BULLETIN

Corpus Christi
Geological Society
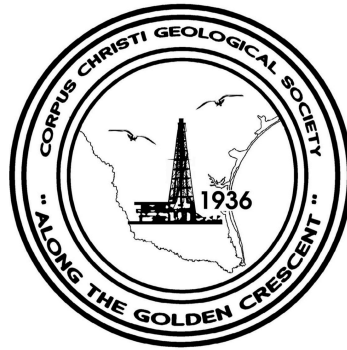
and

Coastal Bend
Geophysical Society

March
2016
ISSN 0739 5620

Bedias Creek Merge
Madison, Grimes, Walker, and Leon Countires, Texas

YOU'VE ARRIVED

Data Now Available

TEXAS

Rock Ridge East

Bedias Creek Merge

Sources: Esri, DeLorme, HERE, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom
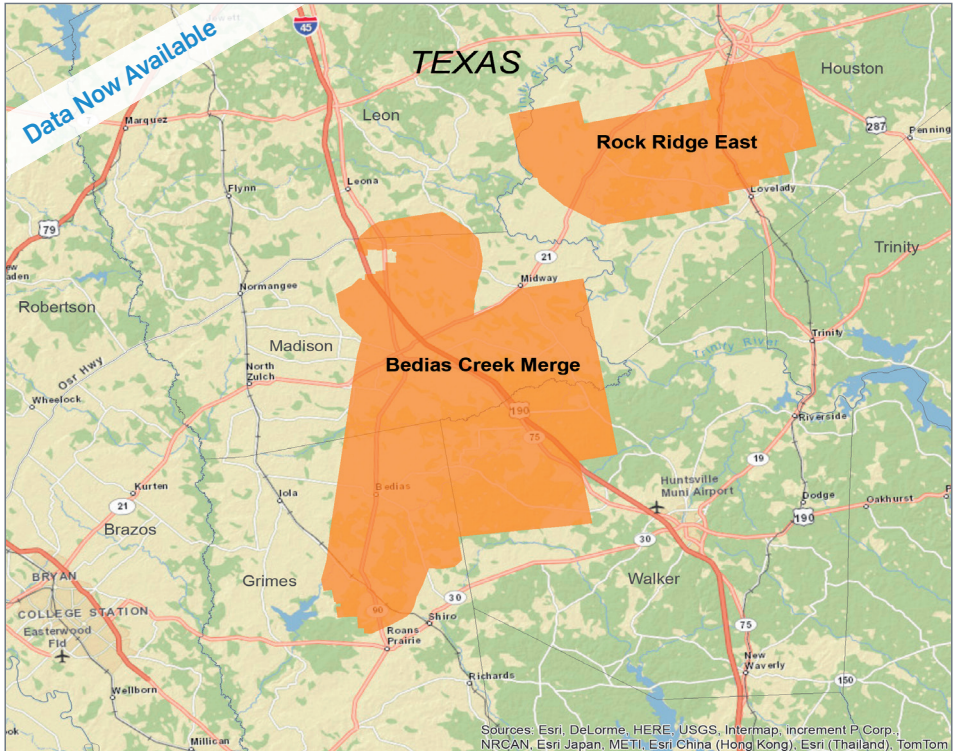
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- 110-fold data acquired using cableless **Sercel UNITE** crews and a dynamite source
- State-of-the-art processing, including 5D Interpolation and Orthorhombic Pre-Stack Time Migration

The best data, the right location, the right time!

Scott Tinley
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✉ scott.tinley@cgg.com

Cheryl Oxsheer
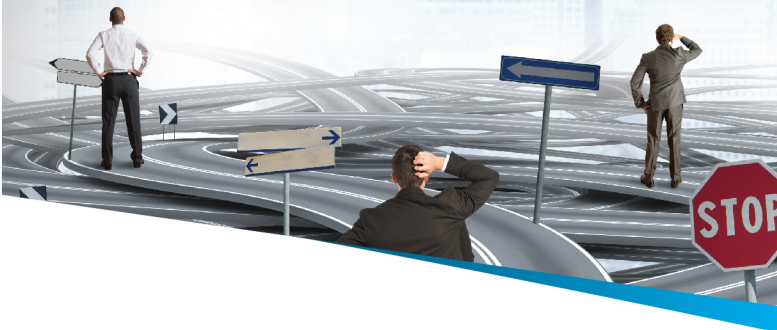☎ +1 832 351 8463
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www.ccgeo.org

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2015-2016

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Visit the geological Web site at www.ccgeo.org

CCGS/CBGS JOINT MEETING SCHEDULE 2015-2016

September 2015						
S	**M**	**T**	**W**	**Th**	**F**	**S**
		1	2	3	2	5
6	7	8	9	*10*	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30			

October 2015						
S	**M**	**T**	**W**	**Th**	**F**	**S**
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	*28*	29	30	31

November 2015						
S	**M**	**T**	**W**	**Th**	**F**	**S**
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	*18*	19	20	21
22	23	24	25	26	27	28
29	30					

Sept. 10, 2015
5:30p.m.—8:30p.m.
Kickoff BBQ
Hoegemeyer's Barbeque Barn

Oct. 28—11:30a.m.—1:00p.m. Speaker: Neil Peake, CCG Geo Consulting Seismic Reservoir Characterization. "Unconventional Reservoirs: An Integrated Workflow Incorporating Surface Seismic, Mineralogy, & rock Properties in the Haynesville Shale."

Nov. 18—11:30a.m.—1:00p.m. Speaker: Lorenzo Garza & Joe Stasulli, Railroad Commission of Texas. "Horizontal Drilling in Texas: A Tale That Begins in the Austin Chalk, but Whose Ending Has Yet To be Written."

December 2015						
S	**M**	**T**	**W**	**Th**	**F**	**S**
		1	2	3	4	5
6	7	8	*9*	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31		

January 2016						
S	**M**	**T**	**W**	**Th**	**F**	**S**
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	*20*	21	22	23
24	25	26	27	28	29	30
31						

February 2016						
S	**M**	**T**	**W**	**Th**	**F**	**S**
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	*17*	18	19	20
21	22	23	24	25	26	27
28	29					

Dec. 9—11:30a.m.--1:00p.m. Speaker: Dmitri Bevc,Ph.D., Chevron, SEG Distinguished Lecturer "Full Wave-Form Inversion: Challenges, Opportunities and impact"

Jan. 20--11:30a.m.—1:00p.m. Speaker: Charles Sicking, VP of R&D/Chief Geophysicist, Global Geophysical Services, Inc. "Predicting Frac Performance and Active Producing Volumes Using Microseismic Data"

Feb. 17—11:30a.m.—1:00p.m. Speaker: Richard Coffin, Ph.D., Dept. Chair, Physical & Envir. Sciences, Texas A&M Univ.— Corpus Christi. "Integration of Geochemistry & Geophysics Applied to Coastal Gas Hydrate Assessment"

CCGS/CBGS JOINT MEETING SCHEDULE 2015-2016

	March 2016							April 2016							May 2016					
S	M	T	W	Th	F	S	S	M	T	W	Th	F	S	S	M	T	W	Th	F	S
		1	2	3	4	5						1	2	1	2	3	4	5	6	7
6	7	8	9	10	11	12	3	4	5	6	7	8	9	8	9	10	11	12	13	14
13	14	15	*16*	17	18	19	10	11	12	13	14	15	16	15	16	17	*18*	19	20	21
20	21	22	23	24	25	26	17	18	19	*20*	21	22	23	22	23	24	25	26	27	28
27	28	29	30	31			24	25	26	27	28	29	30	29	30	31				

March 16-11:30a.m.-1:00p.m. Speaker: Thomas Ewing, Ph.D., Texas Bureau of Economic Geology; Frontera Exploration Consultants, Inc.; Yegua Energy Associates, LLC "Building Texas: Insights from the "Texas Through Time Project"

April 20-11:30a.m-1:00p.m. Speaker: Lee Billingsley, Ph.D., Abraxas Petroleum Corp. "Geoscience Applications to Economic Development of a Relatively Shallow, Low Gravity, Structurally Complex Eagle Ford Oil Development, Atascosa County, Texas"

May 18-11:30-1:00p.m. Distinguished Speaker: State Representative Todd Hunter, District 32

Calendar of Meetings and Events
Calendar of Area Monthly Meetings

Corpus Christi Geological/Geophysical Society........................... Third Wed.—11:30a.m.
SIPES Corpus Christi Luncheons.. Last Tuesday—11:30a.m.
South Texas Geological Society Luncheons................................ Second Wed—noon San Antonio
San Antonio Geophysical Society Meetings................................ Fourth Tuesday
Austin Geological Society... First Monday
Austin Chapter of SIPES... First Thursday
Houston Geological Society Luncheons....................................... Last Wednesday
Central Texas Section of Society of Mining Metallurgy & Exp.... 2nd Tues every other month San Antonio

PRESIDENT'S LETTER

URGENT REQUEST TO CCGS & CBGS MEMBERS

This downturn has become quite a problem for us. We have about a dozen members who have volunteered to help with the upcoming convention in September, and that is greatly appreciated. Things are progressing in-so-far as poster sessions, presentations and field trips, but we are desperate for more industry or personal sponsors for the convention.

I urge each and every one of you to put a call or a personal visit with just one company or individual to pledge a sponsorship. This slowdown has caused us to be SHORT OF FUNDS.

We have approximately 300 members. We need your individual help. The dozen volunteer members are overworked and certainly underpaid. Please help your society.

Mike Lucente
CCGS President

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January 2016

Greetings

The Corpus Christi Geological Society is organizing the Gulf Coast Association of Geological Societies annual convention to be held at the American Bank Center, Corpus Christi, Texas from the 18st to the 20th of September, 2016. The deadline to get your organizations sponsorship in the convention packet is Feb 15th. Sponsorships received after that date will be posted on the website and at the convention venue, but not in the packet.

The GCAGS Convention is a great way to put your organization forward:

- GCAGS has 9000 members, the largest AAPG Section
- 600 -1000 geoscientists and their companies attend the convention
- Professionals from 14 states and 2 countries attended in 2015
- Corpus Christi, the "Sparkling City by the Sea", a popular GCAGS site
- A very cost effective program to attend/publicize your organization

Proceeds from the annual convention fund every program that the GCAGS does, including: Student and Faculty research grants, the Visiting Professor program, Scholarship Fund Matching program, Student Chapter (AAPG) Leadership Summit travel assistance, Gulf Coast Section of Imperial Barrel Award Competition, Professional Honors and Awards, Teacher of the Year Awards, The GCAGS *Transactions*, and the GCAGS *Journal*.

Sponsoring companies will gain added publicity and acknowledgement throughout the entire Convention. In addition, sponsoring companies will gain longer term advertising exposure through acknowledgement pages at the beginning of the GCAGS *Transactions* publication. The following Sponsorship Levels are available:

Double Diamond – Highest Contributing Sponsor

|	
Diamond	$25,000
Emerald	$15,000
Sapphire	$5,000
Topaz	$1,000
Patron	$500

To have your company prominently listed as one of the key sponsors of the upcoming convention please return the attached sponsorship form. If you have any questions, please contact Lonnie Blake at sponsorships@gcags2016.com, or Dawn Bissell at bissells@swbell.net at 361.960.2151 for details.

Lonnie Blake, Sponsorship Chairman
361-876-6614
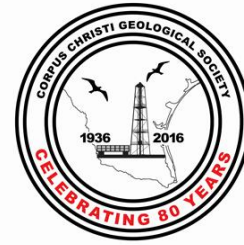
The Gulf Coast Association of Geological Societies and the Gulf Coast Section of SEPM

Corporate Sponsorship Opportunities

Corpus Christi, the "Sparkling City by the Sea" is always a popular GCAGS venue.

What a great way to put your organization forward:

GCAGS – 9000 members, the largest AAPG Section
- 600 - 1000 geoscientists attend
- 900 Professionals representing 450 companies from 14 states and 2 countries attended in 2015

Benefits of sponsorship
- Reinforce your company's name and logo
- Visibility in the exhibit hall
- Stand out from your competitors – give your products and services and edge
- Enhance your standing in the industry
- Earn a profile among young geoscientists – your future workforce

Sponsorship packages – designed to maximize your investment
- **Diamond (D) $25,000+**
- **Emerald (E) $15,000+**
- **Sapphire (S) $5,000+**
- **Topaz (T)$1,000+**
- **Patron (P)$500+**

Sponsor an event or product – for even more visibility
A sponsorship package can include your name and brand on one of these events, products, or publications. Choose from among:
- Convention portfolio bag – $50K exclusive logo/$25K joint logos
- Icebreaker reception – $25K exclusive
- All-Convention luncheon – $25K exclusive
- Presidents' reception – $25K exclusive
- Field trips & short courses – $25K exclusive
- Poster sessions – $10K exclusive
- Judges'/Speakers'/Poster Presenters' breakfast – $5K exclusive
- Technical session rooms – $5K per room exclusive for duration of convention
- Coffee breaks – $5K exclusive

Package Benefits
(depending on level)
- Complimentary Registrations (based on sponsorship level: D—5, E—3, S—2, T—1)
- Logo on banners and signs posted in exhibit hall and elsewhere
- Recognition at keynote speaker address
- Pre– and post-show attendee mailing lists
- Thank-you recognition in the convention program book
- Company name and link on website
- Ads in Transactions volume:
  - D—full-page color
  - E—full-page black & white
  - S—half-page black & white
  - T—quarter-page black & white
  - P—logo
(all ads on Transactions CD can be in color)

GCAGS 2016 will prove to be a great opportunity to build your goodwill and brand. For more information or to make your sponsorship commitment contact:

Lonnie Blake: Phone 361-876-6614
sponsorships@gcags2016.com
–or–
Dawn Bissell: Phone 361-960-2151
bissells@swbell.net

The Gulf Coast Association of Geological Societies
And the Gulf Coast Section of SEPM

66th Annual GCAGS Convention

September 18-20, 2016

Corpus Christi, Texas

CORPORATE SPONSORSHIP INVOICE

Sponsoring Company _____

Amount _____

Contact Person _____

Email _____

Confirm Here How You Want Your Sponsor Name to Appear: _____

If You Have a Logo You Would Like the GCAGS to Use Please Email It To: gcags2016sponsorship@gmail.com

Mail This Form with Your Check (payable to 'GCAGS 2016') To:

ATTN: GCAGS 2016
Corpus Christi Geological Society
PO Box 1068
Corpus Christi, Texas 78403

Amount _____

Sponsor Package _____

Sponsorship Packages:

- **Diamond (D) $25,000+**
- **Emerald (E) $15,000+**
- **Sapphire (S) $5,000+**
- **Topaz (T)$1,000+**
- Patron (P)$500+

Thank you for your generous support!

