomes routine within the industry, the value of seismic technology as a legal tool increasingly becomes of interest. But what exactly does this new technology offer? And what are some of its legal ramifications for resolving, as well as potentially causing, legal problems? That is, is the seismic method a protagonist or an antagonist of the law? For example, although the 3D seismic technique differs from 2D in providing much greater information with higher resolution, for proper subsurface imaging, 3D seismic acquisition design commonly requires it to be shot at distances well beyond the actual surface dimensions of the subsurface target, raising as never before potential trespass questions that extend beyond the targeted subsurface region.

We shall address these questions essentially in two parts: a technical summary followed by a legal discussion. The technical discussion can be used in two ways: for the casual reader, a quick reading of each subsection to gain a general understanding of the steps necessary to obtain accurate seismic information, or for the reader who desires to know more technical

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4 Wei He, *et al*.,"4D Seismic Monitoring Grows as Production Tool," *Oil & Gas J*., May 20, 1996, at 41 [hereafter He].

information, a careful study of the text followed by further study of the cited sources for detailed information.[5] The legal discussion focuses on three matters: (1) the potential relevance and use of 3D seismic data as evidence—a matter that is both exciting and, in some contexts,

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5 For further information on the 3D seismic method, *see*: "Salaries Rise Along With Prices," *American Association of Petroleum Geologists Explorer*, 1996, vol 17, no. 5, p. 10; J. L. Allen & C.P. Peddy, "Amplitutude Variation with Offset: Gulf Coast Case Studies," *Geophysical Development Series*, v. 4, Society of Exploration Geophysicists, Tulsa, 126 pp. (1993)[hereafter Allen & Peddy 1993]; M. Austin, J.D. Pigott, & J.M. Forgotson, "Seismic Stratigraphy of the Upper Pennsylvanian Swope Limestone of Kansas and Oklahoma: An Integrated Approach to Thin Bed Reservoir Prediction," *Geophysical Society of Tulsa 1991 Spring Symposium*, p. 73-84 (1991)[hereafter Austin *et al.* 1991]; W. K. Aylor, "Business Performance and Value of Exploitation 3-D Seismic," *The Leading Edge*, vol. 14, no. 7, p. 797-801 (1995)[hereafter Aylor 1995]; M. E. Badley, *Practical Seismic Interpretation*, Prentice-Hall, Englewood Cliffs, New Jersey, 266 pp. (1985)[hereafter Badley 1985]; M. A. Biot, "Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid, 1. Low Frequency Range, 2. Higher Frequency Range," *Accoustical Society of America Journal*, v. 28, p. 168- 191 (1956)[hereafter Biot 1956]; J. D. Boudvier, C.H. Kaars-Sijpesteijn, D.F. Kluesner, C.C. Onyejekwe, & R.C. van der Pal, "Three-Dimensional Seismic Interpretation and Fault Sealing Investigations, Nun River Field, Nigeria," *American Association of Petroleum Geologists Bulletin*, 73, No. 11, p. 1397-1414 (1992)[hereafter Boudvier *et al.* 1992]; J. Brac, P.Y. Dequirez, F. Herve, C. Jacques, P. Lai11y, V. Richard, & D.T. van Nhieu, "Inversion With A Priori Information: An Approach to Integrated Stratigraphic Interpretation," in R.E. Sheriff, ed., *Reservoir Geophysics, Investigations in #7*, Society of Exploration Geophysicists, Tulsa, p. 251-284 (1992)[hereafter Brac *et al.* 1992]; A. R. Brown, "Interpretation of 3-Dimensional Seismic Data," 3d ed., *American Association of Petroleum Geologists Memoir 42*, Tulsa, 341 pp. (1991)[hereafter Brown 1991]; B. S. Byun, *Velocity Analysis of Multichannel Seismic Data*, Society of Exploration Geophysicists, Tulsa, 518 pp. (1990)[hereafter Byun 1990]; J. P. Castagna & M.M. Backus, "Offset-Dependent Reflectivity–Theory and Practice of AVO Analysis," *Investigatons in Geophysics #8*, Society of Exploration Geophysicists, Tulsa, 348 pp. (1993)[hereafter Castagna & Backus 1993]; S. N. Domenico, "Effect of Brine-Gas Mixture Velocity in an Unconsolidated Sand Reservoir," *Geophysics*, v. 41, p. 882-894 (1976)[hereafter Domenico 1976]; Stuart W. Fagin, *Seismic Modeling of Geologic Structures, Applications to Exploration Problems*, Geophysical Development Series, v. 2, Society of Exploration Geophysicists, Tulsa, 269 pp. (1991)[hereafter Fagin 1991]; M.R. Gadallah, *Reservoir Seismology*, Penn Well Books, 384 pp. (1994)[hereafter Gadallah 1994]; G.H.F. Gardner, *Migration of Seismic Data*, Geophysical Reprint Series, #4, Society of Exploration Geophysicists, Tulsa, 462 pp. (1985)[hereafter Gardner 1985]; R.J. Greaves & T.J. Fu1p, "Three-Dimensional Seismic Monitoring of an Enhanced Oil Recovery Process," *Geophysics*, v. 52, p. 1175-1187 (1987)[hereafter Greaves & Fu1p 1987]; A.R. Gregory, "Aspects of Rock Physics From Laboratory and Log Data That Are