Gulf Coast
Gem & Mineral Society
54th
Gem, Mineral, Jewelry, & Fossil Show

Sat. March 5th, 2016 10am – 6pm

Sun. March 6th, 2016 10am – 5pm

Displays & Shopping for Everyone

- free parking
- kids wheel
- touch table
- silent auction
- mineral & gem identification
- kids 12 and under FREE
- and much more

Adults $5 good for both day

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www.gcgms.org

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THE BLOODMOBILE – IN **MARCH, 2016**
WILL BE AT SOME CONVENIENT LOCATIONS
PLEASE CALL <u>855-4943</u> for those locations or <u>see below</u>

Feeling Lucky this Month? Make someone feel lucky by donating your Blood!
You'll be glad you did!

Happy St. Patrick's Day too!

ATTENTION!!!
When you give blood: They have us listed as <u>C.C. Geological Society</u>. Our number with them is <u>4254</u> & it would be helpful if you can give them that number also.

FOR CURRENT SCHEDULES & LOCATIONS OF THE BLOODMOBILES YOU CAN LOG ON TO:

www.coastalbendbloodcenter.com

This message approved by Mike Lucente….

CBGS PRESIDENT'S LETTER

News -
News continues to be commodity prices. Looks like the production/consumption gap is narrowing. The first exported LNG from Cheniere Energy's Sabine Pass terminal in southwest Louisiana with the Energy Atlantic LNG tanker is expected during late February/early March 2016. Cheniere's Corpus Christi LNG terminal is expected to begin operations in early 2018.

AND On New Year's Eve, a tanker--the Theo T.--pulled out of Corpus Christi, Texas, with roughly 400,000 barrels of crude supplied by ConocoPhillips from the Eagle Ford Shale.

Business -
CBGS golf tournament being scheduled. Scholarship applicants solicited.
Education/Events -
- GSH
   Interpretation Technology Symposium/Exhibition - April 13-14 Norris Conf Center, Houston City Centre
   Numerous technical luncheons if you happen to be in Houston. Check following link.
                Geophysical Society of Houston Calendar
   CBGS has a revenue sharing agreement with GSH. Please mention CBGS if you register for any GSH events.
- SEG
   SEG Convention, 16-21 October, Dallas
   SEG has 450+ eLearning courses online from $0.99 to $150.00(most expensive I saw)
   http: //www.seg.org/professional-development/seg-on-demand
- AAPG
   AAPG Convention, 19-22 June, Calgary
- HGS
   Mudrocks Conference, 8-9 March, Woodlands
- NAPE
    August 10-11, Houston
- OTC
   May 2-5, Houston

Thought for the month
Don't be afraid to give your best to what seemingly are small jobs. Every time you conquer one it makes you that much stronger. If you do the little jobs well, the big ones

will tend to take care of themselves. ~Dale Carnegie

Monthly O&G Statistics

Texas Oil and Gas Info	Current Month	Last Month	Difference	
Texas Production	MMBO/BCF	MMBO/BCF	MMBO/BCF	
Oil	78.9	70.9	8	Nov
Condensate	9.8	11.2	-1.4	
Gas	596	666	-70	Nov
	Current Month	Yr to date - 2016	Yr to date - 2015	
Texas Drilling Permits	510	510	1,102	Jan
Oil wells	425	425	971	
Oil and Gas	282	282	697	
Gas wells	41	41	90	
Other	0	0	0	
Total Completions	965	18,510	27,595	Jan
Oil Completions	951	951	1,450	
Gas Completions	197	197	344	
New Field Discoveries	0	0	4	
Other	6	6	30	

Thought for the month:
A vision without a task is but a dream, a task without a vision is drudgery, a vision with a task is the hope of the world
- Inscription on a wall in Sussex England, circa 1730

Lonnie Blake
President CBGS

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Phone: (361) 884-8824
Fax: (361) 884-9623

CORPUS CHRISTI GEOLOGICAL SOCIETY
COASTAL BEND GEOPHYSICAL SOCIETY

LUNCHEON MEETING ANNOUNCEMENT

WEDNESDAY, MARCH 16TH, 2016

Location:	Congressman Solomon P. Ortiz International Center, 402 Harbor Drive, Corpus Christi, TX 78401 *http://ortizcenter.com*
Bar Sponsor:	To be announced *(sponsors needed!)*
Student Sponsor:	Core Laboratories and Global Geophysical Services
Time:	11:30 am Bar, Lunch follows at 11:45 am, Speaker at 12:00 pm
Cost:	$25.00 (additional $10.00 surcharge without reservation; No-shows may be billed and non-RSVP attendees cannot be guaranteed a lunch); *FREE* for students with reservation (discounted by our generous sponsors)!
Reservations:	Please RSVP by 4PM on the FRIDAY before the meeting! E-Mail: *wes@gislerbrotherslogging.com*

*Please note that luncheon RSVPs are a commitment to the Ortiz Center
and must be paid even if you can't attend the luncheon.*

http://www.corelab.com   *http://www.globalgeophysical.com*

Please thank our generous sponsors!!!

*SPONSORSHIPS FOR THE TUESDAY PINT NIGHT SOCIAL GATHERING AND
WEDNESDAY LUNCHEON MEETING BARS ARE OPEN!!!*

Please consider becoming a CCGS/CBGS sponsor!!!

Building Texas: Insights from the "Texas Through Time" Project

Presented by: Thomas Ewing, Ph.D. – Texas Bureau of Economic Geology, University of Texas - Austin; Frontera Exploration Consultants, Inc.; Yegua Energy Associates, LLC

Summary

In June, 2013, I began work at the Texas Bureau of Economic Geology (BEG) to put together a summary volume on the geology of Texas as geologists currently understand it, to be designed for general audiences. At present, the draft is completed and we are in review and editing/compositing stage; anticipated printing date is February, 2016. The book is fully illustrated in color, and around 360 pages long. It includes a comprehensive series of time-stratigraphic charts and an atlas of paleogeography and other features.

The book begins with a summary of landscapes and regions of the state. Two short chapters focus on general geologic principles and the layering of the earth beneath Texas, and the plate tectonic position of Texas through geologic time. Four subsequent chapters tell the story of Texas history from Proterozoic through Cenozoic, then into the Holocene. Finally, two chapters survey Texas resources and hazards.

To write such a summary involved summarizing and synthesizing hundreds of geological reports and articles. That has led to some interesting new insights, a few of which follow:

- Latest Precambrian-Middle Cambrian rifting includes activity on the Devils River trend at least as far as Van Horn. Interestingly, Cambrian and Ellenburger isopachs don't show subsidence into that area, but instead towards San Antonio.

- One terrane that used to form part of Texas (south of the former Marathon Basin) was detached in the Cambrian and later sheared off to form "Cuyania" in South America. It's possible that Sabinia (the Sabine Block) is also a part of North America and not exotic - but we need crazy deep drilling to be sure!

- Ouachita-Marathon deformation is a 'soft docking' not a high-impact continental collision. It doesn't seem to explain the Late Paleozoic uplifts and basins (ARM), which are more consistent with SW-NE compression and related strike-slip. Compressions from the SW or the ENE (Appalachian collision) are the more likely cause of deformation.

- Permian subsidence overlaps the ARM structuring in time and space, and continues to the end of the Paleozoic. Absence of detrital wedges from Marathon is remarkable, indicating that Permian subsidence continued south of the present-day Marathons.

- Gulf of Mexico extension had two phases. The first extended the region in a SE direction at upper and lower crustal levels. This extension formed a broad, hot and dry basin lying over a thousand feet below sea level, which was then filled by salt as seawater dribbled in. Afterwards, the second phase produced new oceanic crust, which rotated Yucatan over 40° counterclockwise.

- We can look at larger deltas and make intelligent guesses at the rivers that fed them and the highlands that formed sediment. Major streams include a 'Lone Oak River' which drained the Hueco Arch and others areas in the Jurassic and Early Cretaceous; a 'Cox River' draining southwest in the Albian; and a 'Bigfoot River' reaching from Big Bend to central Texas in the late Cretaceous.

The project also includes a website, which forms part of the overall BEG website. It will include statewide information; some material from the book; and a series of 70-plus Great Places to View Texas Geology. These are miniature field trip guides to highlight publicly accessible places to be wowed by Texas rocks and landscapes. Each site includes a nontechnical discussion of what you see, and why it's important; a gallery of photographs; and a few references and websites for more information.

Southeast Texas sites included in the Great Places include: Stone City and Somerville (Eocene), the Rayburn Dam area (Catahoula), LaGrange (Oakville), Brazos Bend (Brazos bottomland), the Liberty/Anahuac (Trinity River and delta), and the Sabine Pass, Bolivar Peninsula and Galveston-Freeport areas in the coastal zone.

In South Texas, these sites include: Goliad-La Bahia (Goliad escarpment), the Aransas Refuge (Ingleside), Padre Island, Roma-Rio Grande City, Sal del Rey, Baffin Bay and the Rio Grande Delta. Northward into Central Texas, familiar sites such as Enchanted Rock and the Inks Lake area are joined by Natural Bridge Caverns, the Uvalde area and the roadcuts out toward Langtry.

About our Presenter:

Dr. Thomas Ewing is a geoscientist with over 33 years of experience in hydrocarbon exploration and research. He is a Registered Professional Geoscientist in the State of Texas (#1320) and an AAPG/DPA Certified Petroleum Geologist (#4538), and holds certification #1610 from SIPES.

He received a B.A. in Geology from the Colorado College (1975), an M.S. in Geochemistry from New Mexico Institute of Mining and Technology (1977), and a Ph.D. in Geological Sciences from the University of British Columbia (1981).

Dr. Ewing was a research geologist for four years at the Texas Bureau of Economic Geology in Austin, working on Gulf Coast geopressured reservoirs, serving as a co-author of the "Atlas of Texas Oil Reservoirs", and compiling the Tectonic Map of Texas. Since 1985 he has been co-owner of Frontera Exploration Consultants, Inc., a San Antonio-based geoscience consulting company; he has consulted to numerous clients in South Texas, New Mexico and elsewhere. He worked with Venus Oil and Venus Exploration from 1985 to 2005 as staff consultant and Senior Explorationist, playing a main role in its successful exploration in the

Yegua Trend of the Gulf Coast Basin, the Cotton Valley trend of Texas and Louisiana, and in West Texas and Kansas. He is now a partner in Yegua Energy Associates, LLC, which is continuing hydrocarbon exploration in these trends.

In 2013, Dr. Ewing received a half-time appointment with the Texas Bureau of Economic Geology as project director to develop "Texas Through Time", an illustrated book and website on the geologic history and earth resources of Texas for a general audience.

Dr. Ewing is a member of many regional and national professional societies. He has served as Treasurer, Vice-President and President (2007-08) of the AAPG Division of Professional Affairs, and has received Life Membership in the DPA (2014). He is an AAPG Delegate from the South Texas Geological Society, and served as Vice-Chairman of the AAPG House of Delegates in 1992-93. He is also served as President of the Energy Minerals Division of the AAPG (1999-2000), and received Honorary Membership in that Division in 2009. Most recently, he completed service as Vice-President for Sections of AAPG (2012-14). He served as President of the South Texas Geological Society in 1990-1991, and as General Chairman of the 1996 GCAGS Convention in San Antonio. He received Honorary Membership in the South Texas Geological Society in 2009, Honorary Membership in the GCAGS in 2010, and BEG Alumnus of the Year in 2011.

Tom has spoken extensively at local, regional, and national geological meetings and published over 75 papers and abstracts. Among other awards, he has twice received the Gulf Coast Section AAPG Levorsen Award (1982 and 1999), and has received the AAPG Distinguished Service Award. He has written articles on Gulf Coast geology and hydrocarbons, the geology and tectonics of Texas, and history and urban geology of the San Antonio area. He wrote the popular guidebook "Landscapes, Water and Man: Geology and Man in the San Antonio Area" published by the South Texas Geological Society in 2008.

In his spare time, he leads field trips in South Texas, and directs a 60-voice German men's chorus, the San Antonio Liederkranz. Tom will be leading a two-day field trip for the September Gulf Coast Association of Geological Society's Annual Convention studying the geology of two sites in South Texas, the Holocene Rio Grande Delta and the Great Sand Sheet.

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Case History

A comparison between methods that discriminate fluid content in unconsolidated sandstone reservoirs

Zhengyun Zhou[1] and Fred J. Hilterman[2]

ABSTRACT

Three seismic attributes commonly used to predict pore fluid and lithology are the fluid factor (ΔF), Poisson impedance (PI), and lambda-rho ($\lambda \rho$). We evaluated the pore-fluid sensitivity of these attributes with both well-log and seismic data in Tertiary unconsolidated sediments from the Gulf of Mexico where sand and shale are the only expected lithologies. While the sensitivity of one attribute versus another to discriminate pore fluid is often debated in the literature, the sensitivities of the three attributes are not independent but can be traced back to the fluid factor, which is a function of the P- and S-wave normal-incident reflection coefficients. Interestingly, the fluid factor, which is a reflectivity attribute, at the top of a hydrocarbon-saturated reservoir, is basically independent of the shale properties above the reservoir. It is a function of the brine and hydrocarbon impedances of the reservoir. The next attribute, Poisson impedance, is then equal to the fluid factor times the sum of the brine and hydrocarbon impedances. Finally, the lambda-rho attribute is equal to the Poisson impedance multiplied by the same impedance sum. Essentially, the same scale factor differentiates these attributes, which does not significantly affect the sensitivity of the attributes. PI is the basis of the sensitivity for these attributes. As a means of testing their sensitivity for predicting pore fluid, we generated the three attributes along with their statistical distributions for different pore fluids for 183 reservoirs. The well-log statistical descriptions were then used to calibrate the seismic amplitude in a 3D survey to reflectivity values, thus allowing pore-fluid classification schemes based on Bayes' decision rules. In essence, seismic-amplitude quantification was based on regional statistics rather than individual wells within the 3D seismic survey to delineate the portions of the reservoir that were saturated with oil, gas, or brine.

INTRODUCTION

Pore-fluid and lithology predictions are two desired products in amplitude-versus-offset (AVO) analysis. To address pore-fluid prediction, Smith and Gidlow (1987) defined the fluid factor as the weighted difference between the reflectivities of P- and S-wave velocity. The weights came from mudrock equation (Castagna, 1985) or local measurements. In AVO gradient versus normal-incident P-wave (NIP) reflectivity crossplots, a brine-saturated (wet) sand falls closer to the mudrock line than the equivalent gas-saturated (gas) sand. Thus, the fluid factor would be near zero for a wet sand, while more negative for a gas sand. Gidlow et al. (1992) and Fatti et al. (1994) invert common-midpoint gathers for impedance reflectivity rather than P-wave and S-wave velocity reflectivity and redefined the fluid factor as the weighted difference between the reflectivities of P-wave and S-wave impedance. Another AVO technique suggested by Gray et al. (1999) inverts for the reflectivity of rock properties, such as the Lamé coefficient (λ), shear rigidity (μ), and density (ρ).

The pore-fluid sensitivity of various AVO reflectivity attributes is discussed by Castagna and Smith (1994) and Smith and Sutherland (1996) based on data from 25 worldwide rock samples. Their results suggest that the fluid factor successfully distinguishes gas sands from wet sands for all AVO classes. Based on the same rock-property data, Smith and Gidlow (2000) compare the fluid factor with reflectivity attributes derived from λ, μ, and ρ. The fluid factor and Gray's suggested attributes are closely related and both are hydrocarbon indicators.

Prestack inversion (Hampson, 1991; Wallace and Young, 1996;

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Wallace and Young, 1997) extends the reflectivity domain to the impedance domain. Lambda-mu-rho, introduced by Goodway et al. (1997), was one of the main pore-fluid discriminators in the impedance domain. Goodway et al. (1997) observe that the data clusters for shale, wet sand, and gas sand have larger separations in the crossplot of $\lambda\rho$ versus $\mu\rho$ than in the crossplot of acoustic impedance (AI) versus shear impedance (SI). In addition, $\mu\rho$ helps to distinguish signatures of anomalous lithologies from hydrocarbon signatures. Many case histories (Besheli et al., 2004; Ojo et al., 2005; Larsen et al., 2006; Young and Tatham, 2007) were reported with applications of $\lambda\rho$ as a pore-fluid indicator.

Lambda-rho ($\lambda\rho$) is a weighted function of the acoustic and shear impedances; it is expressed as $\lambda\rho = (AI)^2 - 2(SI)^2$. Hilterman (2001) relates $\lambda\rho$ to the fluid-modulus term (Gassmann, 1951), assuming the dry-frame Poisson's ratio is approximately 0.125. However, $\lambda\rho$ does not always provide the maximum pore-fluid discrimination when the dry-frame properties of the rock vary. According to Russell et al. (2003), a better pore-fluid discriminator is obtained if the value two, the weight between $(AI)^2$ and $(SI)^2$, is changed slightly based on the dry-frame Poisson's ratio. After crossplotting attributes such as $\mu\rho$ versus $\lambda\rho$, a rotation into the pore-fluid projection axis (Hendrickson, 1999; Whitcombe and Fletcher, 2001) enhances the ability to discriminate with a single attribute. Quakenbush et al. (2006) rotated the AI-SI crossplot to its pore-fluid projection and related the new attribute to Poisson's ratio and density, and thus named it Poisson impedance (PI). While there are numerous AVO attributes for lithology and pore-fluid discrimination, most of them have a very strong link back to the fluid factor introduced by Smith and Gidlow (1987).

In this research, we first used an extensive well-log database to quantify and evaluate the pore-fluid sensitivity of the fluid factor, PI, and $\lambda\rho$ attributes for unconsolidated clastic sediments that are pre-

dominantly class 3 AVO anomalies. As a field validation of the well-log study, seismic AVO attributes were generated from a 3D survey. Then, the seismic attributes were calibrated using statistics derived from the well-log study, so that quantitative pore-fluid predictions can be made from the seismic attributes. Without sufficient well-log constraints within the actual 3D survey area, the fluid-factor reflectivity attribute is a better pore-fluid discriminator than PI or $\lambda\rho$ attributes.

WELL-LOG DATA

Seismic to borehole calibration equations, attributes, and statistical parameters were developed from 151 offshore Gulf of Mexico (GOM) wells selected from the study area in South Marsh Island (SMI). The rocks are unconsolidated clastic sediments from the Pleistocene to Miocene Periods. The general criteria for well selection were as follows:

- One well per lease block (approximately 25 km^2)
- Minimum of 2000 m of logged data
- High-quality well-log curves including the self potential, gamma ray, neutron, density, sonic, shallow and deep resistivity, and caliper. Only a few shear-wave sonics were available and these were not included in the study.

Each suite of well-log curves was edited and intervals of questionable log values and intervals containing hydrocarbons were cataloged for future exclusion when rock-property statistics and seismic attributes were computed. A shale volume curve was generated for each well and then average P-wave slowness and density values at 60-m (200-ft) intervals were extracted for both brine-saturated (wet) sand reservoirs and their encasing shale. Data from a 60-m (200-ft) interval were considered a reservoir statistic if the interval had at least 9 m of density and velocity values for both sand and shale. Individual sand or shale beds with a thickness less than 3 m were excluded from the 60-m (200-ft) interval. Fluid substitution (Gassmann, 1951) for oil- and gas-saturated reservoir properties was conducted using fluid properties from Batzle and Wang (1992) and S-wave velocity estimates from Greenberg and Castagna (1992). Pore pressure and temperature for fluid substitution were taken from the well-log headers. Other fluid-substitution parameters were:

- API = 32
- Specific gas gravity = 0.7
- Salinity = 0
- Gas oil ratio (GOR) = maximum allowable GOR up to 1000 (scft/bbl)
- Water saturation = 30%

As an additional quality control, a sand reservoir was rejected if the ratio of the dry-frame bulk modulus to the shear modulus was not between 0.5 and 2.0. For the depth interval of seismic interest, 2900–3500 m (9500–11,500 ft), rock properties from 183 reservoirs were extracted to generate various seismic attributes and statistics.

Figure 1a and b show velocity and density values for the encasing shale and its respective sand layer with different reservoir pore fluids for the 183 reservoirs. To appreciate the difference between the encasing shale and the sand properties for each reservoir, we plot the wet-sand property along the abscissa and a specific reservoir's property on a vertical line. When the same sand and shale properties are displayed as depth trends (Figure 1c and d), significant differences
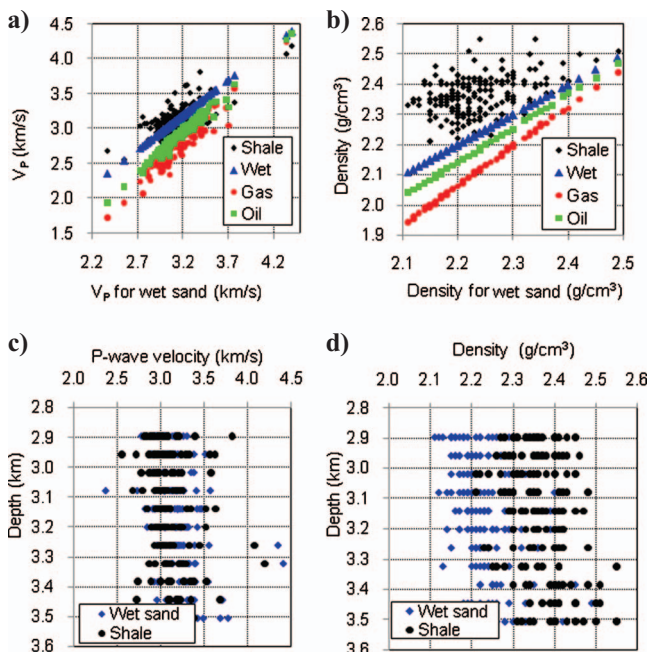

Figure 1. Crossplots of (a) P-wave velocity and (b) density values for encasing shale (black), wet (blue), oil (green), and gas (red) sands versus wet sand from 183 reservoirs in SMI. Depth trends are shown for (c) P-wave velocity and (d) density for wet sand (blue) and shale (black) from the same 183 reservoirs.

between the wet-sand and shale properties are not obvious. For instance, while the encasing shale velocity in Figure 1a appears to be equally split between being faster and slower than its wet-sand reservoir; in Figure 1b, apparently, only 1% of the reservoirs have an encasing shale density that is lighter than the wet sand. This density relationship is not apparent from the density-depth trends for wet sand and shale as shown in Figure 1d.

In Figure 2a, NIP coefficients are plotted for shale over sand with brine-, oil-, and gas-saturation as blue, green, and red points, respectively. Similar to Figure 1a, Figure 2a is plotted with the wet-sand NIP for each reservoir along the abscissa. This allows one to quickly visualize the NIP difference between wet sand and its fluid-substituted hydrocarbon-saturated sand. There is significant correlation between the wet and hydrocarbon-saturated NIP values as expressed by the following relationships:

$$\mathrm{NIP}_{\mathrm{oil}} = -0.05 + 1.09\mathrm{NIP}_{\mathrm{wet}}, \quad R^2 = 0.94, \text{ and } \quad (1a)$$

$$\mathrm{NIP}_{\mathrm{gas}} = -0.09 + 1.14\mathrm{NIP}_{\mathrm{wet}}, \quad R^2 = 0.83, \quad (1b)$$

where, as noted in Table 1, NIP is the normal-incident P-wave reflection coefficient, and the subscripts refer to the reservoir pore-fluids. R^2 is a statistical measure as to how well a regression trend line approximates real data points.

For interpretation purposes, we crossplot the reservoirs' porosities versus the wet-sand NIP values in the upper portion of Figure 2a. In this study area, the wet-sand NIP values only have a slight correlation to porosity. This suggests that the velocity-porosity relationship

is controlled by sedimentation, which is often referred to as a depositional trend (Avseth, et al., 2005).

DEFINITION OF PORE-FLUID ATTRIBUTES

Fluid factor

Our interest is to derive rock-property statistics from the well-log curves to calibrate seismic attributes for a field in South Marsh Island that has both oil and gas reserves. At the same time, we are interested in determining if the seismic attributes are independent. The first attribute examined is the fluid-factor trace, which was defined by Gidlow et al. (1992) as

$$\Delta F(t) = \mathrm{NIP}(t) - \gamma \mathrm{NIS}(t), \quad (2)$$

where $\mathrm{NIP}(t)$ and $\mathrm{NIS}(t)$ are normal-incident traces associated with P-wave and S-wave reflections, respectively. The empirical weight γ minimizes $\Delta F(t)$ in brine-saturated reservoirs. When this occurs, the scalar γ is an estimate of $(\mathrm{NIP}/\mathrm{NIS})_{\mathrm{wet}}$. Of course, γ can be slowly varying both spatially and temporally. For a target reservoir, we assume γ is constant. Considering $\mathrm{NIS}(t)$ is not particularly sensitive to the pore-fluid content, equation 2 becomes

$$\Delta F(t) = \mathrm{NIP}(t) - [(\mathrm{NIP}/\mathrm{NIS})_{\mathrm{wet}}]_{\mathrm{avg}}\mathrm{NIS}(t)$$
$$\approx \mathrm{NIP}(t) - \mathrm{NIP}_{\mathrm{wet}}(t), \quad (3)$$

where $\mathrm{NIP}(t)$ refers to the actual normal-incident trace with its cur-

Table 1. Symbol notation.

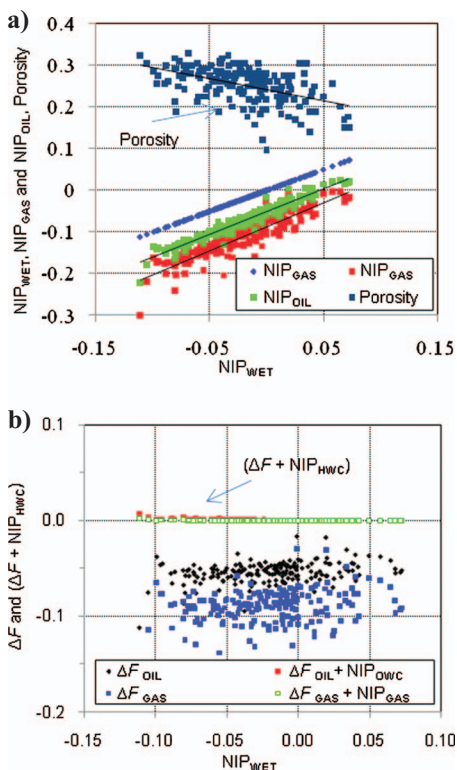|	
λ	Lamé coefficient lambda, or wavelength
μ	Shear rigidity
$\mu(\ ),\ \sigma(\ )$	Mean and standard deviation
ρ	Density (rho)
$\alpha,\ \beta$	P-wave and S-wave velocities
$\gamma,\ \gamma_1$	Weighting factors in ΔF and PI definition
θ	Incident angle
NIP, NIS	P-wave and S-wave normal-incident reflection coefficients
ΔF	Fluid factor, $\mathrm{NIP} - \gamma\mathrm{NIS}$
AI, SI	Acoustic and shear impedances
PI	Poisson impedance, $\mathrm{AI} - \gamma_1 \mathrm{SI}$
$R(\theta)$	Reflection coefficient at incident angle θ
$A(\theta)$	Seismic amplitude at incident angle θ
AP	Seismic amplitude at normal incidence for P-wave, $= K\ \mathrm{NIP}$
AS	Seismic amplitude at normal incidence for S-wave, $= K\ \mathrm{NIS}$
K, k	Constants between seismic amplitude and reflection coefficient, $K = k(4\pi b/\lambda)$ for thin bed
With $\sim$ above	Property estimated from seismic data
Without $\sim$ above	Theoretical property or property from well-log data
Subscripts: wet, oil, gas, hyd, hwc	Properties for brine, oil, gas, and hydrocarbon saturation, and from hydrocarbon-brine contact.
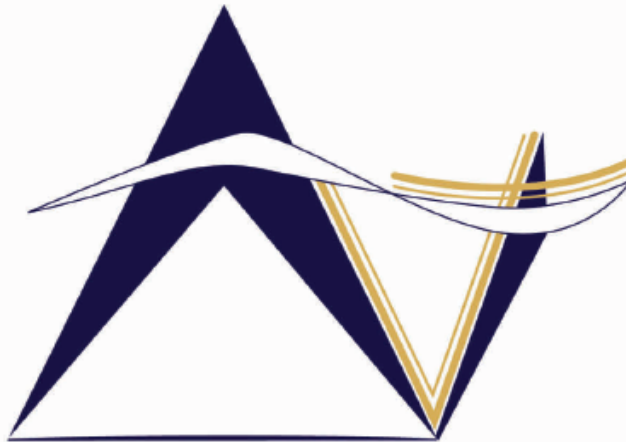
Figure 2. (a) Crossplot of NIP for wet, gas, and oil sands and porosity versus wet-sand NIP (porosity $= -0.53\mathrm{NIP}_{\mathrm{wet}} + 0.24$; $\mathrm{NIP}_{\mathrm{oil}} = 1.09\mathrm{NIP}_{\mathrm{wet}} - 0.05$; $\mathrm{NIP}_{\mathrm{gas}} = 1.14\mathrm{NIP}_{\mathrm{wet}} - 0.09$) and, (b) crossplot of fluid factor and summation of fluid factor and NIP from hydrocarbon-water contact for gas and oil sands versus wet-sand NIP.