troublesome; (2) a new look at the thorny issue of geophysical "trespass"—a matter that is more thorny with 3D seismic data due to the necessity of imaging structure from adjacent lands; and (3) a quick reprise of surface owner issues—a matter that is of greater concern with the 3D seismic method due to access issues and more intense surface use.

Important to Seismic Interpretation," in Charles E. Payton, ed. *Seismic Stratigraphy – Applications to Hydrocarbon Exploration*, American Association of Petroleum Geologists, Tulsa, p. 15-46 (1977)[hereafter Gregory 1977]; J.P. Lindsey, "The Fresnel Zone and Its Interpretive Significance," *The Leading Edge*, Oct. 1989, p. 33-39 (1989)[hereafter Lindsey 1989]; M.K. Jenyon & A.A. Fitch, *Seismic Reflection Interpretation*, Geoexploration Monographs 1, No.8, Gebruder Bomtraeger, Berlin, 318 pp. (1985)[hereafter Jenyon & Fitch 1985); R. McQuillin, M. Bacon, & W. Barclay, *An Introduction to Seismic Interpretation*, Graham & Trotman, London, 287 pp. (1984)[hereafter McQuillin *et al.* 1984]; R. M. Mitchum, Jr., P.R. Vail, & S. Thompson, III, "Seismic Stratigraphy and Global Changes of Sea Level, part 2: The Depositional Sequence as a Basic Unit for Stratigraphic Analysis," in Charles E. Payton, ed. *Seismic Stratigraphy – Applications to Hydrocarbon Exploration*, American Association of Petroleum Geologists, Tulsa, p. 53-62 (1977)[Mitchum *et al*. 1977]; R. M. Mitchum, Jr. & P. R. Vail, "Seismic Stratigraphy and Global Changes of Sea Level, part 7: Seismic Stratigraphic Interpretation Procedure," in Charles E. Payton, ed. *Seismic Stratigraphy – Applications to Hydrocarbon Exploration*, American Association of Petroleum Geologists, Tulsa, p. 135-143 (1977)[Mitchum & Vail 1977]; A.M. Nur & Z. Wang, "Seismic and Acoustic Velocities in Reservoir Rocks," v. 1, *Experimental Studies*, Society of Exploration Geophysicists, Tulsa, 405 pp. (1988)[hereafter Nur & Wang 1988]; J. D. Pigott, R.K. Shrestha, & R.A. Warwick, "Young's Modulus From AVO Inversion," *Society of Exploration Geophysicists 59th Annual Meeting*, v. 2, p. 832-835 (1989)[hereafter Pigott *et al.* 1989]; J. D. Pigott, R.K. Shrestha, & R.A. Warwick, "Direct Determination of Carbonate Reservoir Porosity and Pressure From AVO Inversion," *Society of Exploration Geophysicists 60th Annual Meeting*, v. 2, p. 1533-1536 (1990)[hereafter Pigott *et al.* 1990]; J. D. Pigott, Y. Wang, R.K. Shrestha, J. Forgotson, & J. McDonald, "Reservoir Characterization Using 3D AVO Inversion: Case Study – U.S. Gulf Coast," *Society of Exploration Geophysicists International Meeting*, Beijing, P.R.C., p. 238-248 (1993)[hereafter Pigott *et al.* 1993]; J. D. Pigott, "A Seismic Classification Scheme for Clastic Wedges (Deltas)" Chapter 2, in M.N. Oti & G. Postma, eds., *Geology of Deltas*, A.A. Balkema Publishers, Rotterdam, p. 17-29 (1995)[hereafter Pigott 1995]; J. D. Pigott, & K. Feglo, "Optimizing Red Sea Imaging Through F-K Processing: Northern Sudan Example," *Society of Exploration Geophysicists 66th Annual Meeting* (1996)[hereafter Pigott & Feglo 1996]; J. D. Pigott, & S.V. Tadepalli, "Direct Determination of Clastic Reservoir Porosity and Pressure From AVO Inversion," *Society of Exploration Geophysicists 66th Annual Meeting* [hereafter Pigott & Tadepalli 1996]; J. G. Richardson & R.M. Sneider, "Synergism in Reservoir Management," R.E. Sheriff, ed. *Reservoir Geophysics: Investigations in Exploration Geophysics* v. 7, Society of Exploration Geophysicists, Tulsa, p. 6-11 (1992)[hereafter Richardson & Sneider 1992]; R. E. Sheriff, First, as a short review of just how significant the new 3D seismic technology is at present, and how it differs from the 2D methods of the past, one must first examine the classic makeup of a petroleum team, the people who search for oil and gas. It is geophysicists who use 3D seismic technologies, together with geologists and engineers, who are the critical components of the integrated petroleum team.[6] Today it would be