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rent pore fluid and $\text{NIP}_{\text{wet}}(t)$ refers to the same normal-incident trace if the pore fluid is brine. In theory then, when the reservoir is brine-saturated, $\Delta F(t)$ is zero, while if the reservoir is hydrocarbon-saturated, $\Delta F(t)$ becomes $[\text{NIP}_{\text{hyd}}(t) - \text{NIP}_{\text{wet}}(t)]$. In certain conditions, NIS_{wet} is zero or near zero, which causes the constant γ to be infinite by its definition of $(\text{NIP}/\text{NIS})_{\text{wet}}$. However, this means the $\text{NIS}(t)$ trace is also zero, leaving the fluid factor equal to $\text{NIP}(t)$.

For the 183 reservoirs from South Marsh Island, ΔF, as specified by equation 3, is displayed for both gas- (blue squares) and oil-saturated sands (black dots) in the lower portion of Figure 2b. The magnitude of ΔF can be quantified to the pore-fluid properties through relationships similar to equation 1.

At the top of a hydrocarbon zone, the fluid factor can be expressed as (see Appendix A)

$$\Delta F_{\text{hyd}} = (\text{NIP}_{\text{hyd}} - \text{NIP}_{\text{wet}})$$
$$= -\text{NIP}_{\text{hwc}} + (\text{NIP}_{\text{hyd}}\text{NIP}_{\text{wet}}\text{NIP}_{\text{hwc}}), \qquad (4)$$

where NIP_{hyd} and NIP_{wet} refer to the normal incidence at the interface of shale over hydrocarbon-saturated sand and shale over wet sand, respectively. NIP_{hwc} refers to the normal incidence at a hydrocarbon-water contact, such as an interface between the gas-saturated and brine-saturated portions of a reservoir. The second term on the right side in equation 4 is a higher-order term of NIP, and thus can be neglected. Then, the fluid factor at the top of a hydrocarbon-saturated zone is approximated as

$$\Delta F_{\text{hyd}} \approx -\text{NIP}_{\text{hwc}}$$
$$\approx \frac{\text{AI}_{\text{hyd}} - \text{AI}_{\text{wet}}}{\text{AI}_{\text{hyd}} + \text{AI}_{\text{wet}}}, \qquad (5)$$

where AI is acoustic impedance and the subscripts hyd and wet refer
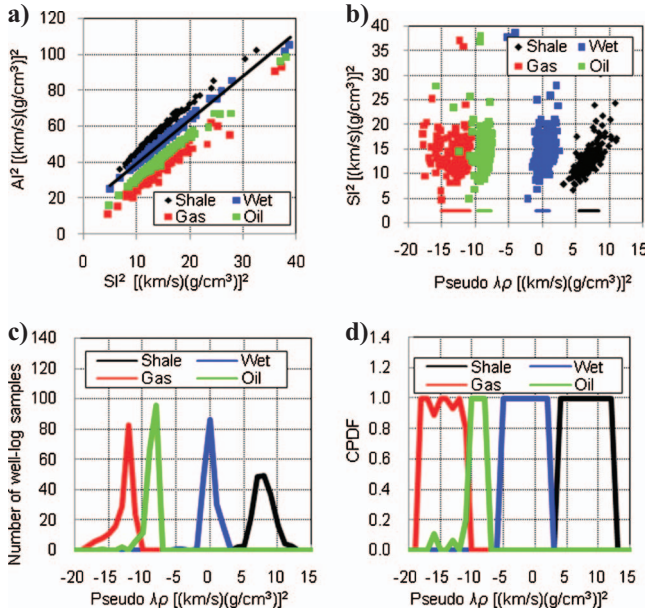
Figure 3. (a) Crossplot of AI^2 versus SI^2, ($\text{AI}^2_{\text{wet}} = 2.42\text{SI}^2_{\text{wet}} + 15.44$); (b) crossplot of SI^2 versus pseudo-lambda-rho ($= \text{AI}^2 - 2.42\text{SI}^2 - 15.44$); (c) pseudo-lambda-rho histograms; and (d) pseudo-lambda-rho conditional probability density functions, CPDF, for shale (black), wet sand (blue), oil sand (green), and gas sand (red) from 183 reservoirs.

to hydrocarbon and brine saturation. Equation 5 indicates that ΔF is independent of the properties of the encasing medium and is only a function of the reservoir properties. The result of adding $[(\text{NIP}_{\text{hyd}} - \text{NIP}_{\text{wet}}) + \text{NIP}_{\text{hwc}}]$ for the 183 reservoirs as shown in Figure 2b is near-zero values when compared to the fluid factors plotted below them. Landrø (2001) had similar results for time-lapse studies. As shown by Wright (1986), NIP_{hwc} is always positive and the reflection amplitude increases with offset.

The shale beneath the reservoir might have different properties than the shale above the reservoir. However, if the NIP and NIS values for the lower and upper shale fall on the same wet trend curve (see example in Figure 2a), then the fluid factor for the reservoir bottom interface is the negative of the top-interface fluid factor. Thus, in an unconsolidated clastic basin, the fluid factor is normally independent of the shale properties above and below the sand reservoir.

Poisson impedance and $\lambda\rho$

Trace inversions of $\text{NIP}(t)$ and $\text{NIS}(t)$ yield the layer properties of acoustic impedance, $\text{AI}(t)$, and shear impedance, $\text{SI}(t)$. Quakenbush et al. (2006) defined the weighted difference between $\text{AI}(t)$ and $\text{SI}(t)$ as PI. The scale factor γ_1 in Poisson impedance is defined here as the average ratio between AI and SI in a wet zone, $[(\text{AI}/\text{SI})_{\text{wet}}]_{\text{avg}}$, so that

$$\text{PI}(t) = \text{AI}(t) - \gamma_1 \text{SI}(t) = \text{AI}(t) - [(\text{AI}/\text{SI})_{\text{wet}}]_{\text{avg}}\text{SI}(t)$$
$$\approx \text{AI}(t) - \text{AI}_{\text{wet}}(t), \qquad (6)$$

where $\text{AI}(t)$ refers to the actual acoustic impedance trace with its current pore fluid and $\text{AI}_{\text{wet}}(t)$ refers to the same acoustic impedance trace if the pore fluid is brine. Similar to the fluid factor, PI for a brine-saturated sand is close to zero; for an oil-saturated sand, it is negative; and, for a gas-saturated sand, more negative. Because seismic data lack low-frequency components, the actual impedance inversion often uses low-frequency AI and SI trends from available well-log or seismic interval-velocity control. Without well-log control, the estimated AI and SI from inversion may not reliably quantify PI.

If PI is multiplied by the background $(\text{AI} + \gamma_1 \text{SI})$ and γ_1^2 is set to two, the AVO attribute becomes lambda-rho $(\lambda\rho)$:

$$\text{PI} \times (\text{AI} + \gamma_1\text{SI}) = (\text{AI} - \gamma_1\text{SI})(\text{AI} + \gamma_1\text{SI})$$
$$= \text{AI}^2 - \gamma_1^2\text{SI}^2 = \lambda\rho, \quad \text{if } \gamma_1^2 = 2. \qquad (7)$$

In $\lambda\rho$, the difference term, $(\text{AI} - \gamma_1\text{SI})$ is much more sensitive to pore fluid and lithology than the summation term, $(\text{AI} + \gamma_1\text{SI})$. In this paper, we will follow a suggestion by Russell et al. (2003) and empirically estimate γ_1^2 to calculate a pseudo-lambda-rho, $\widetilde{\lambda\rho}$, rather than accept a value of two for γ_1^2. It is desirable to have the value of γ_1^2 set to the ratio AI^2/SI^2 for the brine-saturated reservoir, so that $\widetilde{\lambda\rho}$ becomes

$$\widetilde{\lambda\rho} = \text{AI}^2 - \gamma_1^2\text{SI}^2 = \text{AI}^2 - [(\text{AI}^2/\text{SI}^2)_{\text{wet}}]_{\text{avg}}\text{SI}^2$$
$$\approx \text{AI}^2 - \text{AI}^2_{\text{wet}}. \qquad (8)$$

PORE-FLUID ATTRIBUTES AT WELL-LOG RESOLUTION

Figure 3a shows the crossplot of AI^2 and SI^2 derived from the rock properties of the 183 reservoirs for shale and sand with brine, gas,

and oil saturations. Linear trends are obvious for the plotted four categories (shale, wet, gas, and oil) because the S-wave velocity was predicted from the P-wave velocity using a linear equation. Equation 9a depicts the linear relation between AI^2 and SI^2 for wet sand. By rotating the coordinate axes to the wet-sand line, we obtain $\widetilde{\lambda\rho}$ in equation 9b and illustrated it in Figure 3b.

$$\text{AI}^2 = 2.42\text{SI}^2 + 15.44, \tag{9a}$$

$$\widetilde{\lambda\rho} = \text{AI}^2 - (2.42\text{SI}^2 + 15.44). \tag{9b}$$

The $\widetilde{\lambda\rho}$ values have been translated by the scalar 15.44 so that the wet-sand attribute has a mean value of zero. The empirical factor γ_1^2 (Russell et al., 2003) in $\widetilde{\lambda\rho}$ makes the slope of the four categories in Figure 3b more vertical than the factor two would. A standard deviation around the mean value (total length of two standard deviations) for each of the four categories is shown below the data clusters in Figure 3b. Figure 3c and d show the histograms and conditional probability density functions (CPDFs) (Duda et al., 2000) for $\widetilde{\lambda\rho}$.

Figure 4a contains the crossplot of AI and SI for the same reservoirs used in Figure 3. Equation 10a linearly relates AI and SI for wet sand. Rotating the coordinate axes to the wet-sand line yields the PI attribute in equation 10b, which is illustrated in Figure 4b

$$\text{AI} = 1.34\text{SI} + 2.03, \tag{10a}$$

$$\text{PI} = \text{AI} - (1.34\text{SI} + 2.03). \tag{10b}$$

As was done for the $\widetilde{\lambda\rho}$ attribute, the PI values have been translated so that the expected value of the PI attribute for wet-sand is zero. The breadth and position of the standard deviation lines below the four categories in Figure 4b are very similar in appearance to that observed for $\widetilde{\lambda\rho}$ in Figure 3b. The PI histograms and CPDFs are plotted
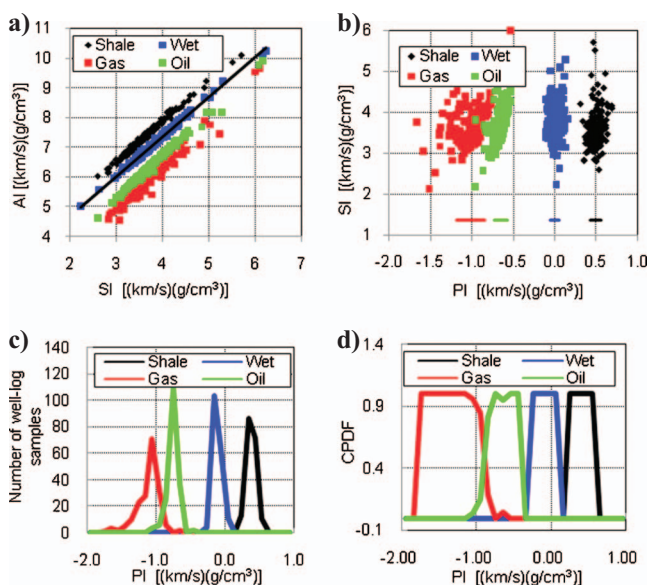
in Figure 4c and d. The PI classification of pore fluid will follow Bayes' decision rule (Avseth et al., 2005), which selects the classification with the maximum CPDF. This rule generates the PI classification criteria for pore fluid from Figure 4d as shown in Table 2.

NIP and NIS for shale over brine-, gas-, and oil-saturated sand were also calculated from the well-log database and are crossplotted in Figure 5a. Equation 11a quantifies the linear relationship between NIP and NIS for wet sand. Because the intercept of the wet-sand linear trend is not zero, an intercept term is included in the calculation of the fluid-factor ΔF in equation 11b:

$$\text{NIP} = 0.72\text{NIS} - 0.03, \tag{11a}$$

$$\Delta F = \text{NIP} - (0.72\text{NIS} - 0.03). \tag{11b}$$

Figure 5b shows the crossplot of NIS versus ΔF. For a wet-sand reflection, ΔF is close to zero, while for an oil-sand reflection, ΔF is negative, and for a gas-sand reflection, ΔF is more negative. The standard deviation lines in Figure 5b are broader with respect to the position of the clusters than observed either in Figures 3b or 4b. In fact, the position of the standard deviation lines for oil and gas overlap, indicating a difficulty in predicting oil from gas using the fluid factor. Figure 5c and d show histograms and CPDFs of ΔF for brine,

Table 2. Pore-fluid classification based on PI from well-log database.

Classification	PI range
Gas sand	$\text{PI} \leq -0.9$
Oil sand	$-0.9 < \text{PI} \leq -0.35$
Wet sand	$-0.35 < \text{PI} \leq 0.15$
Shale	$0.15 < \text{PI}$

Figure 4. (a) Crossplot of AI versus SI, ($\text{AI}_{\text{wet}} = 1.34\text{SI}_{\text{wet}} + 2.03$); (b) crossplot of SI versus PI ($= \text{AI} - 1.34\text{SI} - 2.03$); (c) PI histograms; and (d) PI conditional probability density functions, CPDF, for shale (black), wet sand (blue), oil sand (green), and gas sand (red) from 183 reservoirs.
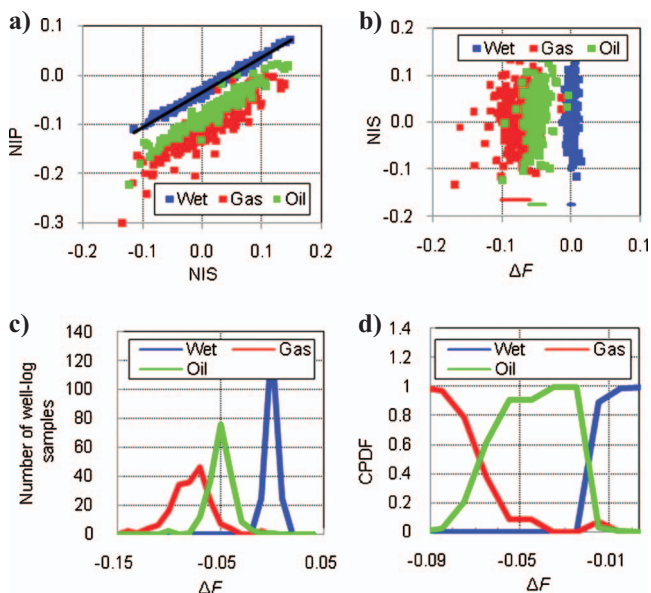
Figure 5. (a) Crossplot of NIP and NIS for shale over wet, oil, and gas saturations, ($\text{NIP}_{\text{wet}} = 0.72\text{NIS}_{\text{wet}} - 0.03$); (b) crossplot of NIS versus fluid factor ΔF ($= \text{NIP} - 0.72\text{NIS} + 0.03$); (c) ΔF histograms; and (d) ΔF CPDFs for wet (blue), oil (green), and gas sands (red).
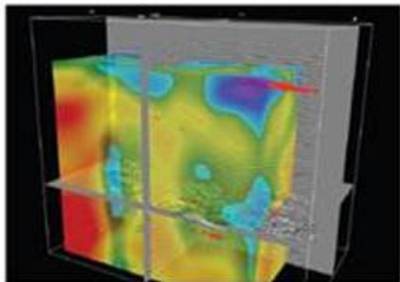
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oil, and gas saturation. From the CPDFs, Bayes' classification criteria for the fluid factor are shown in Table 3.

Sensitivity of pore-fluid attributes

Table 4 lists the mean and standard deviation values for the fluid factor, PI, and $\widetilde{\lambda\rho}$ attributes shown in Figures 3–5. The three attributes have different units and are normalized to compare their effectiveness for pore-fluid discrimination. The fluid factor and PI statistics were normalized to $\widetilde{\lambda\rho}$. After normalization, the gas standard deviation for PI is very close to that for $\widetilde{\lambda\rho}$, while the fluid-factor standard deviations is about 1.6 times that for $\widetilde{\lambda\rho}$ or PI. Based on Table 4, the PI sensitivity for pore-fluid discrimination is approximately the same as the $\widetilde{\lambda\rho}$ attribute and because of this, only the PI attribute is applied to field data.

Relationship between pore-fluid attributes

The fluid factor, PI, and $\widetilde{\lambda\rho}$ attributes are closely related. To illustrate this, let the acoustic impedance of a sand reservoir be AI and when the equivalent reservoir is brine-saturated the acoustic impedance is AI_{wet}. Also, let $\Delta AI = AI - AI_{wet}$ and $2AI = AI + AI_{wet}$, then the following holds

$$\text{Fluid Factor} \cong \Delta AI/2AI = \Delta AI \times (2AI)^{-1}, \tag{12a}$$

$$PI = \Delta AI = \Delta AI \times (2AI)^{0}, \tag{12b}$$

$$\widetilde{\lambda\rho} = \Delta AI \times 2AI = \Delta AI \times (2AI)^{1}. \tag{12c}$$

Table 3. Pore-fluid classification based on fluid factor from well-log database.

Classification	ΔF range
Gas sand	$\Delta F \leq -0.066$
Oil sand	$-0.066 < \Delta F \leq -0.02$
Wet sand	$-0.02 < \Delta F$

Table 4. Mean and standard deviation for original and normalized fluid factor, PI and $\widetilde{\lambda\rho}$ from well-log database.

		Mean			Standard Deviation		
		Wet	Oil	Gas	Wet	Oil	Gas
Original	Fluid factor	0.000	-0.047	-0.080	0.005	0.013	0.021
	PI	0.00	-0.65	-1.01	0.06	0.08	0.17
	$\widetilde{\lambda\rho}$	0.00	-8.69	-12.99	0.98	1.00	2.07
Normalize to $\widetilde{\lambda\rho}$	Fluid factor	0.00	-7.66	-12.98	0.75	2.09	3.35
	PI	0.00	-8.36	-12.98	0.72	1.01	2.15
	$\widetilde{\lambda\rho}$	0.00	-8.69	-12.99	0.98	1.00	2.07

In short, the fluid factor, PI, and $\lambda\rho$ attributes consist of the sensitivity term ΔAI and the scalar term 2AI, where the scalar term has a different exponent for each attribute. Thus, the sensitivity basis for these three attributes is mainly associated with ΔAI, PI. In fact, if the PI attribute from Figure 4, $PI = AI - 1.34SI + 2.03$, is substituted for AI_{wet} and the fluid factor and $\widetilde{\lambda\rho}$ are recomputed using equations 12a and 12c, respectively, the results would be very similar to those observed in Figures 5b and 3b, respectively.

In the next section, the PI and fluid-factor statistics derived from regional wells near the study area are quantitatively applied to a 3D seismic survey for predicting the gas, oil, and brine portions of a reservoir.

SEISMIC DATA

Fairfield Industries provided the marine 3D seismic data for this study in SMI where the reservoir is located. Figure 6a depicts the time map of the reservoir horizon along with ten wells. The depth of the target zone is approximately 3000 m (10,000 ft). The wells had the following production status when the seismic survey was acquired. Wells 1 through 7 were abandoned oil wells and are indicated by black solid circles in Figure 6. Wells 8 and 9 are producing oil wells and are indicated by purple solid circles, while Well 10 is a producing gas well and is indicated by a red star. The reservoir is located beneath a major fault which accounts for the distorted time image as shown by comparing the time map (Figure 6a) to the depth map developed from the ten wells (Figure 6b).

SEISMIC ATTRIBUTES

Fluid factor from seismic data

Smith and Gidlow's (1987) linear approximation of Zoeppritz's equation is

$$RC(\theta) = \frac{1}{2}\left(\frac{\Delta\alpha}{\alpha} + \frac{\Delta\rho}{\rho}\right)\frac{1}{\cos^2\phi} - \frac{4\beta^2}{\alpha^2}\left(\frac{\Delta\beta}{\beta}\right.$$
$$\left. + \frac{\Delta\rho}{\rho}\right)\sin^2\phi - \frac{1}{2}\frac{\Delta\rho}{\rho}\left(\tan^2\phi - \frac{4\beta^2}{\alpha^2}\sin^2\phi\right), \tag{13}$$

where $RC(\theta)$ is the reflection coefficient at incident angle θ, α is the average P-wave velocity of the upper and lower media, β is the average S-wave velocity, ρ is the average density, Δ is the difference of rock properties (lower medium properties minus upper), and ϕ is the average of the incident and transmitted angles. By dropping the higher-order terms and assuming $\alpha = 2\beta$ and $\phi = \theta$, equation 13 yields

$$RC(\theta) = NIP/\cos^2\theta - 2NIS \times \sin^2\theta. \tag{14}$$

If the reflection coefficients at two different incident angles, $RC(\theta_1)$ and $RC(\theta_2)$, are available,

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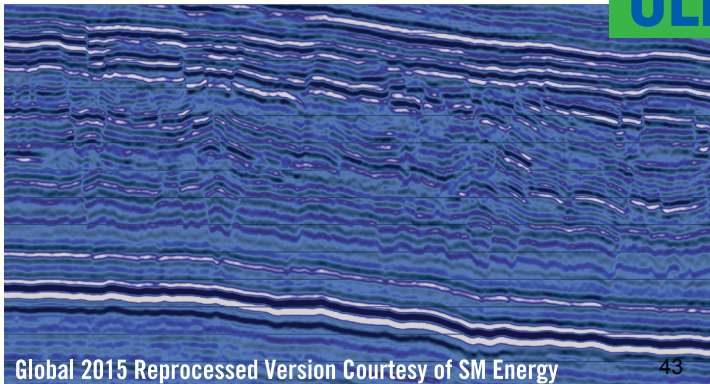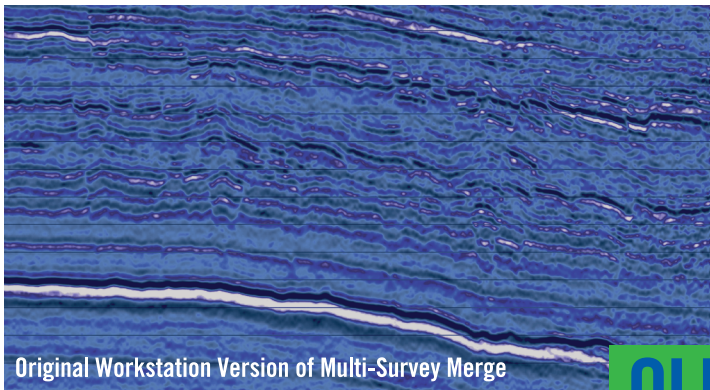
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then NIP and NIS are derived as (Zhou and Hilterman, 2007)

$$\text{NIP} = \frac{\text{RC}(\theta_1)\cos^2\theta_1\sin^2 2\theta_2 - \text{RC}(\theta_2)\cos^2\theta_2\sin^2 2\theta_1}{\sin^2 2\theta_2 - \sin^2 2\theta_1},$$

(15a)

and

$$\text{NIS} = \frac{2[\text{RC}(\theta_1)\cos^2\theta_1 - \text{RC}(\theta_2)\cos^2\theta_2]}{\sin^2 2\theta_2 - \sin^2 2\theta_1}.$$ (15b)

Conventional seismic angle-stacks provide amplitudes, $A(\theta)$, rather than reflection coefficients, $\text{RC}(\theta)$. Lin and Phair (1993) expressed the seismic amplitude for a thin bed as

$$A(\theta) = k\frac{4\pi b}{\lambda}\text{RC}_{\text{top}}(\theta)\cos(\theta_{\text{tr}}),$$ (16)

where $A(\theta)$ is the thin-bed seismic amplitude at incident angle θ, k is a constant value (can be considered a data-processing scalar), b is the thin-bed thickness, λ is the wavelength in the thin bed ($b < \lambda/8$), $\text{RC}_{\text{top}}(\theta)$ is the reflection coefficient from the upper boundary, and θ_{tr} is the transmitted angle. For a single seismic survey, k and λ can be considered constants, especially when we focus on a target reservoir. Assuming the bed thickness, b, does not change for the target reservoir, equation 16 can be written as

$$A(\theta) = K \times \text{RC}(\theta)\cos(\theta),$$ (17)

where $K = k \times (4\pi b/\lambda)$ and the incident and transmitted angles are assumed equal. If we replace the reflection coefficient $\text{RC}(\theta)$ with the amplitude $A(\theta)/\cos(\theta)$ in equations 15a and 15b, then we get

$$\text{AP} = \frac{\frac{A(\theta_1)}{\cos\theta_1}\cos^2\theta_1\sin^2 2\theta_2 - \frac{A(\theta_2)}{\cos\theta_2}\cos^2\theta_2\sin^2 2\theta_1}{\sin^2 2\theta_2 - \sin^2 2\theta_1}$$
$$= K \times \text{NIP},$$ (18a)

and

$$\text{AS} = \frac{2\left[\frac{A(\theta_1)}{\cos\theta_1}\cos^2\theta_1 - \frac{A(\theta_2)}{\cos\theta_2}\cos^2\theta_2\right]}{\sin^2 2\theta_2 - \sin^2 2\theta_1} = K \times \text{NIS},$$ (18b)

where, as noted in Table 1, AP and AS are the seismic thin-bed responses at normal incidence for P- and S-wave reflections.

Horizon maps for the target reservoir were generated from the near-angle stack (10°) and the far-angle stack (30°), and then equations 18a and 18b were applied to obtain the $\widetilde{\text{AP}}$ and $\widetilde{\text{AS}}$ maps shown in Figure 6c and d. As noted in Table 1, a symbol representing a property derived from seismic field data has a tilde ($\sim$) above it, while theoretical properties do not have a tilde.

From additional well control, it is known that the target reservoir is brine-saturated in the northern part of the study area (enclosed by the dashed blue box in Figure 6c and d). The color-bar scales associated with the horizon amplitude maps indicate the existence of the constant K because reflection coefficients are between ± 1. To calculate the seismic fluid factor and make a quantitative prediction of saturation, K needs to be estimated and removed from $\widetilde{\text{AP}}$ and $\widetilde{\text{AS}}$. In

this paper, we applied a normalization method to convert the seismic amplitudes $\widetilde{\text{AP}}$ and $\widetilde{\text{AS}}$ into normal-incident values $\widetilde{\text{NIP}}$ and $\widetilde{\text{NIS}}$ as were developed from the well-log data.

Normalization to the unit normal (Johnson and Leone, 1964) is defined as

$$u_i = \frac{x_i - \mu(\mathbf{x})}{\sigma(\mathbf{x})},$$ (19)

where u_i is the normalized value of the data sample x_i, which is assumed to have a normal distribution, and μ and σ are the mean and standard deviation of data set $\mathbf{x}$. Equation 19 then can be rewritten as

$$y_i = u_i\sigma(\mathbf{y}) + \mu(\mathbf{y}).$$ (20)

where $\mathbf{y}$ is another data set. Equations 19 and 20 convert data x_i into a unit normal distribution u_i and then into the statistical distribution of the data y_i. In our study, we converted seismic amplitudes into normal-incident reflection coefficients. As an example, using the attribute NIP, we have

$$\widetilde{\text{NIP}}_i = \frac{\widetilde{\text{AP}}_i - \mu(\widetilde{\text{AP}})}{\sigma(\widetilde{\text{AP}})}\sigma(\text{NIP}) + \mu(\text{NIP}),$$ (21)

where $\mu(\widetilde{\text{AP}})$ and $\sigma(\widetilde{\text{AP}})$ are the mean and standard deviation of $\widetilde{\text{AP}}$ from the seismic data, while $\mu(\text{NIP})$ and $\sigma(\text{NIP})$ are the mean and standard deviation of the NIP derived from well-log data. A key point here is how to calculate the mean and standard deviation of seismic and well-log data.