"Limits on Resolution of Seismic Reflections and Geologic Detail Derivable from Them," in Charles E. Payton, ed. *Seismic Stratigraphy – Applications to Hydrocarbon Exploration*, American Association of Petroleum Geologists, Tulsa, p. 3-14 (1977)[hereafter Sheriff 1977]; R. E. Sheriff, Enclyclopedic *Dictionary of Exploration Geophysics*, 3d Edition, Society of Exploration Geophysicists, Tulsa, 376 pp. (1991)[hereafter Sheriff 1991]; R. E. Sheriff, *Reservoir Geophysics: Investigations in Exploration Geophysics*, #7, 400 pp. (1992)[hereafter Sheriff 1992]; R. T. Shuey, "A Simplification of the Zoeppritz Equations," *Geophysics*, v. 50, p. 609-64 (1985)[hereafter Shuey 1985]; M. T. Taner & R.E. Sheriff, "Application of Amplitude, Frequency, and Other Attributes to Stratigraphic and Hydrocarbon Determination," in Charles E. Payton, ed. *Seismic Stratigraphy – Applications to Hydrocarbon Exploration*, American Association of Petroleum Geologists, Tulsa, p. 301-327 (1977)[hereafter Taner & Sheriff 1977]; W. M. Teleford, L.P. Geld Art, & R.E. Sheriff, *Applied Geophysics*, 2nd Edition, Cambridge University Press, Cambridge, 770 pp. (1990)[hereafter Teleford *et al.* 1990]; P. R. Vail, R.M. Mitchum, Jr., & S. Thompson, III, **"**Seismic Stratigraphy and Global Changes of Sea Level, Part 3: Relative Changes of Sea Level From Coastal Onlap," in Charles E. Payton, ed. *Seismic Stratigraphy – Applications to Hydrocarbon Exploration*, American Association of Petroleum Geologists, Tulsa, p.63-97 (1977)[hereafter Vail *et al.* 1977a]; P. R. Vail, R.G. Todd, & J.B. Sangree, "Seismic Stratigraphy and Global Changes of Sea Level, Part 5: Chronostratigraphic Significance of Seismic Reflections," in Charles E. Payton, ed. *Seismic Stratigraphy–Applications to Hydrocarbon Exploration*, American Association of Petroleum Geologists, Tulsa, p. 99-l33 (1977)[hereafter Vail et al. 1977b]; R. A. Warwick, & J.D. Pigott, "Interpretation of Lateral Variations in Carbonate Porosity by Detailed Stacking Velocity Analysis: Mississippian Bioherm Example, Hardeman Basin, Texas," *Estimation and Practical Use of Seismic Velocities*, EAEG/SEG Research Workshop, Cambridge, England, 460-469 (1990)[hereafter Warwick & Pigott 1990]; M.R.J. Wyllie, A.R. Gregory, & L.W. Gardner, "Elastic Wave Velocities in Heterogeneous and Porous Media" *Geophysic*s, v. 21: p. 41-70 (1956)[hereafter Wyllie *et al.* 1956]; O. Yilmaz, *Seismic Data Processing, Investigations in Geophysics*, v. 2, Society of Exploration Geophysicists, Tulsa, 526 pp. (1987)[hereafter YILMAZ 1987]; K. Zoeppritz, Erdbebenwellen VI/IB, "On the Reflection and Propagation of Seismic Waves," *Gottinger Nachrichten*, I, p. 66-84 (1919)[hereafter Zoeppritz 1919].