Figure 7a and b show the histograms of NIP and NIS for gas, oil, and wet sand that were derived from the well-log data. From these two figures, the gas-sand NIP histogram in Figure 7a is more negative than the wet-sand histogram, while the three pore-fluid histograms in Figure 7b for NIS overlap each other. The reason for the relative position of the histograms is that the S-wave velocity, V_S, does not change appreciably with saturation, while P-wave velocity, V_P, does. Similar histogram relationships can be seen in Figure 7c and d, which are for the seismic amplitudes, $\widetilde{\text{AP}}$ and $\widetilde{\text{AS}}$, using data from
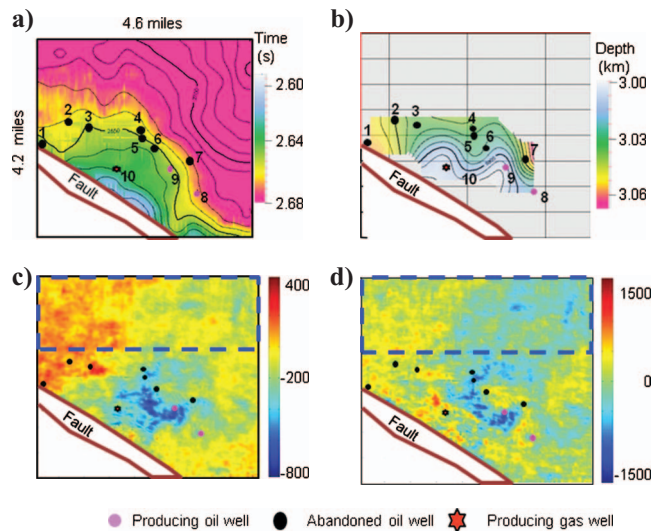

Figure 6. (a) Structural time map of reservoir horizon; (b) depth map from available ten wells; and normal-incident seismic-amplitude maps (c) $\widetilde{\text{AP}}$, and (d) $\widetilde{\text{AS}}$ generated from angle stacks using equation 18a and 18b.

the whole survey and data from the assumed wet area in the northern part of the survey. The $\widetilde{\text{AS}}$ histogram curve from the assumed wet area is in the center of the histogram curve from the whole survey (Figure 7d), while the $\widetilde{\text{AP}}$ histogram from the assumed wet area is slightly more positive than the histogram from the whole survey (Figure 7c). Table 5 shows the mean and standard deviation values for the well-log and seismic histograms.

There are two options for applying the normalization equation. The first option is to consider $\widetilde{\text{AP}}$ and $\widetilde{\text{AS}}$ as having separate mean and standard deviation values for each of the three subsets that identify the pore-fluid state. With option 1, equations 22a and 22b normalize $\widetilde{\text{AP}}$ and $\widetilde{\text{AS}}$ to normal-incident reflection coefficients:

$$\widetilde{\text{NIP}}_i^{(1)} = \left[\frac{\widetilde{\text{AP}}_i - \mu(\widetilde{\text{AP}}_{\text{wet}})}{\sigma(\widetilde{\text{AP}}_{\text{wet}})} \right] \sigma(\text{NIP}_{\text{wet}}) + \mu(\text{NIP}_{\text{wet}}), \quad (22a)$$
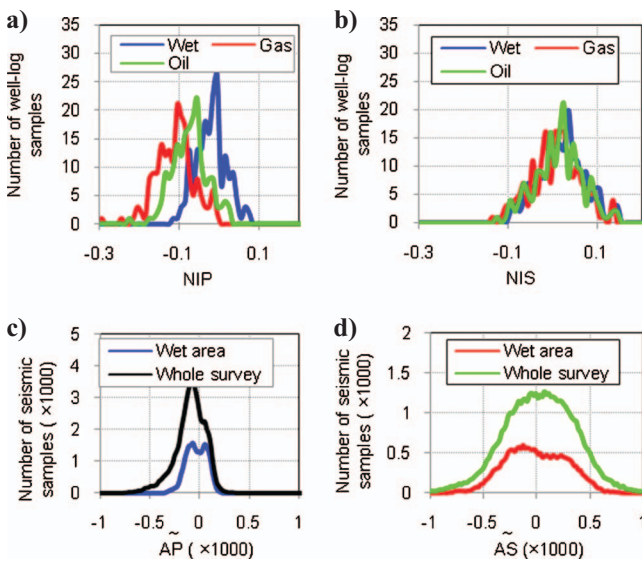
Figure 7. Histograms of (a) NIP and (b) NIS for wet (blue), oil (green), and gas (red) reservoirs based on well-log data. Histograms from seismic-amplitude maps are plotted for (c) $\widetilde{\text{AP}}$ and (d) $\widetilde{\text{AS}}$ from whole survey and assumed wet area in the northern part of the 3D survey.

Table 5. Mean and standard deviation values for NIP and NIS from well-log data and $\widetilde{\text{AP}}$ and $\widetilde{\text{AS}}$ from seismic data.

		P-wave		S-wave	
		Mean (μ)	Standard deviation (σ)	Mean (μ)	Standard deviation (σ)
NIP or NIS	Wet	−0.02	0.038	0.021	0.0527
	Wet, oil, and gas	−0.068	0.0568	0.014	0.0536
$\widetilde{\text{AP}}$ or $\widetilde{\text{AS}}$	Wet	−32.25	102.28	−9.29	287.17
	All survey	−95.21	153.13	26.18	346.27

$$\widetilde{\text{NIS}}_i^{(1)} = \left[\frac{\widetilde{\text{AS}}_i - \mu(\widetilde{\text{AS}}_{\text{wet}})}{\sigma(\widetilde{\text{AS}}_{\text{wet}})} \right] \sigma(\text{NIS}_{\text{wet}}) + \mu(\text{NIS}_{\text{wet}}),$$

$$(22b)$$

where $\widetilde{\text{NIP}}_i^{(1)}$ and $\widetilde{\text{NIS}}_i^{(1)}$ are estimates of NIP and NIS from normalized $\widetilde{\text{AP}}_i$ and $\widetilde{\text{AS}}_i$. $\widetilde{\text{AP}}_{\text{wet}}$ and $\widetilde{\text{AS}}_{\text{wet}}$ represent seismic amplitudes from the brine-saturated portions of the survey. NIP_{wet} and NIS_{wet} are NIP and NIS well-log values for brine-saturated reservoirs. The superscript (1) indicates that option 1 for normalization is being computed. Equations 22a and 22b relate to brine saturation; similar expressions exist when the pore fluid is oil or gas. The histogram distributions of NIP shift significantly when the saturation is changed from gas, oil, and brine, and thus the mean values for each pore-fluid case are significantly different (Figure 7a). To apply equations 22a and 22b exactly, the mean and standard deviations for seismic data that are brine-, oil-, and gas-saturated are required. However, the saturation state for the entire seismic survey is unknown, because the objective of the study was to determine the boundaries of the gas and oil reservoirs. Thus, in this first option, it is difficult to accurately normalize $\widetilde{\text{AP}}$ and $\widetilde{\text{AS}}$ for the whole survey to the well-log data scale of $\widetilde{\text{NIP}}_i^{(1)}$ and $\widetilde{\text{NIS}}_i^{(1)}$. So we generated normalization equations according to seismic data from the assumed wet area in the northern part and the wet-sand NIP and NIS data from the well logs. The normalization equations (equations 22a and 22b) are then applied to the whole data set. Because different mean and standard deviation values are applied to $\widetilde{\text{AP}}$ and to $\widetilde{\text{AS}}$, the relative ratio between $\widetilde{\text{AP}}$ and $\widetilde{\text{AS}}$ is not maintained during normalization. The ratio after normalization tends to be similar to the ratio between NIP and NIS for the wet-sand properties from the well-log curves. This option can help to reduce scaling errors introduced during processing.

Figure 8a and b show the estimated $\widetilde{\text{NIP}}^{(1)}$ and $\widetilde{\text{NIS}}^{(1)}$ maps after applying the first option of normalization, equations 22a and 22b. Figure 8c shows a crossplot of $\widetilde{\text{NIP}}^{(1)}$ versus $\widetilde{\text{NIS}}^{(1)}$ values from Figure 8a and b. The application of the linear relationship between $\widetilde{\text{NIP}}^{(1)}$ and $\widetilde{\text{NIS}}^{(1)}$ in the assumed wet area is given in equation 23a. Equation 23b provides the fluid factor based on equation 23a.

$$\widetilde{\text{NIP}}^{(1)} = 0.66\widetilde{\text{NIS}}^{(1)} - 0.034, \quad R^2 = 0.84, \quad (23a)$$

$$\widetilde{\Delta F}^{(1)} = \widetilde{\text{NIP}}^{(1)} - (0.66\widetilde{\text{NIS}}^{(1)} - 0.034). \quad (23b)$$

Because a horizon map has been used to determine the relationship between $\widetilde{\text{NIP}}^{(1)}$ and $\widetilde{\text{NIS}}^{(1)}$ rather than a seismic section of traces, it is possible to include an intercept value, which will normalize the wet-sand values to a zero mean (Simm et al., 2000). The application of equation 23b to the maps in Figure 8a and b yields the fluid-factor map shown in Figure 8d. The classification criteria in Table 3, which are based on well-log data, are applied to the fluid-factor map, and the predicted pore-fluid map with time contours is shown in Figure 8e and with depth contours in Figure 8f.

The second normalization option is to consider $\widetilde{\text{AP}}$ and $\widetilde{\text{AS}}$ as having the same scale factor from well-log data. Equations 24a and 24b are the normalization equations applied for $\widetilde{\text{AP}}$ and $\widetilde{\text{AS}}$.

$$\widetilde{NIP}_i^{(2)} = \frac{\widetilde{AP}_i - \mu(\widetilde{AS}_{ALL})}{\sigma(\widetilde{AS}_{ALL})} \sigma(NIS_{ALL}) + \mu(NIS_{ALL}), \quad (24a)$$

$$\widetilde{NIS}_i^{(2)} = \frac{\widetilde{AS}_i - \mu(\widetilde{AS}_{ALL})}{\sigma(\widetilde{AS}_{ALL})} \sigma(NIS_{ALL}) + \mu(NIS_{ALL}), \quad (24b)$$

where $\widetilde{AS}_{ALL}$ is $\widetilde{AS}$ from the whole seismic survey. NIS_{ALL} is the NIS derived by combining the data of brine-, gas- and oil-saturation from well-log data. In Figure 7b, the NIS histograms for various water saturations are very similar. Thus, we can generate the normalization equation based on $\widetilde{AS}$ from the whole survey and NIS for the combination of the data of gas, oil, and wet sands from the well-log database. The normalization equation is then applied to both $\widetilde{AP}$ and $\widetilde{AS}$. This second option maintains the relative ratio between $\widetilde{AP}$ and $\widetilde{AS}$. Figure 9a and b contain the $\widetilde{NIP}^{(2)}$ and $\widetilde{NIS}^{(2)}$ maps after applying option 2 normalization, which is equation 24.

Figure 9c shows the crossplot derived from the $\widetilde{NIP}^{(2)}$ and $\widetilde{NIS}^{(2)}$ maps. The linear equation between $\widetilde{NIP}^{(2)}$ and $\widetilde{NIS}^{(2)}$ for the area assumed to be brine saturated is given in equation 25a. Equation 25b provides the fluid factor based on equation 25a:

$$\widetilde{NIP}^{(2)} = 0.33\widetilde{NIS}^{(2)} + 0.0022, \quad R^2 = 0.84, \quad (25a)$$

$$\widetilde{\Delta F}^{(2)} = \widetilde{NIP}^{(2)} - (0.33\widetilde{NIS}^{(2)} + 0.0022). \quad (25b)$$

The subsequent fluid-factor map for option 2 is shown in Figure 9d. The well-log classification criteria in Table 3 are applied to the seismic fluid-factor map, and the predicted pore-fluid map with time contours is shown in Figure 9e and with depth contours in Figure 9f.

In the final classification maps (Figures 8e, 8f, 9e, and 9f), red refers to gas sand; green, oil sand; and, blue, wet sand. In Figure 8e and f, the classification for wells 1, 2, 3, 8, and 10 matches the known well production, while others do not. With regard to the producing wells, the classification of two of the three wells matches the known production. In Figure 9e and f, the classification of wells 1, 2, 3, 8, 9, and 10 matches the known well production. The classification of all three producing wells matches the known production. In both Figures 8 and 9, the depth maps correlate better than the time maps with the pore-fluid contacts from the classification schemes. In short, option 2 for normalizing the seismic amplitude to the normal-incident scale produced a better classification scheme based on the known production from the wells and based on the similarity of pore-fluid contact boundaries with the depth contours.
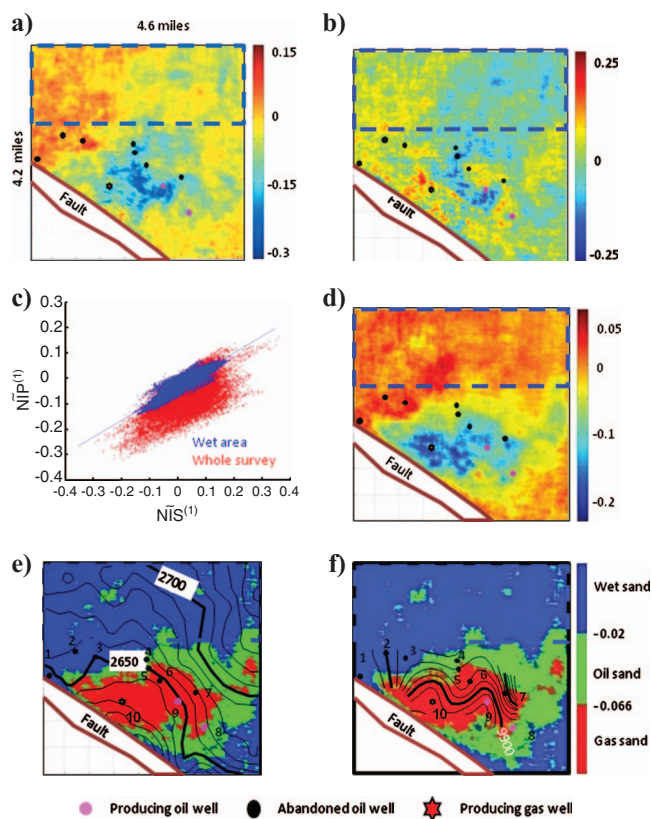

Figure 8. (a) $\widetilde{NIP}^{(1)}$ map and (b) $\widetilde{NIS}^{(1)}$ map after applying Option 1 of the normalization methods to $\widetilde{AP}$ and $\widetilde{AS}$ maps; (c) crossplot of $\widetilde{NIP}^{(1)}$ versus $\widetilde{NIS}^{(1)}$ from map values in (a) and (b) for the whole survey area and for the assumed wet area. The linear equation, $\widetilde{NIP}^{(1)} = 0.66\widetilde{NIS}^{(1)} - 0.034$, is based on the wet area. The fluid-factor $\widetilde{\Delta F}^{(1)}$ map (d) is based on the linear equation in (c). The final classification maps are obtained by applying Table 3 to the map in (d) and then overlaying with time contours (e) and depth contours (f) from well picks.
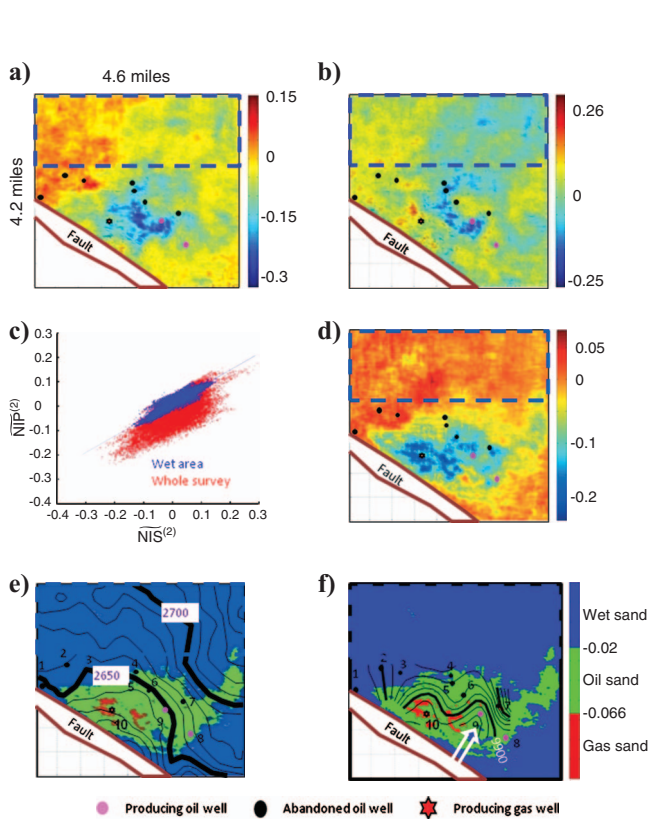

Figure 9. (a) $\widetilde{NIP}^{(2)}$ map and (b) $\widetilde{NIS}^{(2)}$ map after applying option 2 of the normalization methods to $\widetilde{AP}$ and $\widetilde{AS}$ maps; (c) crossplot of $\widetilde{NIP}^{(2)}$ versus $\widetilde{NIS}^{(2)}$ from map values in (a) and (b) for the whole survey area and for the assumed wet area. The linear equation, $\widetilde{NIP}^{(2)} = 0.33\widetilde{NIS}^{(2)} + 0.0022$, is based on the wet area. The fluid-factor $\widetilde{\Delta F}^{(2)}$ map (d) is based on the linear equation in (c). The final classification maps are obtained by applying Table 3 to the map in (d) and then overlaying with time contours (e) and depth contours (f) from well picks.

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$\widetilde{PI}$ from seismic data

Seismic wavelets were estimated from reflections around the reservoir for three angle-stack volumes. However, even though numerous wells were located within the 3D survey area, none of the wells had both density and velocity logs through the reservoir zone to con-
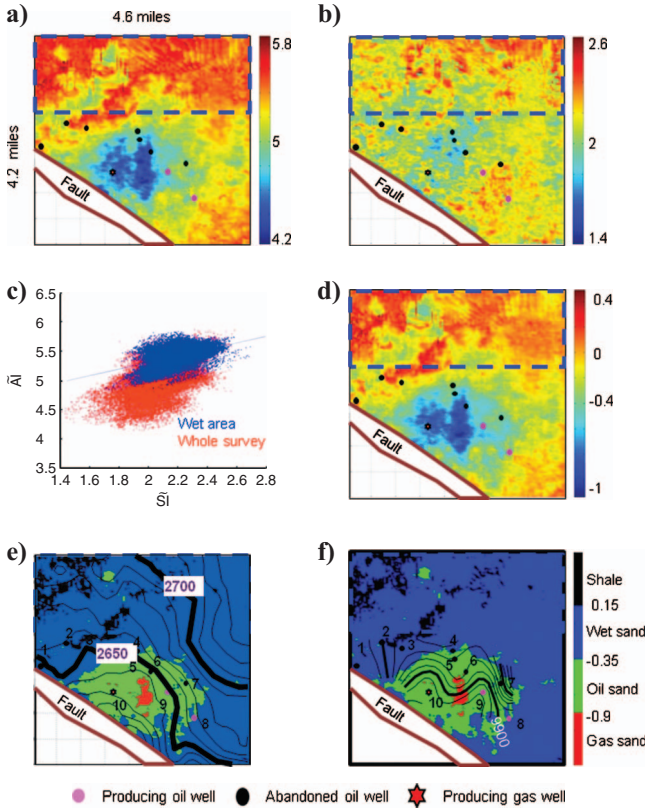

Figure 10. Horizon maps for (a) acoustic impedance ($\widetilde{AI}$) and (b) shear impedance ($\widetilde{SI}$) after inversion of seismic angle stacks in SMI; (c) crossplot of $\widetilde{AI}$ versus $\widetilde{SI}$ from (a) and (b). The wet area is assumed to be the dashed box area in the northern portion of the maps in (a) and (b). The linear equation, $\widetilde{AI} = 0.56\widetilde{SI} + 4.18$, is based on the wet area. The Poisson impedance $\widetilde{PI}$ map (d) is based on the linear equation in (c). The final classification maps are obtained by applying Table 2 to the map in (d) and then overlaying with time contours (e) and depth contours (f) from well picks.

trol the wavelet estimate or the initial low-frequency trends. A single linear low-frequency trend was finally used for the initial AI and another for SI. The three angle-stack volumes were simultaneously inverted for $\widetilde{AI}$ and $\widetilde{SI}$ (Tonellot et al., 2001). Figure 10a and b shows the acoustic impedance ($\widetilde{AI}$) and shear impedance ($\widetilde{SI}$) maps for the target horizon. Theoretically, because the inversion method yields properly scaled impedances, no scale normalization is needed. Figure 10c shows the crossplot of $\widetilde{AI}$ versus $\widetilde{SI}$ map values for the area assumed to be brine-saturated and for the whole survey area. The linear relation given in equation 26a between $\widetilde{AI}$ and $\widetilde{SI}$ in the wet area provides the PI in equation 26b.

$$\widetilde{AI} = 0.56\widetilde{SI} + 4.18, \quad R^2 = 0.21, \tag{26a}$$

$$\widetilde{PI} = \widetilde{AI} - (0.56\widetilde{SI} + 4.18). \tag{26b}$$

The classification criteria in Table 2 were applied to the $\widetilde{PI}$ map in Figure 10d to yield the pore-fluid classification maps with time contours shown in Figure 10e, and with depth contours shown in Figure 10f. The color identification scheme for all sands is the same as the one in Figure 9e and f, while black is introduced to refer to shale. In general, the classification of wells 1, 2, 3, 4, and 9 matches the known well production, while the others do not. The classification of one of the two oil producing wells matches the known production. Unfortunately, the classification of the gas well is not correct. In Figure 10e, neither the gas-oil contact nor the oil-water contact correlates to the time contours. In Figure 10f, the gas-oil contact does not correlate to the depth contours, but the oil-water contact has a limited correlation to the depth contours. The pore-fluid classification from the fluid-factor map in Figure 9f is considered better than the $\widetilde{PI}$ classification in Figure 10f.

DISCUSSION

The rock properties derived from the well-log curves do not vary in the depth range of 2900–3500 m (9500–11,500 ft). To test possible statistical variations, the depth range was divided into two parts, 2900–3200 m (9500–10,500 ft) and 3260–3500 m (10,700–11,500 ft). Then, every sample and every other sample to every fifth sample were selected to form new subsets. Table 6 lists the mean and standard deviation values for these subsets. The difference of the mean and standard deviation for each set from the original data set is also shown in Table 6. The statistical differences caused by depth are in the same order of magnitude as the differences caused by alternating

Table 6. Mean and standard deviation (std) values of NIP and NIS from difference subsets of SMI well-log data set.

	Sample skipped	NIP		NIP difference		NIS		NIS difference	
		Mean	Std	Mean	Std	Mean	Std	Mean	Std
2900–3500 m (9500–11500 ft)	0	−0.0199	0.038	0	0	−0.0475	0.0501	0	0
	1	−0.0178	0.0388	0.0021	0.0008	−0.044	0.0508	0.0035	0.0007
	2	−0.0207	0.0395	−0.0008	0.0015	−0.0489	0.0509	−0.0014	0.0008
	3	−0.0154	0.0421	0.0045	0.0041	−0.0394	0.0543	0.0081	0.0042
	4	−0.0111	0.0387	0.0088	0.0007	−0.0376	0.0518	0.0099	0.0017
2900–3200 m (9500–10500 ft)	0	−0.0244	0.0383	−0.0045	0.0003	−0.053	0.0498	−0.0055	−0.0003
3260–3500 m (10700–11500 ft)	0	−0.011	0.036	0.0089	−0.002	−0.0365	0.0492	0.011	−0.0009

the samples selected. So in our field example, the statistical variation within the selected depth interval can be neglected.

In Figure 8f, five of 10 wells match with the known production, which includes two of the three producing wells. The northern part of the gas-oil contact is consistent with the depth contours from the well picks. No depth contours are available to evaluate the oil-water contact.

In Figure 9f, six of 10 wells match with the known production, which includes all three of the producing wells. The northern part of oil-water contact is consistent with the depth contours. The classification indicates a gas cap in the western part of the structure.

In Figure 10f, four of ten wells match with the known production, which includes one of three producing wells. The oil-water contact is consistent with the depth contours, while the gas-oil contact is inconsistent with the depth contours. A possible reason is that impedance inversion without well control to accurately estimate the seismic wavelets or provide initial impedance trends gives unreliable results for $\widetilde{AI}$ and $\widetilde{SI}$.

Because the fluid content at the abandoned wells may not be totally brine-saturated, the producing wells are better to evaluate the success of the three methods. In general, the pore-fluid classification based on the fluid factor with option 2 normalization, $\widetilde{\Delta F}^{(2)}$ in Figure 9f is better than the fluid-factor prediction with option 1 normalization $\widetilde{\Delta F}^{(1)}$ in Figure 8f, which is better than $\widetilde{PI}$ pore-fluid prediction in Figure 10f.

Because the problem of determining partial gas-saturated reservoirs from fully saturated reservoirs was not an objective of this research, it is not unreasonable to expect that the procedures outlined in this study would have the potential to quantify water saturation. We have illustrated techniques to differentiate the fluid factor of a fully saturated gas reservoir from the fluid factor of an oil-saturated reservoir and the fluid factor for a partial gas-saturated reservoir is close to that for an oil-saturated reservoir. Solving the partial gas-saturation problem with quantification techniques similar to those presented in this study is definitely worthy of future investigation.

The linear trends of the rock properties displayed in Figures 1–5 must be viewed with some reservations as the S-wave velocity for sand and shale were estimated using linear expressions of the P-wave velocity and lithologic content. While these transformations are considered to be fairly robust, crossplot examples from Castagna et al. (1998) illustrate the magnitude of scatter that can be expected when actual laboratory measurements of S-wave velocity are used in seismic attributes rather than empirical and/or theoretical estimates.

Results from this study indicate areas for future research such as predicting thin-bed reservoir thickness from the amplitude of the fluid-factor response. As noted previously, the fluid factors from the top and bottom interfaces of a hydrocarbon-saturated reservoir are approximately $(-\text{NIP}_{\text{hwc}})$ and NIP_{hwc}, respectively, if the lithologies (shale, limestone, etc.) above and below the reservoir are the same. While the NIP reflection coefficients for gas-saturated sands vary from -0.3 to 0.0 in Figure 5a, the fluid factor is much more stable with a value of approximately -0.09 (Figure 5b). A thin bed can have different NIP values for the top and bottom reservoir interfaces making the thickness of a reservoir difficult to predict from the seismic response. However, the fluid factor, once calibrated for a local area as was done in Figure 5b, can be treated as a constant leaving the bed thickness (in two-way time) as the main variable in the seismic amplitude. Note, to some extent, the porosity of the sand can vary from prospect to prospect in the local area and the thickness can still be estimated from the fluid factor.

CONCLUSIONS

We compare three AVO attributes, fluid factor, PI, and $\widetilde{\lambda\rho}$ from their definitions to examples from well-log data and seismic data. These three AVO attributes are closely related. For a shale/sand sequence with no unexpected lithologies present such as coal or limestone, even though the fluid factor is theoretically derived from the difference of two reflectivities from the top interface of a very thick reservoir, it is independent of the medium properties above the interface if we neglect an insignificant higher-order term of reflectivity. As such, the fluid factor equals the negative of the normal-incident reflection coefficient generated at a hydrocarbon-water contact having properties derived from the reservoir.

PI which theoretically reduces to $\text{AI} - \text{AI}_{\text{wet}}$, is also the basis for the sensitivity measurements of pseudo-lambda-rho and the fluid factor. The difference between these three attributes is the power of the scalar term, $(\text{AI} + \text{AI}_{\text{wet}})$, that is then multiplied with PI. From our interpretation of the well-log histograms in this class 3 AVO environment, PI has essentially the same pore-fluid discrimination as $\widetilde{\lambda\rho}$.

In the SMI field example, the fluid-factor attribute yielded a better pore-fluid classification than PI based on a rather subjective validation. Without robust well control, the PI attributes lose their advantage over the fluid factor for pore-fluid discrimination. The results for $\widetilde{\lambda\rho}$ would be similar to the PI results. We apply normalization technology of seismic-amplitude maps to normal-incident maps. This exercise was an attempt to quantify the amplitude on reflectivity maps similar to the quantification of impedance maps.

Crossplotting attribute values from horizon maps can provide linear relationships between attributes such as AI and SI rather than just ratios. This additional term, the intercept, allows a translation of the estimated brine-saturated values of the attribute to near-zero values.

ACKNOWLEDGMENTS

APPENDIX A

RELATIONSHIP BETWEEN FLUID-FACTOR AND FLUID-CONTACT REFLECTIONS

At the top of a hydrocarbon reservoir, the fluid factor is expressed as

$$\Delta F_{\text{hyd}} = \text{NIP}_{\text{hyd}} - \text{NIP}_{\text{wet}}, \qquad \text{(A-1)}$$

where the subscripts hyd and wet refer to hydrocarbon and brine saturation.