6 2 Peebler, R. P., 1996, "Extended Integration—The Key to Future Productivity Leap," *Oil & Gas J*. May 20, 1996 at 57 [hereafter Peebler 1996].

unthinkable to exclude geophysicists. However, the integration of geophysics with these other disciplines is a relatively recent development. Historically, there has been a lack of appreciation for seismic techniques due to (1) the inherent interpretational ambiguity of the forerunner 2D (two-dimensional) seismic analyses; (2) the costly mistakes in interpretations as a result of having to make interpolations; and (3) the early lack of suitable computers to conduct the enormous amount of number crunching required to clearly and accurately image the subsurface in three dimensions. All of this changed in the 1970s, first with the theoretical 3D seismic studies in the first part of the decade,[7] and then with the parallel development of more substantial mainframe computers in the second half of the decade, which led to the 3D seismic method's practical deployment.[8] With improved global positioning technology in the 1980s, the use of 3D seismic technology expanded from the onshore to the offshore. By the 1990s, the 3D seismic method was replacing the two dimensional (2D) seismic method as the preferred geophysical tool.

Application of the 3D seismic method for imaging rocks, fluids, and their structures to their fullest geometrical extent has negated the extrapolation of data between 2D seismic lines and between wells. Figures 1A and 1B (pp. 418-419) illustrate dramatically the difference in information content between these two seismic technologies. Figure 1A represents a structural contour map from the Gulf of Thailand interpreted from 2D seismic data, and Figure 1B shows the same area mapped from 3D seismic data. Observe the revised interpretations of the faults, their number and their orientation, and most importantly, observe how these faults can now be observed to compartmentalize the potential rock reservoirs. For example, observe that some wells, previously believed to

7 *See* Walton, G.G., 1972, "Three-Dimensional Seismic Method," *Geophysics*, v. 37, p. 417-430 and French, W.S., 1974, "Two-Dimensional and Three-Dimensional Migration of Model-Experiment Reflection Profiles," *Geophysics*, v. 39, p. 265-277.

8 *See* Bone, M.R., B.F. Giles, and E.R. Tegland, 1976, "3-D High Resolution Data Collection, Processing and Display," paper presented at 46th SEG Meeting, Houston, Texas.

be within the same unit, now can be shown to be separated by fault boundaries. An additional example of the power of visualizing the subsurface through the interpretation of 3D seismic data is illustrated by Figures 2A and 2B (pp. 420-421). Figure 2A illustrates a 2D seismic display from offshore Texas. Figure 2B is a 3D seismic horizontal section from the same area showing a buried meandering river channel, a geologic feature that is significantly more challenging to find on Figure 2A without the 3D method. These two examples illustrate only a few of the advantages of imaging the subsurface in three dimensions. These and other 3D seismic techniques have exponentially added information to the seismic interpreter's practical portfolio of tools, allowing the geophysicist to now become an integral part of the geological and engineering team for making quantitative interpretations requisite for an effective and economically prudent field development strategy.

Presently, 3D seismic exploration and exploitation is a multimillion-dollar technology, no longer in the experimental stages of development. The method is used both offshore and onshore in a variety of regions worldwide. Importantly, the 3D method promises to become the exclusive seismic tool for future field development, allowing in some instances the ability to image snapshots of the extent and movement of reservoir fluids through time (4D seismic), whereas previously reservoir drainage was only modeled and inferred from well production test data.

§ 11.02. How 3D Seismic Works, How It Differs from 2D and What It Tells Us.

In this technical discussion, we follow a logical progression, commencing with an explanation of certain fundamentals of reflection seismic theory, the acquisition of the seismic signal, the computer-intensive procedures of processing, the procedures of interpretation, and finally the potential limits and errors of the technique. Since it is necessary to understand the 2D Seismic method in order to fully comprehend the differences of 3D, the presentation will be directed toward an informed nongeophysicist (with a cursory knowledge of petroleum geology) who desires to understand both the 2D and 3D seismic methods with a minimum of technical language. Owing to the almost impossible task of summarizing an immense subject in a meaningful—yet abbreviated—fashion, the