The proof of equation 4 is easily shown by introducing a new parameter, e:

$$\Delta F_{\text{hyd}} = \text{NIP}_{\text{hyd}} - \text{NIP}_{\text{wet}} = -\text{NIP}_{\text{hwc}} + e. \quad \text{(A-2)}$$

Then,

$$e = \text{NIP}_{\text{hyd}} - \text{NIP}_{\text{wet}} + \text{NIP}_{\text{hwc}}. \quad \text{(A-3)}$$

The NIP terms in equation A-3 are then expressed in terms of their respective acoustic impedances, AI, to yield

$$e = \frac{\text{AI}_{\text{hyd}} - \text{AI}_{\text{shale}}}{\text{AI}_{\text{hyd}} + \text{AI}_{\text{shale}}} - \frac{\text{AI}_{\text{wet}} - \text{AI}_{\text{shale}}}{\text{AI}_{\text{wet}} + \text{AI}_{\text{shale}}} + \frac{\text{AI}_{\text{wet}} - \text{AI}_{\text{hyd}}}{\text{AI}_{\text{wet}} + \text{AI}_{\text{hyd}}}. \quad \text{(A-4)}$$

Equation A-4 can also be written as

$$e = \frac{A - B + C}{(\text{AI}_{\text{hyd}} + \text{AI}_{\text{shale}})(\text{AI}_{\text{wet}} + \text{AI}_{\text{shale}})(\text{AI}_{\text{wet}} + \text{AI}_{\text{hyd}})}, \quad \text{(A-5)}$$

where

$$A = (\text{AI}_{\text{hyd}} - \text{AI}_{\text{shale}})(\text{AI}_{\text{wet}} + \text{AI}_{\text{shale}})(\text{AI}_{\text{wet}} + \text{AI}_{\text{hyd}}), \quad \text{(A-6)}$$

$$B = (\text{AI}_{\text{hyd}} + \text{AI}_{\text{shale}})(\text{AI}_{\text{wet}} - \text{AI}_{\text{shale}})(\text{AI}_{\text{wet}} + \text{AI}_{\text{hyd}}), \quad \text{(A-7)}$$

$$C = (\text{AI}_{\text{hyd}} + \text{AI}_{\text{shale}})(\text{AI}_{\text{wet}} + \text{AI}_{\text{shale}})(\text{AI}_{\text{wet}} - \text{AI}_{\text{hyd}}). \quad \text{(A-8)}$$

Inserting equations A-6–8 into the numerator of equation A-5 and rearranging yields

$$A - B + C = (\text{AI}_{\text{hyd}} - \text{AI}_{\text{shale}})(\text{AI}_{\text{wet}} - \text{AI}_{\text{shale}})$$
$$\times (\text{AI}_{\text{wet}} - \text{AI}_{\text{hyd}}). \quad \text{(A-9)}$$

Substituting equation A-9 into equation A-5, we obtain

$$e = \frac{(\text{AI}_{\text{hyd}} - \text{AI}_{\text{shale}})(\text{AI}_{\text{wet}} - \text{AI}_{\text{shale}})(\text{AI}_{\text{wet}} - \text{AI}_{\text{hyd}})}{(\text{AI}_{\text{hyd}} + \text{AI}_{\text{shale}})(\text{AI}_{\text{wet}} + \text{AI}_{\text{shale}})(\text{AI}_{\text{wet}} + \text{AI}_{\text{hyd}})}$$
$$= \text{NIP}_{\text{hyd}}\text{NIP}_{\text{wet}}\text{NIP}_{\text{hwc}}. \quad \text{(A-10)}$$

Combining equations A-2 and 10 yields equation A-11, which is the same as equation 4:

$$\Delta F_{\text{hyd}} = \text{NIP}_{\text{hyd}} - \text{NIP}_{\text{wet}}$$
$$= -\text{NIP}_{\text{hwc}} + (\text{NIP}_{\text{hyd}}\text{NIP}_{\text{wet}}\text{NIP}_{\text{hwc}}). \quad \text{(A-11)}$$

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Type Logs of South Texas Fields, Vol. II, Wilcox (Eocene) Trend. Compiled by M. A. Wolbrink. 98 p., 1979. Ring binder.
CCGS 016TL $25.00

Field Trip Guidebooks
South Texas Uranium. J. L. Cowdrey, Editor. 62 p., 1968.
CCGS 102G $12.00

Hidalgo Canyon and La Popa Valley, Nuevo Leon, Mexico. CCGS 1970 Spring Field Conference. 78 p., 1970.
CCGS 103G $8.00

Padre Island National Seashore Field Guide. R. N. Tench and W. D. Hodgson, Editors. 61 p., 1972.
CCGS 104G $5.00

Triple Energy Field Trip, Uranium, Coal, Gas—Duval, Webb & Zapata Counties, Texas. George Faga, Editor. 24 p., 1975.
CCGS 105G $10.00

Minas de Golondrinas and Minas Rancherias, Mexico. Robert Manson and Barbara Beynon, Editors. 48 p. plus illus., 1978.
CCGS 106G $15.00

Portrero Garcia and Huasteca Canyon, Northeastern Mexico. Barbara Beynon and J. L. Russell, Editors. 46 p., 1979.
CCGS 107G $15.00

Modern Depositional Environments of Sands in South Texas. C. E. Stelting and J. L. Russell, Editors. 64 p., 1981.
CCGS 108G $15.00

Geology of Peregrina & Novillo Canyons, Ciudad Victoria, Mexico, J. L. Russell, Ed., 23 p. plus geologic map and cross section, 1981.
CCGS 109G $10.00

Geology of the Llano Uplift, Central Texas, and Geological Features in the Uvalde Area. Corpus Christi Geological Society Annual Spring Field Conference, May 7-9, 1982. Variously paginated. 115 p., 53 p.
CCGS 110G $15.00

Structure and Mesozoic Stratigraphy of Northeast Mexico, prepared by numerous authors, variously paginated. 76 p., 38 p., 1984.
CCGS 111G $15.00

Geology of the Big Bend National Park, Texas, by C. A. Berkebile. 26 p., 1984.
CCGS 112G $12.00

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http://www.lib.utexas.edu/books/landsapes/index.php Free service. Rare, fragile, hard-to-find, public domain documents covering various topics about the landscape of Texas. Includes the Texas Geological Survey from 1887 until 1894.

USGS TAPESTRY OF TIME AND TERRAIN http://tapestry.usgs.gov The CCGS is donating to all of the 5th and 6th grade schools in the Coastal Bend. Check it out--it is a spectacular map. You might want to frame one for your own office. The one in my office has glass and a metal frame, and It cost $400 and it does not look as good as the ones we are giving to the schools.

FREE TEXAS TOPOS'S http://www.tnris.state.tx.us/digital.htm these are TIFF files from your state government that can be downloaded and printed. You can ad them to SMT by converting them first in Globalmapper. Other digital data as well.

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http://antwrp.gsfc.nasa.gov/apod/asropix.html Astronomy picture of the day--awesome. I click this page everyday.

http://www.spacimaging.com/gallery/ioweek/iow.htm Amazing satellite images. Check out the gallery.

http://www.ngdc.noaa.gov/seg/topo/globegal.shtml More great maps to share with kids and students.

www.ccgeo.org Don't forget we have our own we page.

http://terra.nasa.gov/gallery/ Great satellite images of Earth.

www.ermaper.com They have a great free downloadable viewer for TIFF and other graphic files called ER Viewer.

http://terrasrver.com Go here to download free aerial photo images that can be plotted under your digital land and well data. Images down to 1 meter resolution, searchable by Lat Long coordinate. Useful for resolving well location questions.

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Aransas Pass/McCampbell Deep
Bartell Pass
Blackjack
Burgentine Lake
Copano Bay, South
Estes Cove
Fulton Beach
Goose Island
Half Moon Reef
Nine Mile Point
Rockport, West
St. Charles
Tally Island
Tract 831-G.O.M. (offshore)
Virginia

BEE COUNTY
Caesar
Mosca
Nomanna
Orangedale(2)
Ray-Wilcox
San Domingo
Tulsita Wilcox
Strauch_Wilcox

BROOKS COUNTY
Ann Mag
Boedecker
Cage Ranch
Encintas
ERF
Gyp Hill
Gyp Hill West
Loma Blanca
Mariposa
Mills Bennett
Pita
Tio Ayola
Tres Encinos

CALHOUN COUNTY
Appling
Coloma Creek, North
Heyser
Lavaca Bay
Long Mott
Magnolia Beach
Mosquito Point
Olivia
Panther Reef
Powderhorn
Seadrift, N.W.
Steamboat Pass
Webb Point
S.E. Zoller

CAMERON COUNTY
Holly Beach
Luttes
San Martin (2)
Three Islands, East

Vista Del Mar
COLORADO COUNTY
E. Ramsey
Graceland N. Fault Blk
Graceland S. Fault Blk
DEWITT COUNTY
Anna Barre
Cook
*******Nordheim**
Smith Creek
Warmsley
Yorktown, South
DUVAL COUNTY
DCR-49
Four Seasons
Good Friday
Hagist Ranch
Herbst
Loma Novia
Petrox
Seven Sisters
Seventy Six, South
Starr Bright, West
GOLIAD COUNTY
Berclair
North Blanconia
Bombs
Boyce
Cabeza Creek, South
Goliad, West
St Armo
Terrell Point
HIDALGO COUNTY
Alamo/Donna
Donna
Edinburg, West
Flores-Jeffress
Foy
Hidalgo
LA Blanca
McAllen& Pharr
McAllen Ranch
Mercedes
Monte Christo, North
Penitas
San Fordyce
San Carlos
San Salvador
S. Santallana
Shary
Tabasco
Weslaco, North
Weslaco, South
JACKSON COUNTY
Carancahua Creek
Francitas
Ganado & Ganado Deep
LaWard, North
Little Kentucky

Maurbro
StewartSwan Lake
Swan Lake, East
Texana, North
West Ranch
JIM HOGG COUNTY
Chaparosa
Thompsonville,N.E.
JIM WELLS COUNTY
Freebom
Hoelsher
Palito Blanco
Wade City
KARNES COUNTY
Burnell
Coy City
Person
Runge
KENEDY COUNTY
Candelaria
Julian
Julian, North
Laguna Madre
Rita
Stillman
KLEBERG COUNTY
Alazan
Alazan, North
Big Caesar
Borregos
Chevron (offshore)
Laguna Larga
Seeligson
Sprint (offshore)
LA SALLE COUNTY
*****Pearsall**
LAVACA COUNTY
Halletsville
Hope
Southwest Speaks
Southwest Speaks Deep
LIVE OAK COUNTY
Atkinson
Braslau
Chapa
Clayton
Dunn
Harris
Houdman
Kittie West-Salt Creek
Lucille
Sierra Vista
Tom Lyne
White Creek
White Creek, East
MATAGORDA COUNTY
Collegeport

MCMULLEN COUNTY
Arnold-Weldon
Brazil
Devil's Waterhole
Hostetter
Hostetter, North
NUECES COUNTY
Agua Dulce (3)
Arnold-David
Arnold-David, North
Baldwin Deep
Calallen
Chapman Ranch
Corpus Christi, N.W.
Corpus Christi West C.C.
Encinal Channel
Flour Bluff/Flour Bluff, East
GOM St 9045(offshore)
Indian Point
Mustang Island
Mustang Island, West
Mustang Island St.
        889S(offshore)
Nueces Bay/Nueces Bay
        West
Perro Rojo
Pita Island
Ramada
Redfish Bay
Riverside
Riverside, South
Saxet
Shield
Stedman Island
Turkey Creek
REFUGIO COUNTY
Bonnieview/Packery Flats
Greta
La Rosa
Lake Pasture
Refugio, New
Tom O'Connor
SAN PATRICIO COUNTY
Angelita East
Commonwealth
Encino
Enos Cooper
Geronimo
Harvey
Hiberia
Hodges
Mathis, East
McCampbell Deep/Aransas Pass
Midway
Midway, North
Odem

Plymouth
Portilla (2)
Taft
Taft, East
White Point, East
STARR COUNTY
El Tanque
Garcia
Hinde
La Reforma, S.W.
Lyda
Ricaby
Rincon
Rincon, North
Ross
San Roman
Sun
Yturria
VICTORIA COUNTY
Helen Gohike, S.W.
Keeran, North
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Benavides
Davis, South
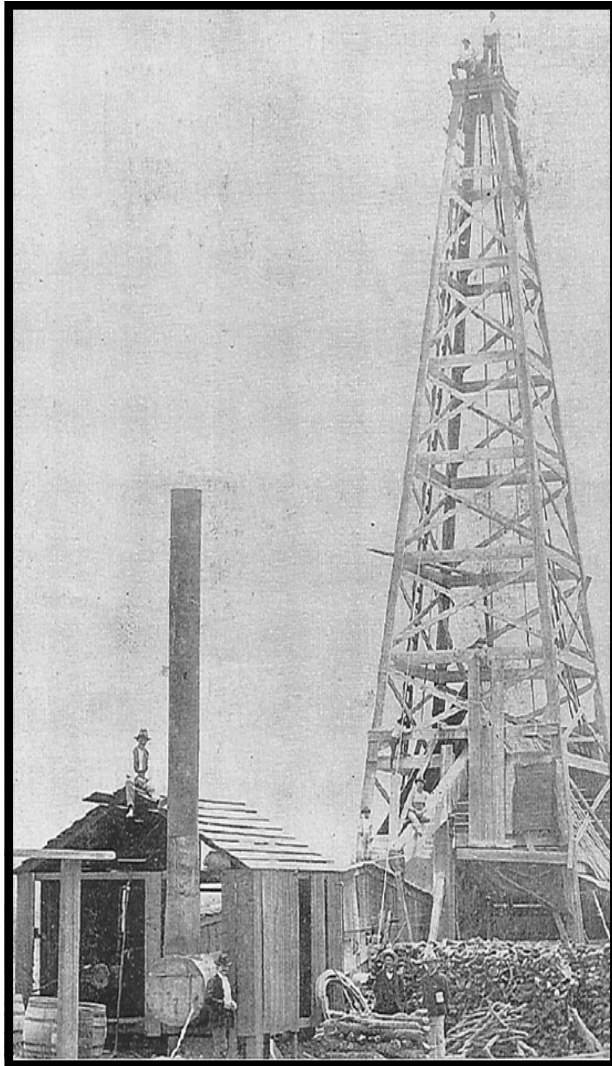Jennings/Jennings, West
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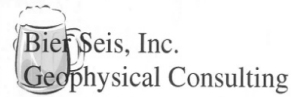
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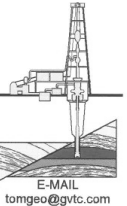
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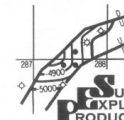606 N. Carancahua, Ste. 610
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